Middle Holocene Oyster Shells and the Shifting Role of History in Ecological Restoration: How a Dynamic Past Informs Shellfish Ecosystem Reconstruction at an Australian Urban Estuary

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abstract

At Western Australia's Swan-Canning Estuary, extensive subfossil shellfish assemblages of Middle Holocene origin were largely destroyed through dredging for cement production in the first half of the twentieth century. This case-study of an extractive industry driving shellfish ecosystem decline builds on existing historical studies of commercial over-harvesting of oysters, and historical and paleo-ecological investigations of sustainable, long-term indigenous oyster harvests, presenting an important new perspective on global shellfish ecosystem decline and the enduring cultural value of shellfish resources by revealing processes of cross-cultural knowledge transfer, unfolding environmental understanding and extensive environmental change across Western Australia's post-European settlement history. We explore these histories in detail for the first time, before considering their relevance to a shellfish ecosystem reconstruction initiative currently underway at this major Australian urban estuary.

keywords: *Swan-Canning Estuary, Middle Holocene oyster shells, ecological restoration, shellfish ecosystem reconstruction, conservation paleobiology, extractive industries, catastrophism, Derbarl Yerrigan*

Oysters and mussels were once ubiquitous features of coastal and estuarine environments globally, critical in creating and maintaining habitats and for ecosystem functioning and health.[1] Today, more than 85 per cent of the world's shellfish ecosystems are either severely degraded or destroyed. Most of this destruction occurred after the turn of the nineteenth century, driven by commercial over-harvesting, disease outbreaks and the effects of habitat loss, siltation and pollution.[2] These destructive processes have been widely studied in support of ecological restoration initiatives, drawing on documentary records, archaeological findings and palaeobiological data to establish reconstruc-

[1] C.L. Gillies et al., 'Australian shellfish ecosystems: Past distribution, current status and future direction', *PLoS ONE* **13** (2) (2018): e0190914.

[2] H. Lotze et al., 'Depletion, degradation and recovery potential of estuaries and seas', *Science* **312** (2006): 1806.

tion targets and reveal environmental change across both centennial (shaped mainly by anthropogenic influence) and millennial (shaped mainly by natural environmental influences) timescales. At Chesapeake Bay, for example, understanding of oyster reef decline integrates historical evidence of recent (late nineteenth to early twentieth century) commercial over-exploitation, an archaeological record of sustainable indigenous harvests (c. 3,500 to 400 years ago), and palaeobiological data pointing to short-term impacts of colonial-era (c. 1500s–1800s) land clearing and agriculture, and long-term shifts in oyster abundance and growth rates extending back to the Estuary's formation in the Pleistocene (c. 500,000 years ago). By the late twentieth century, wild oyster populations were at approximately one per cent of historical levels.[3] Declines on this scale, combined with the extent of recent eutrophication and sedimentation, and anticipated climate change impacts, expose a divergence between ideal and realistic restoration goals by suggesting that a return to the abundance observed by European explorers at Chesapeake Bay is impossible. 'Restoration' is therefore designed not to return the environment to a fixed point in time, but instead involves rehabilitating damaged ecosystems to restore lost structure and function.[4]

Described as the world's 'best studied estuary', Chesapeake Bay underlines the shifting role of historical knowledge in global shellfish reconstruction initiatives and the field of restoration ecology generally. Combining prehistoric, historical and recent perspectives on environmental change is increasingly recognised as vital to accurately understanding pristine ecosystem functioning, appreciating the full scale of ecological degradation across time, and establishing realistic targets for regenerating damaged ecosystems.[5] Such insights

[3] T.C. Rick et al., 'Millennial-scale sustainability of the Chesapeake Bay Native American oyster fishery', *Proceedings of the National Academy of Sciences* **113** (23) (2016): 6568–6573.

[4] T.C. Rick and R. Lockwood, 'Integrating paleobiology, archaeology, and history to inform biological conservation', *Conservation Biology* **27** (1) (2013): 45–54.

[5] J. Carey, 'The complex case of Chesapeake Bay restoration', *Proceedings of the National Academy of Sciences* **118** (25) (2021): 1–2.

reflect a deeper shift in restoration ecology away from returning ecosystems to historical trajectories and towards approaches that employ historical knowledge to provide reference points for how ecosystems have functioned in the past, inform understanding of how altered ecosystems might function in the future, and guide decision-making in ecological conservation and ecosystem intervention. According to Higgs et al. (2014), the changing role of history also embraces a cultural dimension by reinforcing human connections to place, exposing disruptive and damaging relationships over time, and supporting critical perspectives that inform restoration goals with awareness of ecosystem change operating across both long-term and short-term timescales.[6]

Here, we consider multiple temporal perspectives on environmental change at Western Australia's Swan-Canning Estuary in relation to a major current ecosystem restoration project. Surrounded by the city of Perth (population 2.14 million), the Swan-Canning, or *Derbarl Yerrigan* to its traditional owners, the Whadjuk Noongar people, is an urban estuary that has been subjected to pronounced anthropogenic impacts in the era of European settlement. These include extensive catchment development for farming and urban expansion; major modifications to its hydrology through the installation of dams and weirs on its rivers; deepening of its entrance channel to accommodate a deep-water harbour and substantially decreased freshwater inflow since the 1970s; and widespread shoreline modification and in-water infrastructure development. Additional environmental stressors are being caused by the impacts of a warming and drying climate, including higher water temperatures and the exacerbation of hypoxia and harmful algal blooms that dramatically reduce system-wide ecological health.[7] Alongside a raft of management interventions across the catchment and estuary, the Swan-

[6] E. Higgs et al., 'The changing role of history in restoration ecology', *Frontiers in Ecology and the Environment* **12** (2014): 499–506.

[7] C.S. Hallett et al., 'Observed and predicted impacts of climate change on the estuaries of south-western Australia, a Mediterranean climate region', *Regional Environmental Change* **18** (2018): 1357–1373.

Canning is today the site of a major shellfish habitat restoration initiative being led by The Nature Conservancy Australia (TNC), one of thirteen 'Reef Builder' projects rebuilding lost shellfish ecosystems in bays and estuaries across southern Australia.[8]

In their review of Australian shellfish ecosystems, Gillies and colleagues point to dramatic declines in the extent and condition of the two most common communities, developed by *Saccostrea glomerata* and *Ostrea angasi* oysters, 'during the mid-1800s to early 1900s in concurrence with extensive harvesting for food and lime production, ecosystem modification, disease outbreaks and a decline in water quality'.[9] In losing extensive flat oyster (*O. angasi*) shell deposits through dredging for cement production during the first half of the twentieth century, the Swan-Canning Estuary fits within this historical framework. Recent studies of North American and Australian indigenous shellfish consumption across millennial timescales illuminate the more unique aspects of the Swan-Canning case-study. Locations including Chesapeake Bay, Florida's Gulf Coast and Southeast Queensland reveal long-term sustainability in indigenous harvests, presenting a stark contrast to comparatively recent histories of commercial over-exploitation and emphasising the cultural importance of shellfish ecosystems to First Nations communities.[10]

The Swan-Canning Estuary stands apart from these examples for two critical reasons. The first is a lack of comparable archaeological evidence. Australia's south-west corner and the Swan-Canning region in particular is notable for 'an apparent dearth of coastal and other shell middens [and] an ethnographic record suggesting that molluscs were not eaten by Aborigines during late prehistoric to colonial times'.[11] Secondly, the flat oyster assemblages once found

[8] J. Bradley, 'A reef in the history of time', *The Monthly*, February 2021. https://www.themonthly.com.au/issue/2021/february/1612098000/james-bradley/reef-history-time#mtr; (accessed 27 June 2023).

[9] Gillies et al., 'Australian shellfish ecosystems'.

[10] L. Reeder-Myers et al., 'Indigenous oyster fisheries persisted for millennia and should inform future management', *Nature Communications* **13** (2022): 2383

[11] C.E. Dortch, G.W. Kendrick and K. Morse, 'Aboriginal mollusc exploitation in southwestern Australia', *Archaeology in Oceania* **19** (1984): 81–104

within the Estuary were not living shellfish ecosystems at the time of European settlement, but rather comprised of shell deposits formed during the Middle Holocene, between 6,500 and 4,500 years ago. We use the term 'subfossil assemblages' to describe these deposits, as they were not fossilised structures and of less than fossil age at the time of their destruction.

These exceptional features contribute to a more complex relationship between the past and the present at the Swan-Canning Estuary, as we explore here. Although our case-study fits within a broader pattern of historical environmental destruction, the subfossil assemblages open a window onto the Estuary's long-term environmental history, in ways that move beyond a simple contrast between sustainable indigenous harvests and unsustainable commercial exploitation. As relics of the paleo-estuary, the assemblages were a focus of cross-cultural transfer of environmental knowledge during the formative years of Western Australia's European settlement. Theories of their origin changed again the twentieth century after intersecting with early experiments in live oyster cultivation, contributing to a growing awareness of how the Estuary's environment had been altered across the post-settlement era. Their destruction was driven by demand for lime in cement production, presenting a valuable example of extractive industry driving shellfish ecosystem decline.[12]

This paper outlines these multiple environmental histories for the first time, before considering their relevance to the current reconstruction initiative. In particular, we demonstrate the extent of environmental change in the Swan-Canning Estuary across both geological (i.e. since the Middle Holocene) and historical (since European settlement) timeframes and locate shellfish ecosystem reconstruction within these contexts. We show how these overlapping contexts clarify key choices in restoration strategy, which is based on

(81–83). See also: S.J. Meagher and W.D.L. Ride, 'Use of natural resources by the Aborigines of South-Western Australia', in R.M. Berndt and C.H. Berndt (eds), *Aborigines of the West* (Nedlands, WA: University of Western Australia Press, 1979), pp. 66–80 (p. 74).

[12] E. Doran, 'Shell roads in Texas', *Geographical Review* **55** (2) (1965): 223–40.

establishing beds of the blue mussel (*Mytilus galloprovincialis*) rather than reefs of the flat oyster (*O. angasi*) that is the basis of subfossil assemblages and a reef-building species common to sheltered embayments along southern Australian coasts in the historical era, but no longer endemic to the Swan-Canning system.[13] By linking the present and future Estuary to deep-time, colonial and twentieth-century pasts, we foreground the cultural values of shellfish ecosystems and assemblages across time, thus underlining the shifting roles of historical knowledge in ecological restoration today.

The Swan-Canning Estuary's subfossil assemblages in historical perspective

Historical studies of Australian shellfish ecosystems have focussed on quantifying past distributions and analysing causes of decline, generally with the aim of establishing reference points or baselines to guide modern restoration efforts.[14] Thurstan and colleagues (2020) incorporate archaeological data, documentary records and oral histories to outline rapid declines in Sydney rock oyster (*S. glomerata*) populations along Queensland's south-eastern and central coasts, which declined to one-tenth of historical levels by the late twentieth century through over-harvesting, siltation from land settlement in catchment areas, outbreaks of parasites and diseases and, more recently, habitat modification linked to urban expansion.[15] Alleway and Connell (2014) analyse documentary records for South Australia's *O. angasi* fishery between the early colonial period and mid-1940s to reveal that oyster reefs were removed from a 1,500 km stretch of coastline before knowledge of their existence was lost to

[13] Gillies et al., 'Australian shellfish ecosystems'.

[14] See Ibid. and C.L. Gillies et al., 'Restoring Angasi oyster reefs: What is the endpoint ecosystem we are aiming for and how do we get there?' *Ecological Management and Restoration* **18** (2017): 214–222.

[15] R. Thurstan et al., 'Charting two centuries of transformation in a coastal social-ecological system: A mixed methods approach', *Global Environmental Change* **61** (2020): 1–11.

collective memory, precipitating a shifted conservation baseline.[16] Evidence for disease impacts linked to expanding oyster cultivation between 1880 and 1900 have been located through careful investigations of contemporary fisheries reports and early scientific publications.[17] Other studies have focussed on cultural drivers of ecosystem decline, including Frawley's (2020) discussion of how capitalist imperatives drove socio-economic reorganisation of harvesting and cultivation but failed to prevent long-term declines in exploited shellfish populations in Queensland,[18] and Christensen's (2019) explanation for the collapse of the Shark Bay pearl oyster (*Pinctada albina*) fishery from a confluence of fisher behaviour, management intransigence, global market forces and environmental variability.[19]

For the Swan-Canning Estuary, we unearthed diverse anecdotal observations of subfossil assemblages for the period between European exploration and their destruction in the first half of the twentieth century, data from the few palaeontological investigations available, and extensive administrative and cartographic records emanating from their commercial exploitation as a source of lime for building and cement manufacture in the first half of the twentieth century. This commercial exploitation was dominated by the operations of the Swan Portland Cement Company (SPCC). We use this archive map the known extent of subfossil deposits and locate them within both the Estuary as it was in 1827, when the assemblages are first

[16] H.K. Alleway and S.D. Connell, 'Loss of an ecological baseline through the eradication of oyster reefs from coastal ecosystems and human memory', *Conservation Biology* **29** (2015): 795–804.

[17] D.M. Ogburn, I. White and D.P. McPhee, 'The disappearance of oyster reefs from Eastern Australian estuaries—impact of colonial settlement or mudworm invasion?', *Coastal Management* **35** (2007): 271–287.

[18] J. Frawley, 'Adapting to change in Australian estuaries: Oysters in the techno-fix cycles of colonial capitalism', in U. Kirchberger and B.M. Bennett (eds), *Environments of Empire: Networks and Agents of Ecological Change* (Chapel Hill, NC: The University of North Carolina Press, 2020), pp. 176–196.

[19] J. Christensen, 'The pearler's problem: Management, markets and the marine environment in the Shark Bay pearling industry', in P. Machado, S. Mullins and J. Christensen (eds), *Pearls, People and Power: Pearling and the Indian Ocean Worlds* (Athens, OH: Ohio University Press, 2019), pp. 118–147.

recorded in documentary records, and during the Middle Holocene, when the assemblages functioned as living shellfish ecosystems. We also use maps to illustrate the destruction of the subfossil assemblages in the context of the Estuary's environmental transformation and decline in the twentieth century. The maps and our discussion help to draw out the cultural dimensions of the Estuary's shellfish communities across time, in recognition that maps themselves act culturally; as Mitchell Whitelaw puts it, 'visualisation is a medium for reflection, a way to both represent and intervene in the landscapes we live in'.[20]

Subfossil assemblages: origins and character

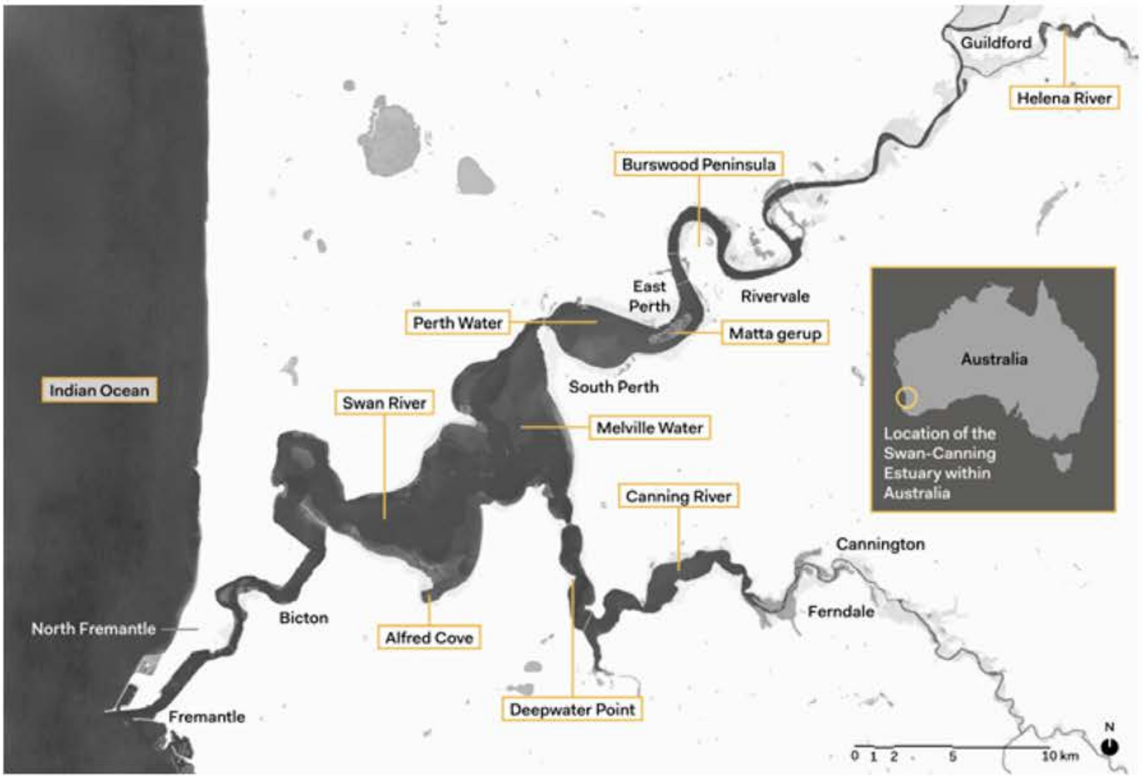
The earliest written descriptions of the Swan-Canning's subfossil shell deposits derive from James Stirling's exploration in March 1827, a visit that led to Britain proclaiming its new Swan River Colony two years later. Stirling's party had ascended the Estuary as far as *Matta gerup* (tr. 'knee deep'; Figure 1), adjacent to Burswood Peninsula, 'when they were prevented going further by meeting with the Flats, that here extended themselves the whole width of the River & 1 1/2 mile in length', according to Stirling's clerk, the naval officer W.C. Gilbert:

> They were reduced to the necessity of taking everything out of the boats, and landing them on one of the many islands that are formed in this part of the River by the floods, and to drag the boats over by main force, there being not sufficient water to float the Gig. In doing this the party were above their knees in mud, and obliged to walk over extensive beds of Oyster Shells, which lacerated their feet much.[21]

[20] M. Whitelaw, *Australasian Data Practices: Mining, Scraping, Mapping, Hacking*. https://mtchl.net/australasian-data-practices/ (accessed 27 June 2023).

[21] 'Journal of W.C. Gilbert, an officer of the Success, of Captain J. Stirling's exploration of the Swan River, &c, 1827', in J. Schoobert (ed.), *Western Australian Exploration Volume One December 1826–December 1835: The Letters, Reports & Journals of Exploration and Discovery in Western Australia* (Victoria Park, WA: Hesperian Press, 2005), p. 61.

Figure 1. The Swan-Canning Estuary, showing locations referred to in text.



Map created by Daniel Jan Martin.

The incident is also detailed by the expedition's naturalist, the botanist Charles Frazer. 'From extensive beds of oyster shells, which lie a foot deep in soft mud, our feet became dreadfully lacerated', he recorded.[22]

Three details here are important. The first is that Frazer and Gilbert both mention 'oysters' and not a variety of mollusc known to occur naturally in the modern Estuary. Taxonomic analysis of deposits at Guildford, upstream of *Matta gerup*, show the subfossil assemblages there were dominated by *O. angasi*.[23] In the 1830s,

[22] C. Fraser, 'Remarks on the botany, &c. of the banks of the Swan River, Isle of Bauche, Baie Geographie, and Cape Naturalist by Mr Charles Fraser, Colonial Botanist in New South Wales', in Schoobert (ed.), *Western Australian Exploration*, pp. 46–59, at p. 50.

[23] Gillies et al., 'Australian shellfish ecosystems', 4.

colonist George Fletcher Moore used the word ‘clam’ to describe mussels (probably Carter’s freshwater mussel *Westralunio carteri*) that he found further upstream at Henley Brook. The second is that Stirling’s party encountered the oysters buried to the depth of at least one foot. When, in 1927, Western Australia’s Public Works Department (PWD) probed the shallows immediately west of *Matta gerup*, shell patches were encountered at depths ranging from one to eight feet.[24] Not all deposits were covered, however. The naturalist James Pollard examined Burswood Peninsula in the early 1940s and described it as ‘almost entirely a shell bed, the shell in many parts exposed’.[25] Such uneven and relatively thin sedimentation reflects the character of these deposits as subfossil rather than older, fossilised structures. Thirdly, although the shell at *Matta gerup* was rigid enough to lacerate the explorers’ feet, suggesting a consolidated structure consistent with true ‘reefs’, at Burswood, immediately adjacent, Pollard refers to ‘beds’. In Melville Water, anecdotal accounts from dredging mention ‘deposits’ of ‘decayed shell’.[26] These assemblages likely comprised of disaggregated shell from *O. angasi* and other shellfish species accumulated over time from structures dating from the Middle Holocene. The point is simply that reefs and beds are both typical features of shellfish ecosystems.[27] The observations from 1827 therefore indicate the Swan-Canning Estuary once supported thriving *O. angasi* communities comparable to the living structures that occurred widely along temperate Australian coastlines in the nineteenth century.

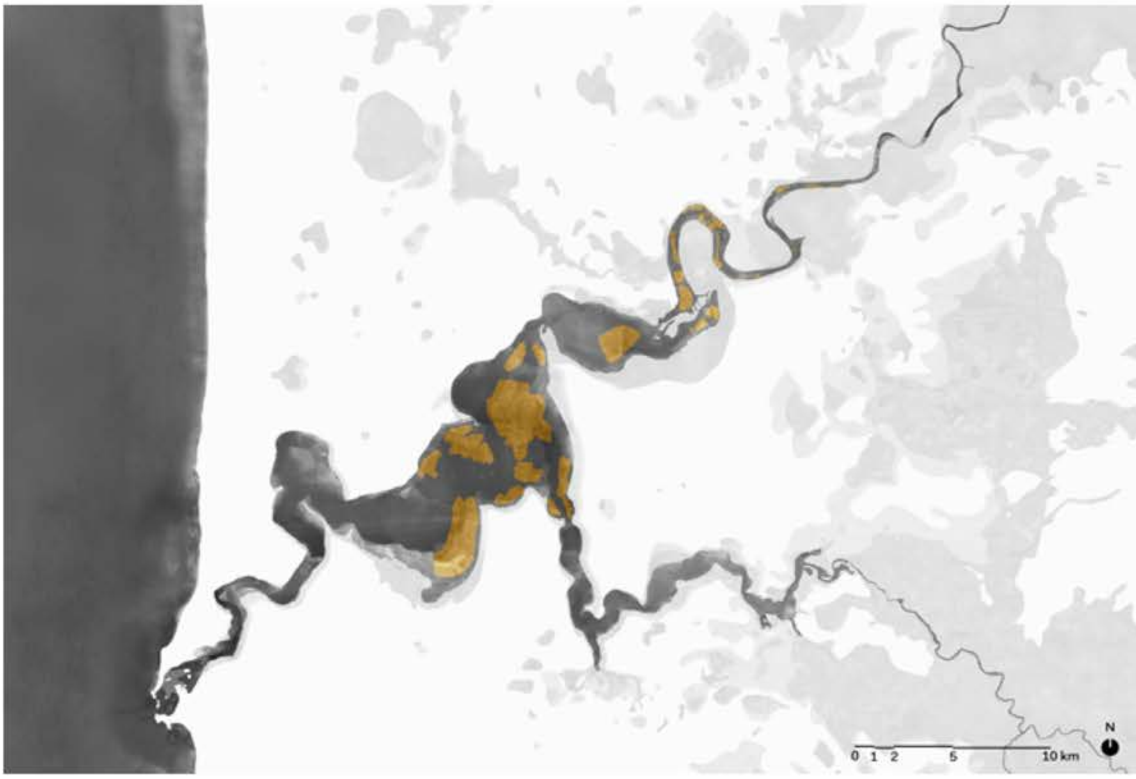
[24] Public Works Department, Items 13380 and 13381, ‘Swan River improvements: Probings to determine shell deposits between Causeway and A.N.A. sheds. 09/1927. R. Taylor’, Cons. 3465, State Records Office of Western Australia [hereafter SROWA].

[25] J. Pollard, ‘Swan River shell deposits’, *Walkabout*, 1 March 1943, pp. 26–27.

[26] Swan Portland Cement Limited, *A Saga of Progress: The History of Fifty-two Years of Cement Making in Western Australia, 1921–1973* (Perth: Swan Portland Cement Co., 1973), pp. 1–3.

[27] C. Crawford et al., ‘Relationship of biological communities to habitat structure on the largest remnant flat oyster reef (*Ostrea angasi*) in Australia’, *Marine and Freshwater Research* **71** (8) (2020): 972–983.

Figure 2. Known Subfossil shell deposits of the Swan-Canning Estuary. The subfossil assemblages are depicted here over a reconstruction of the estuary edge and wetland landscape at colonisation. In the grey tones are historic wetland locations indicated by clayey, silty and peaty surface geologies, and areas of shallow groundwater, indicating ephemeral wetlands and creeks.



Source: Derived from Department of Mines, Industry Regulation and Safety (DMIRS) surface geology maps, Department of Water and Environmental Regulation (DWER) groundwater contour dataset, Western Australian Land Information Authority (WALIA) medium scale topographic dataset and historical maps and archives. Map created by Daniel Jan Martin.

Figure 2 shows that extensive deposits once occurred in the middle Estuary, although the full extent of the assemblages was likely even greater than shown here. The accounts from Stirling's party in 1827 and from the PWD's investigations in 1927 reveal many deposits were buried, a scenario to be expected in light of the sedimentary processes common to an estuary. The thin layer of sediment didn't hinder dredging by the SPCC but it is likely that many nearshore deposits too shallow to be dredged were instead buried deeper during reclamation works at Burswood, along the northern side of Perth Water through to East Perth, and other places between the 1880s and 1970s.[28] Furthermore, lowering sea levels since the Middle Holocene means that contiguous shell deposits exist beyond the Estuary's current shorelines and underlie river suburbs today. A bore dug at South Perth in 1930 created a stir in local geological circles when oyster shell was found amongst the spoil, and subsequent bore lithologies reveal widespread shelly deposits of Middle Holocene and earlier origin underneath what are today the inner suburbs of Perth.[29] Within the Estuary, shell deposits are also known to have been removed to reduce hazards for recreational activity, for example, at Bicton (a swimming area) and Deep-Water Point (rowing and water-skiing). The total volume of shell dredged from Perth Water by the PWD in the twentieth century is unknown. What Figure 2 illustrates, then, are the assemblages known to have been be dredged by the SPCC, and thus it reflects the scale of environmental change resulting from cement production alone.

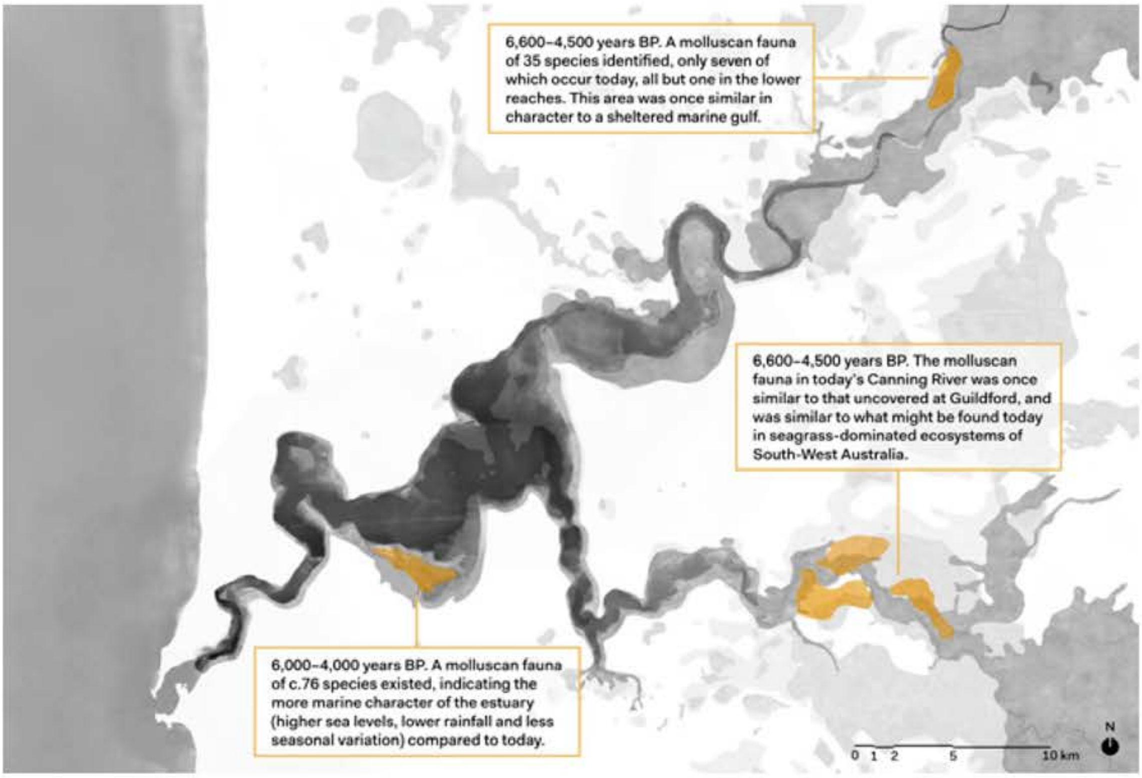
Figure 3 depicts the profile of the Estuary in the Middle Holocene, when the subfossil deposits originated. What is known about their age and composition derives from investigations led by palaeontologist George Kendrick in three areas: a stretch of the upper Swan Estuary near the confluence of the Helena River at Guildford; around Ferndale and Cannington in the upper reaches of the Canning Estuary; and at Point Waylen, Alfred Cove, in Melville Water. These were among the last deposits remaining after commercial dredging had concluded, although 'river improvement' was continuing to destroy them; Kendrick's samples at Guildford (1969–71) and the Canning (mid-1970s) were obtained from the spoil produced during channel works to clear and deepen navigational channels.[30]

[28] *West Australian*, 22 January 1931.

[29] *Daily News* [Perth], 9 January 1930.

[30] G.W. Kendrick, 'Middle Holocene marine molluscs from near Guildford, Western Australia, and evidence for climate change', *Journal of the Royal Society of Western Australia* **59** (4) (1977): 97–104.

Figure 3. *Derbarl Yerrigan*, Middle Holocene. The Estuary's form is reconstructed as a flooded terrain, where clayey, silty and peaty surface geologies and depth to groundwater information are used as indicators for a historically submerged Holocene landscape.



Source: derived from DMIRS surface geology maps, DWER groundwater contour dataset, WALIA medium scale topographic dataset and historic maps and archives. Map created by Daniel Jan Martin.

All date from between approximately 6,600 and 4,500 years ago. The Estuary was then a very different system. The sea level was up to two metres higher, contributing to its larger size. As the climate of Southwest Australia was also then more arid, the Estuary had a more marine character, with a hydrologic cycle shaped by diminished river discharge and more stable salinity regimes.[31] We reconstruct this sys-

[31] I. Yassini and G.W. Kendrick, 'Middle Holocene ostracodes, foraminifers and environments of beds at Point Waylen, Swan River Estuary, southwestern Australia', *Alcheringa* **12** (2) (1988): 107–121.

tem by taking clayey, silty and peaty surface geologies and depth to groundwater information as indicators of previously flooded terrain. The result is a vision of the paleo-Estuary more similar to a sheltered marine gulf of the temperate Australian coastline today than the variable, salt-wedge estuary encountered in 1827.

The taxonomy of the deposits reflects this different environmental character. Pollard (1943) describes Melville Water assemblages as comprising 'fifty per cent […] oyster, and the balance cockle, muscle, rib, fan and winkle-type shell'.[32] This would be typical of an *O. angasi* reef ecosystem that occurred in the lower reaches of estuaries and sheltered inlets and bays along Australia's temperate coasts before their widespread destruction through over-fishing.[33] Other varieties of filter-feeding bivalves, gastropods, sea anemones and tube worms identified by Kendrick are broadly typical of *Halophila* sp. and *Ruppia* sp. seagrass communities in temperate estuarine and coastal environments in Southwest Australia today.[34] Most of these invertebrate species no longer occur in the Swan-Canning Estuary; only seven of the 31 species identified at Guildford have been found living within the system, and all but one in the lower reaches only.[35] The deposits at Point Waylen (1975) allowed for more careful sequencing and reveal a shift towards faunal impoverishment likely linked to increasing winter rainfall between c. 6,000 and c. 4,000 years ago. Only twelve mollusc species occurred naturally in the Estuary at this time, including a native blue mussel (likely *Mytilus planulatus*), compared to a Middle Holocene fauna of 76 species. Comparable work at the Peel Inlet, 60 kilometres south of the Swan-Canning Estuary, suggests a shift in climate helped to drive the demise of similarly diverse and abundant molluscan ecosystems.[36]

[32] Pollard, 'Swan River shell deposits', p. 28.

[33] Gillies et al., 'Restoring Angasi oyster reefs'.

[34] A. Brearley, *Ernest Hodgkin's Swanland: Estuaries and Coastal Lagoons of Southwestern Australia* (Crawley: The University of Western Australia Press, 2005), p. 71.

[35] Kendrick, 'Middle Holocene marine molluscs'.

[36] Yassini and Kendrick, 'Middle Holocene ostracodes'; P.N. Chalmer, E.P. Hodgkin and G.W. Kendrick, 'Benthic faunal changes in a seasonal estuary of south-western Australia', *Records of the Western Australian Museum* **4** (4) (1976): 383–410.

Cross-cultural transfers and the catastrophist interpretation

That dead oyster shell occurred across the Estuary when the same or similar species could not be found alive perplexed settlers at the Swan River Colony. Moore considered the matter in 1831: 'it is singular that oysters have not been found (except one or two) though the shells are very numerous about the flats and in Melville Water – beds of them'.[37] In an 1842 vocabulary of the Noongar language, Moore again remarked that 'Deep and extensive beds of oyster-shells are found on the flats in the Swan River, but no live oysters have yet been described in that vicinity'.[38] The scale of some deposits revealed during dredging confounded such questions around origin and age. In Melville Water, Pollard found 'deposits vary between four and fourteen feet in depth' and another account suggests fifteen to twenty feet was common.[39] One was even dredged to a depth of 48 feet.[40] These were accumulations of disaggregated shell deposited across extended timeframes, though this wasn't readily apparent at the time. Instead, the idea that had taken hold was that the Estuary's subfossil assemblages had perished suddenly, in a severe flood. Pollard gleaned as much in conversation with the dredgers, reporting that:

> [those] who know where all the shell lies modestly disclaimed any theories of their own on the origin of the beds, but were content to reiterate those of scientists-visitors whom from time to time they have received as guests on the dredge – theories of storm and flood of an olden time and the catastrophic destruction of marine life in the river by fresh water pouring down from the watershed over a prolonged period.[41]

[37] G.F. Moore, *The Millendon Memoirs: George Fletcher Moore's Western Australian Diaries and Letters, 1830–1841*, edited with an introduction by J.M.R. Cameron (Victoria Park, WA: Hesperian Press, 2006), pp. 157–158.

[38] G.F. Moore, *A Descriptive Vocabulary of the Language in Common Use Amongst the Aborigines of Western Australia* (London: William S. Orr & Co, 1842). We thank Tony Rouphael for sharing this reference.

[39] Pollard, 'Swan River shell deposits'; *Daily News*, 9 January 1930.

[40] Swan Portland Cement, *A Saga of Progress*, pp. 1–3.

[41] Pollard, 'Swan River shell deposits'.

The fact Moore addressed the subfossil assemblages in his 1842 vocabulary reveals the influence of Noongar knowledge in shaping settler understanding of the local environment. Another broker in this process was Francis Armstrong, the colony's first official interpreter. During the early 1830s Armstrong documented several aspects of the Noongar relationship to the Estuary, including the name *Derbarl Yerrigan* and some of the fishing practices employed.[42] An explanation for the existence of extensive shell deposits emerged out of these same exchanges. From his work, Armstrong learnt that living reefs and beds had been killed off by freshwater inundation during a flood so tremendous it had inundated the plains surrounding *Matta gerup* for nine lunar months. The flood had occurred recently, perhaps in 1828, between Stirling's exploration and the colony's proclamation.[43] This became the basis for a popular and enduring explanation that persisted for more a century. It was echoed, for example, in Colebatch's centenary history of Western Australia:

> The enormous, seemingly inexhaustible, deposits of oyster shells in the riverbed demonstrate that, at some, perhaps remote, period these bivalves bred here […] What happened to them? A tenable theory is that on some occasion the mouth of the Swan became blocked so completely as to exclude the entrance of salt water from the sea. Then came a rush of fresh water from the hills causing the oysters to perish in one mighty cataclysm; one all-embracing havoc.[44]

Creation stories of great floods are common to indigenous societies in Australia's coastal regions. Passed on through oral tradition from the ancestral past, they are thought to be of great longevity, emerging out of gradual postglacial sea-level rises at least 7000 years ago.[45] One study at Port Philip Bay suggests eustatic change in the

[42] See *Perth Gazette*, 29 Oct., 5 Nov. and 12 Nov. 1836; A.J. Thompson, The interpreter: The legacy of Francis Fraser Armstrong (BA Hons Dissertation, Murdoch University, 2015).

[43] *Western Mail*, 29 Jan. 1920; *Daily News*, 30 July 1926.

[44] H. Colebatch, *A Story of a Hundred Years: Western Australia, 1829–1929* (Perth: Government Press, 1929), p. 338.

[45] P.D. Nunn and N.J. Reid, 'Aboriginal memories of inundation of the Aus-

Middle Holocene that significantly altered tidal and salinity regimes, with corresponding shifts in marine shell fauna, are the origin of indigenous accounts of a great flood recorded in the mid-nineteenth century.[46] It is certainly the case that Noongar concepts of time and relationships to Country are inter-related and extend across timescales in ways that early settlers did not comprehend. This contributed to misunderstandings in other contexts, as in 1834, when Noongar reports prompted an expedition to be despatched north of Perth to rescue what were believed to be the survivors of a recent shipwreck; none were found, and the reports probably related to Dutch castaways along the mid-west Western Australian coast in the seventeenth and eighteenth centuries.[47] What Armstrong had encountered was therefore more likely a segment of local knowledge that linked Noongar people to ancestors and Country through accounts of environmental change, rather than a deliberate explanation of why edible oysters could not be found within the Estuary.

There are other reasons, however, why a sudden and severe flood was such a compelling explanation. Armstrong's missionary impulses and contemporary scientific ideas helped to shape his interpretation of Noongar testimony. There is an obvious affinity to biblical accounts of the Great Flood, which may have resonated with his determination to introduce Christianity to the Noongar people.[48] Moreover, catastrophist ideas were perfectly legitimate at this time as explanations of observable phenomena. Theories of sudden and violent sea-level changes were expressed frequently in the narratives of Western Australia, and while this literature was familiar to settlers in the Swan River Colony, there is less evidence of adherence to the gradualism theory of John Hutton or Charles Lyell's recent *Principles*

tralian coast dating from more than 7000 years ago', *Australian Geographer* **47** (1) (2016): 11–47.

[46] G.R. Holdgate, B. Wagstaff and S.J. Gallagher, 'Did Port Phillip Bay nearly dry up between ⊠2800 and 1000 cal. yr BP? Bay floor channelling evidence, seismic and core dating', *Australian Journal of Earth Sciences* **58** (2) (2011): 157–175.

[47] *Perth Gazette and Western Australian Journal*, 4 October 1834.

[48] Thompson, 'The interpreter', pp. 28–42.

of Geology (1830–33).[49] A devastating flood could also be reconciled with empirical experience. One of the largest floods ever recorded at Perth had occurred in 1830, less than a year after the colony was proclaimed. That May, the upper Estuary rose six metres over 'the usual level', leaving the 'whole of the Causeway Flats and surrounding country [...] under water for months'.[50] This event and the notion that a similar one had caused the demise of once-flourishing oyster reefs duly shaped perceptions of the Estuary's hydrology. John Lort Stokes, a trained hydrographer, captured this on his visit in 1838. 'Like all the Australian rivers with which we are yet acquainted', he wrote, 'the Swan is subject to sudden and tremendous floods, which inundate the corn lands in its vicinity, and sweep away all opposing obstacles with irresistible impetuosity'.[51] The durable nature of oyster shells also confounded ideas of their age. Pollard believed the samples he examined were 'not fossils [and] no more worn or weathered than are the shells cast up on the seashores to-day. They may be less than a century old'.[52] The shell from Guildford that Kendrick examined was often 'clean' or free of sediment and only broken or abraded during dredging itself, yet was proven by radio-carbon dating to be of Middle Holocene origin.[53]

Creating new 'oyster beds'

Signs of alternative explanations for the subfossil assemblages emerged in the late nineteenth century through the work of marine biologist William Saville-Kent. Western Australia's inaugural Commissioner of Fisheries, Saville-Kent worked during 1893–5 to reha-

[49] T.G. Vallance, 'Presidential address: origins of Australian geology', *Proceedings of the Linnaean Society of New South Wales* **100** (1) (1975): 13–43.

[50] T.L. Riggert, *The Swan River Estuary: Development, Management and Preservation* (Perth: Swan River Conservation Board, 1978), pp. 19–22.

[51] J.L. Stokes, *Discoveries in Australia, Volume One* (London: T. & W. Boone, 1846), chap. 1.3.

[52] Pollard, 'Swan River shell deposits'.

[53] Kendrick, 'Middle Holocene marine molluscs'.

bilitate the colony's pearling industry, acclimatise freshwater fish in the temperate South-west, and establish a local table oyster industry. Upon arriving, he made an inspection of the Estuary. Local ideas were initially persuasive. He found it was

> plainly evident, after an inquiry into the conditions that now obtain, that the vast oyster beds that originally existed here were destroyed by some sudden and complete alteration of the character of the Swan River Estuary. This probably took the form of an extraordinary flood, which, bringing down an abnormal quantity of silt, narrowed or barred up the river mouth to such an extent that the fresh flood waters were retained in the river channel for so long a period that all the oysters were killed.[54]

Four years later, after his appointment ended and in the more considered format of his *The Naturalist in Australia* (1897), he advanced a different theory:

> In prehistoric years the Swan River estuary was the site of enormous banks of the ordinary cold water or Common Oyster, *Ostrea edulis* [*O. angasi*] [...] Portions of the river bed are at the present date solid masses of this oyster's shells, and similar accumulations on either side mark the former much more considerable area of permanent salt water. With the process of time the river channel and its connecting reaches have become more or less extensively silted up, and so it has at length been brought about that where, formerly, water sufficiently salt for the growth of oysters was permanently present, it has been, as now during flood seasons, so long replaced by that which is perfectly fresh that the oysters have been destroyed.[55]

Significantly, this shift from catastrophism to a gradualist interpretation was undoubtedly influenced by experiments in translocating live oysters that Saville-Kent had initiated.

Settlers in Western Australia had a similar appetite for oysters as British people everywhere and by the late nineteenth century several tonnes were being imported each month from fisheries in eastern

[54] *Western Mail*, 15 April 1893.

[55] W. Saville-Kent, *The Naturalist in Australia* (London: Chapman and Hall, 1897), p. 246.

Australia.[56] Inevitably, efforts were made to establish a local supply. An early attempt was made in the mid-1860s when the entrepreneur Edmund Stirling imported live *S. glomerata* and planted them around the entrance to the Estuary and on the islands adjacent to Fremantle. Little is known about this experiment, but there is no evidence it succeeded.[57] Saville-Kent preferred rock oysters (*S. cucullata*) from Shark Bay (about 800 km north of Perth) for his own experiment, which he initiated in April 1893 by laying down live shellfish around a breakwater at Fremantle, recently built as a part of harbour construction works. Though he saw it as an initial step towards establishing 'remunerative oyster beds throughout a large portion of the extensive fists in the immediate neighbourhood of the river mouth',[58] he was less sanguine by the time his term as Commissioner ended. 'During the writer's stay in the colony', he wrote in 1897, 'these oysters had increased in size and commenced to propagate, though whether the species can be permanently acclimatised in a station so far south of its natural habitat remains to be demonstrated'.[59] When the breakwater was investigated by W.E. Learoyd, a fisheries inspector from New South Wales, during 1896, ongoing harbour construction had impacted the site and all that could be found were 'several small clusters' of five or six oysters, with only one or two in each cluster alive.[60] Learoyd nonetheless believed that oysters could survive in this location; 'it is a very suitable place for the rock oyster to thrive. […] the natural condition of the water, the climate, and the situation artificially made [i.e. the breakwater] all combine to make this a likely place for oyster culture'.[61]

The striking feature of this experiment is its location. By select-

[56] G. Blainey, *Black Kettle and Full Moon* (Camberwall, Vic: Penguin, 2003), pp. 302–305.

[57] *The Bulletin*, 12 Nov. 1947.

[58] *Western Mail*, 15 April 1893. See also W. Saville-Kent, 17 July 1894, in Fisheries Department item 1894/2470, 'Oysters – Fremantle breakwater / Rous Head', Cons. 477, SROWA.

[59] Saville-Kent, *The Naturalist in Australia*, p. 246.

[60] *West Australian,* 27 Oct. 1896.

[61] Ibid.

ing the ocean side of the breakwater forming the Estuary's entrance as the most suitable habitat for rock oysters, Saville-Kent opted for a site where estuarine influence was the most marginal. Less than a year after Learoyd's inspection, however, the opening of Fremantle Harbour established a permanent and deepened ocean outlet that substantially modified the Estuary's hydrological cycles by enabling greater tidal intrusion and creating a marine-like habitat within its lower reaches. By the turn of the century, a number of small-scale 'oyster beds' had been established just beyond the harbour limits at North Fremantle to keep imported *S. glomerata* alive for local sale. These later moved upstream, to East Fremantle and Bicton, to avoid clashes with other commercial, residential and recreational activities.[62] One area at East Fremantle later became known as the 'Oyster Beds' after a seafood restaurant opened there. Rock oysters from northern waters were later kept at these sites too.[63] The beds operated into the mid-1950s, across a period of change in catchment areas marked by dam building and salinisation of the Swan-Avon River.[64] Their decline is linked to the greater availability of refrigeration and improved road transport, which facilitated more rapid live oyster imports and left local farms unviable.

Destroying subfossil assemblages

The potential to derive lime from the subfossil assemblages was considered as early as 1842 by the builder James Austin. Supplies known to the colonists consisted of coastal limestone, limestone

[62] *Western Mail*, 27 May 1898; Secretary, Fremantle Local Board of Health, 19 January 1903, in Fremantle Local Board of Health, item 1905/46, 'Oyster beds in Swan River', Cons. 2790, SROWA.

[63] Fisheries Inspector Brown, 6 September 1913, in Fisheries Department item 1921/0024, vol. 1, 'Fisheries – Oyster – Cultivation of Oysters', Cons. 1759, SROWA; Fisheries Inspector Bowler, 7 Jan. 1949, in Fisheries Department item 1948/0323, 'Fisheries – Departmental – Oyster cultivation experiments – General file', SROWA.

[64] Brearley, *Ernest Hodgkin's Swanland*, p. 86; Riggert, *The Swan River Estuary*, p. 18. The dams are Canning Dam (1940) and Mundaring Weir, built 1902 and extended in 1951 and 1959.

outcrops around the Estuary, and 'the shells of oysters, cockles, &c, which have been raised from the beds of rivers & etc, in this colony. These if well purged from saline impregnation, and carefully calcined would produce a very excellent cement', Austin remarked, 'but I am apprehensive that the very limited quantity that could be conveniently found added to the cost of labour in raiding them, would, for the present, be a great barrier to its adoption'.[65] Imported cement, coastal lime kilns or small-scale lime-burning adjacent to building sites met the colony's needs throughout the nineteenth century. Across this period, interference with the Estuary's deposits was light. In the 1830s, canals were dug at *Matta gerup* and Burswood to enable boats to transit the shallows, and in the 1860s growing timber exports led to channel deepening in the Canning to allow barges to ascend upstream.[66] With the acquisition of the bucket dredge *Black Swan* in 1872, the colonial government proceeded to dredge navigational channels in Perth Water to open routes through 'soft mud, varied in some places with oyster shell banks'.[67] During the 1890s, deposits around *Matta gerup* were also used in early reclamation works along the foreshore of Perth and East Perth.

The advantage of using oyster shell for shoreline reclamation was its hard, durable quality. Subfossil assemblages continued to be used in reclamation in the twentieth century, though the quantities disturbed are unknown. The deposits were also suitable for road making, as shell broke down into particles large enough to provide drainage while retaining bonding properties. It was therefore commonly used to construct and resurface footpaths during the early 1900s. An inner-city horse-racing track was also made and regularly re-laid from this material.[68] Much of this came from deposits in Perth Water. Reclamation works, the requirements of local governments and removal of deposits as navigational hazards continued across the Es-

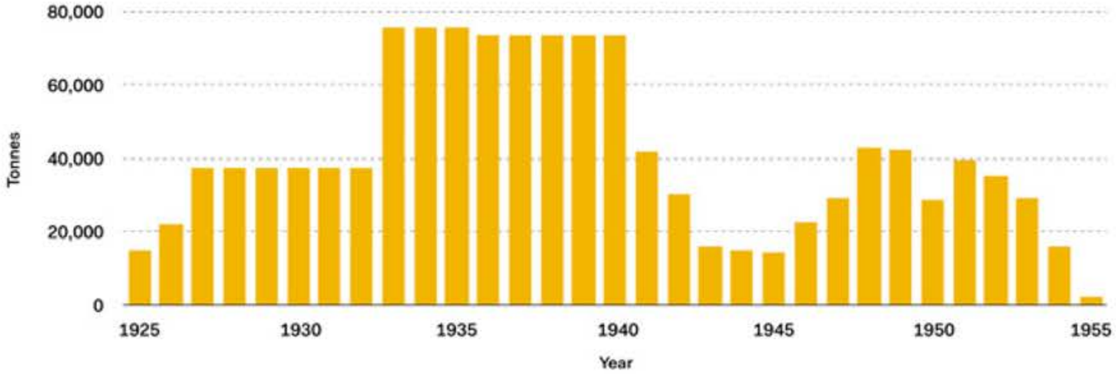
[65] *Perth Gazette and Western Australian Journal*, 2 Dec. 1843.

[66] *Inquirer and Commercial News*, 5 April 1865; Riggert, *The Swan River Estuary*, pp. 24–25.

[67] *Inquirer and Commercial News*, 5 April 1865.

[68] *West Australian*, 19 November 1928; *West Australian*, 21 Oct. 1953; *Daily News*, 24 Jan. 1930.

Figure 4. Shell dredged (tonnes) from the Swan-Canning Estuary by the Swan Portland Cement Company, 1925–55.



Source: Monthly and annual returns filed by the SPCC in Department of Lands & Surveys items 1923/4706, vols 1–4, 'Shell from Swan River – Permission to dredge – Swan Portland Cement Co', Cons. 541, SROWA.

tuary into the 1960s, by which stage little remained of the once-extensive subfossil assemblages.[69] Information on quantities removed for these purposes could not be located during research, though it clearly contributed to their destruction in the twentieth century.

By contrast, volumes removed annually by the SPCC can be determined on the basis of royalties paid to the State Government and documented in archival collections. Figure 4 shows these quantities. It was only in 1918 that steps were taken to establish a modern cement works in Western Australia, and another six years of negotiation and construction before the SPCC's operation commenced. When it did, it was on an industrial scale: shell was extracted by means of a grab dredge and carried by barge to a plant at Rivervale, at the base of Burswood Peninsula, where it was mixed in equal portions with coastal limestone and heated to over 1,000 degrees C to produce Portland cement.[70] At

[69] Resident Engineer, Harbours & Rivers, 25 Jan. 1960 and 1 Sept. 1961, in Public Works Department item 177S/37 vol. 1, 'Swan River Miscellaneous Surveys', Cons. 5683, SROWA.

[70] *Daily News*, 21 June 1918; *West Australian*, 8 Aug. 1939; *Daily News*, 24 July 1948.

first, dredging focussed on deposits at *Matta gerup*. Within two years a second dredge was in operation and the assemblages encountered during Stirling's exploration had been removed. The company briefly worked in waters just upstream, but as dredging there interfered with the operation of Perth's main power station, the company was forced to shift further upstream between 1927 and 1936. When these deposits were exhausted, operations moved to Melville Water, which was further from Rivervale, but the site of the largest assemblages.[71] More powerful dredges were acquired, along with larger barges to transport the shell. The Second World War hindered this activity when Melville Water was closed for military (flying boat) operations and manpower regulations reduced the workforce available to SPCC.[72] This encouraged experiments in manufacturing cement from higher proportions of limestone and explains why dredging never returned to its 1930s peak despite the post-war building boom. Nonetheless, shell continued to be removed until 1955, when the Melville Water deposits were largely exhausted. A new cement works adjacent to abundant limestone and marine shell deposits opened south of Fremantle later that year, and the Rivervale works transitioned to use only limestone in its operation thereafter.[73]

Discussion: Applying historical insight to ecological restoration

Our history of the Swan-Canning Estuary's Middle Holocene oyster shells was prepared in support of TNC's local Reef Builder project. In what ways, then, is it relevant to this initiative in ecological restoration? In an Australian context, this case-study has several unique aspects, including a constrained archaeological record relative

[71] General Manager, Tramways, Ferries & Electricity, 7 April 1933; Under Secretary of Works, 23 Feb. 1934, in Department of Lands & Surveys item 1923/4706, vol. 2.

[72] Under Secretary of Lands, 25 July 1942; Engineer for Harbours & Rivers, 2 February 1935, in Department of Lands & Surveys item 1923/4706, vol. 3.

[73] Secretary, Swan Portland Cement Company, 15 July 1947 and 10 May 1956, in Department of Lands & Surveys item 1923/4706, vol. 4.

to other parts of the continent, a focus on subfossil deposits rather than living shellfish communities and the role of industrial cement manufacture in driving environmental destruction. For these reasons, a declensionist model of rapid ecological decline driven by habitat destruction and commercial over-exploitation of oysters for human consumption cannot be readily applied, complicating the notion of a 'baseline' for shellfish ecosystem restoration at the Swan-Canning Estuary.[74] Instead, our approach is to look to examples of oyster reef restoration informed by historical understanding that extends across overlapping millennial, centennial and decadal timescales, and where the scale of anthropogenic environmental transformation works against reconstruction objectives that aim to restore degraded ecosystems to a fixed point in time. Accordingly, we place short-term histories of environmental destruction in a long-term context of environmental change, apply insights from our environmental history of the subfossil assemblages to clarify objectives and practice in TNC's reconstruction initiative, and foreground themes of cross-cultural engagement and evolving environmental understanding within the framework of this ongoing ecological restoration project.

At Chesapeake Bay, Lockwood and Mann (2019) examine a 500,000-year fossil record to show that oysters were considerably larger, longer-lived and far more abundant during the Pleistocene than today. Their 'conservation paleobiology perspective' reveals shifted baselines in restoration strategies that adopt lesser targets in terms of oyster life history and abundance, sheds light on the functioning of pristine ecosystems to inform modern ecological monitoring and positions anthropogenic impacts within a long-term framework.[75] Although the constrained archaeological archive and limited palaeobiological data imposes limitations on a comparable perspective for the Swan-Canning Estuary, the dimensions of what once existed can be sketched out from available evidence. Assuming a weight of *O. angasi* shell of

[74] Lotze et al., 'Depletion, degradation and recovery'.

[75] R. Lockwood and R. Mann, 'A conservation palaeobiological perspective on Chesapeake Bay oysters', *Philosophical Transactions of the Royal Society B* **374** (2019): 20190209.

between 800 and 1.2 tonnes per cubic metre, and an average height of flat oyster reefs of 10 centimetres, it can be calculated that approximately 10 square metres of 'living reef equivalent' were extracted per tonne of shell dredged by the SPCC. Therefore, given returns showing 1.25 million tonnes removed between 1925 and 1955, something in the order of 1,000 to 1,500 hectares of living reef equivalent were destroyed. This, however, does not account for all that was lost through dredging and reclamation, so an estimate of two million tonnes removed for an equivalent of 1,600 and 2,400 hectares of living reef is more realistic. Based on numbers of living oysters of ~430 per square metre on healthy *O. angasi* reefs in Tasmania, this amounts to between 688 million and 1.9 billion adult oysters, suggesting it was formerly a foundation species for the Swan-Canning Estuary.

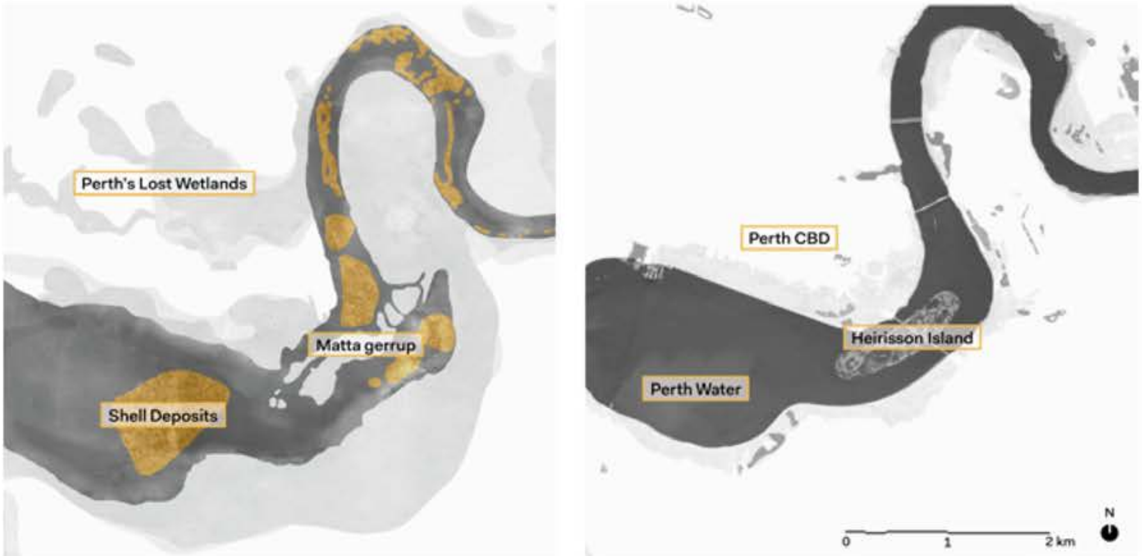
Although there is no way of determining what proportion of any assemblage was living reef ecosystem at a fixed point of time, the fact is that all shellfish reefs or beds comprise both living and dead animals. Irrespective of their state, they provide ecosystem benefits beyond water filtration, creating and maintaining habitat for other species and contributing to shoreline protection.[76] A major benefit of the subfossil assemblages was therefore the provision of habitat for fish and invertebrates. Crawford et al. demonstrate a three-fold increase in faunal community abundance on Australian remnant *O. angasi* reefs compared to nearby sediment-dominated seabed. Of particular importance in their study is a ten-fold increase in arthropoda (shrimp, prawns, crabs) and echinoderm (sea stars, brittle stars) abundance, and a four-fold increase in abundance of other molluscs.[77] Precise comparisons to the Swan-Canning are impossible, as the first detailed survey of estuarine fauna appeared in the same year (1955) that dredging by the SPCC ceased, having been undertaken by the zoologist Dominic Serventy in response to growing concern over the system's degraded state.[78] But given that at the

[76] Gillies et al., 'Restoring Angasi oyster reefs'.

[77] Crawford et al., 'Relationship of biological communities to habitat structure'.

[78] D. Serventy, 'Fauna of the river', in *Swan River Reference Committee: Report by Sub-committee on Pollution of Swan River* (Perth: The Committee, 1955), p. 72.

Figure 5 The Estuary around *Matta gerup*, 1827 (left, showing subfossil assemblages) and today (right). The detailed reconstruction of the estuary edge and wetland landscape at colonisation depicts historic wetland locations, as indicated by clayey, silty and peaty surface geologies, and areas of shallow groundwater, indicating ephemeral wetlands and creeks, in grey tones.



Source: derived from DMIRS surface geology maps, DWER groundwater contour dataset, WALIA medium scale topographic dataset and historic maps and archives. Map created by Daniel Jan Martin.

height of dredging between 1933 and 1940, up to 90 hectares of an analogous 'living reef' habitat were being removed annually, the broader ecological impacts must have been considerable. Cumulatively, the destruction of the subfossil assemblages was likely a major factor in ecological degradation on a system-wide scale, due to the physical disturbance of dredging itself, the reduction in sediment and shoreline stability, and the loss of habitat on a wide scale, with cascading effects on faunal abundance and biodiversity.

Figure 5 draws attention to this by depicting known subfossil assemblages around *Matta gerup* over a reconstruction of the estuary edge and wetland landscape in c. 1829 (left), compared to the same urbanised estuary today (right). The environment encountered by European settlers has shallows formed by *O. angasi* deposits and adjacent mudflats, with salt marsh extending across Burswood Peninsula and the wide estuarine margins immediately to the south; there are also salt marshes to the north, with fringing vegetation separating the Estuary's margins and Perth's lost freshwater lakes and wetlands.[79] The contrast to the present day is stark. Subfossil assemblages have disappeared, lakes and wetlands have disappeared, and estuarine margins are reclaimed, resulting in a more regularly-contoured edge. What were formerly diverse subtidal and fringing habitats have become relatively uniform and barren, and the surrounding landscape is formed by Perth's central business district and inner suburbs. Understanding the ecological benefits of subfossil assemblages in the pristine environment casts the records of exploration in a new light. Stirling commented in 1827 that 'Fish we saw in abundance',[80] and Frazer similarly alludes to rich and abundant estuarine environment at this time. 'The quantity of black swans, pelicans, ducks and aquatic birds seen on the river [sic] was truly astonishing', he recorded in 1827. 'Without any exaggeration, I have seen a number of black swans which could not be estimated at less than 500 rise at once'.[81]

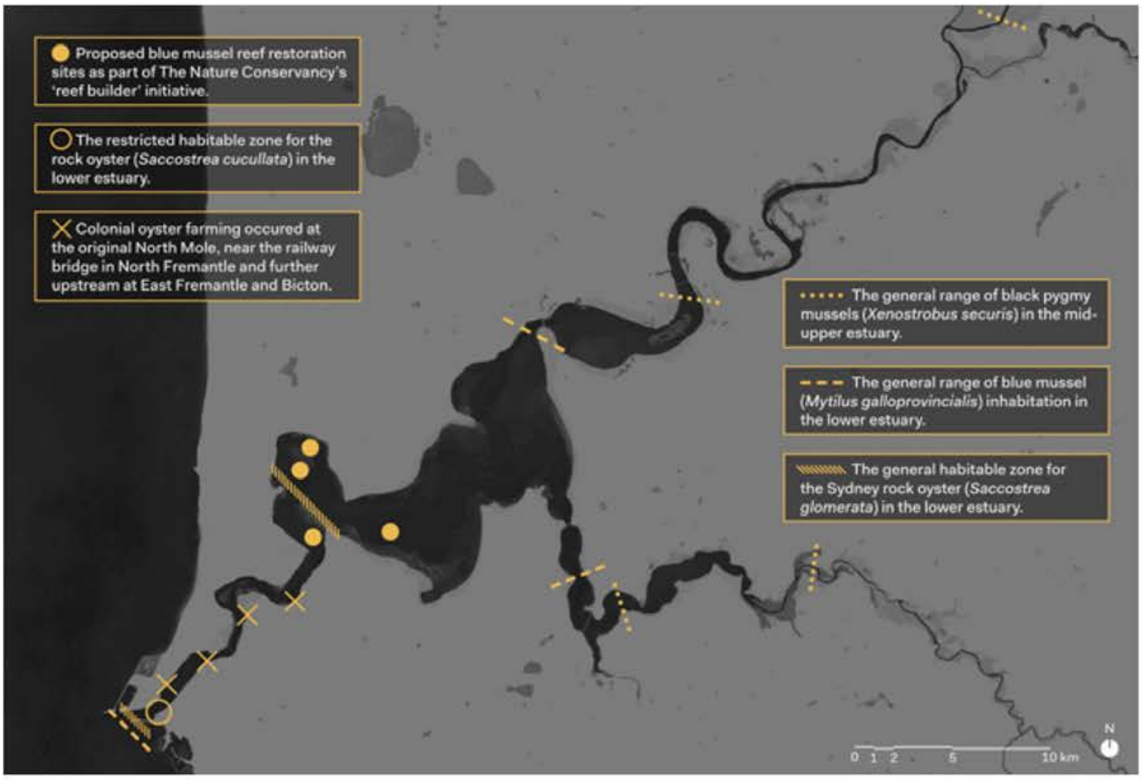
Historical insight is also essential for clarifying defining features of the shellfish restoration programme. Saville-Kent is a central figure linking the past to the present. In flirting with and then abandoning notions of a great flood as responsible for the demise of flat oysters and siting his own experiments in rock oyster cultivation along the breakwater at Fremantle, he anticipated the environmental consequences of harbour construction – a hydrological transition as sudden and profound as any other in the Estuary's history across geological time. Figure 6 provides an insight into this transition. Greater tidal exchange and more marine conditions year-round in the lower reaches after 1897 allowed oyster farming to move from

[79] Brearley, *Ernest Hodgkin's Swanland*, pp. 91–94.

[80] Captain James Stirling to Governor Darling, 1827, in *Historical Records of Australia*, ed. by Frederick Watson (Sydney: Government Printer, 1923), Series 3, vol. 6: *Tasmania April–December 1827; Western Australia March 1826–January 1830; Northern Territory August 1824–December 1829*, pp. 553–557.

[81] Fraser, 'Remarks on the botany'.

Figure 6. The Swan-Canning Estuary today, showing habitable zones for flat oyster and blue mussel species, sites of past oyster farming activity, and key locations in TNC's 'Reef Builder' initiative. The Estuary edge includes current surface water areas and the floodplain fringe.



Source: derived from WALIA medium scale surface water datasets and DWER floodplain mapping dataset. Map created by Daniel Jan Martin.

the breakwater to the area between North Fremantle and Bicton, depicted here. After commercial farming ceased, declines in winter rainfall and higher temperatures linked to a changing climate continued to alter the system.[82] Although *O. angasi* has since been found in small numbers within the Estuary, it is no longer considered endemic. On the other hand, *Mytilus* mussels occur widely in temperate Australian waters. Anecdotal evidence suggests the variety found by Serventy in 1955 became more widespread during the course of

[82] Hallett et al., 'Observed and predicted impacts of climate change'.

the twentieth century, with populations persisting on rocks, jetties and pylons.[83] Of uncertain taxonomic status, and morphologically indistinguishable from *M. galloprovincialis*, it can be considered as naturally occurring in the system, notwithstanding the *Mytilus* taxa's designation as an invasive species.[84] Better suited than *Ostrea* oysters to the conditions of the current and anticipated future Estuary, and capable of restoring lost ecosystem functions including water filtration, nutrient cycling and the provision of habitat and food across multiple trophic levels, it is the focus of restoration efforts. Figure 5 shows a wide area of the Estuary's lower reaches is suitable for blue mussels. Within this area, TNC is aiming to rebuild self-sustaining shellfish reefs interspersed over an area of approximately 10 hectares.

Though modest in comparison to the area formerly covered by subfossil assemblages, and hence the flat oyster communities in the Middle Holocene, the restoration initiative represents the pragmatic balance that must be negotiated to minimise conflict between a multitude of uses in this highly urbanised waterway and impacts on other sensitive estuarine habitats. These commercial, recreational and conservation imperatives reflect the cultural values of the Swan-Canning Estuary today. Thurstan and colleagues address similar questions of cultural values in ecological restoration in their study of social-ecological change in southern Queensland's shellfish ecosystems. With reference to socio-ecological change involving southern Queensland's shellfish ecosystems, Thurstan and colleagues address this question of cultural values in ecological restoration:

> When reconstructing historical conditions, it is not only necessary to understand patterns of ecological change, but also to acknowledge the integral role that human communities have played in structuring these systems over the centuries […] identifying historical connections between human communities and coastal ecosystems demonstrates the extent to which communities have depended upon these ecosystems in the past, the variety of ways in which they have valued these systems over time (e.g., beyond resource use), and thus

[83] Riggert, *The Swan River Estuary*, pp. 64–65.

[84] I. Popovic et al., 'Twin introductions by independent invader mussel lineages are both associated with recent admixture with a native congener in Australia', *Evolutionary Applications* **13** (3) (2020): 515–532.

how community engagement might be best leveraged for restoration or conservation initiatives.[85]

The Swan-Canning case-study is enriched by histories of cross-cultural knowledge transfer, catastrophist explanations for the existence of subfossil assemblages and experiments with the cultivation of live oysters. These histories yield insights that extend beyond temporal frameworks for environmental change, by underlining the cultural relationships tying Noongar and European or settler populations to shellfish ecosystems across time, thereby linking ecological restoration to the Estuary's deep-time, colonial and twentieth-century pasts.

Conclusion

Our study of the Swan-Canning Estuary's Middle Holocene oyster shells provides historical context for a major ecosystem reconstruction initiative that combines both short-term (or historical) and long-term (or paleo-ecological) perspectives on environmental change. Together, these emphasise the dynamic nature of the estuarine environment. Recent studies in biological conservation have applied a similar framework. In 2012, a species identified in fossil deposits dated to the late Pleistocene was found alive at Melville Water, having likely been re-introduced via shipping. Its ancient extirpation and sudden reappearance reveals changes to molluscan species composition that reflect 'changing conditions in the estuary seasonally, annually and climate changes over geological time', as the system gradually transitioned from marine to more estuarine conditions, and then rapidly back again to increasingly marine conditions in the twentieth century.[86] At Chesapeake Bay, a 'conservation palaeobiological perspective' on oyster reef restoration sets out

[85] Thurstan et al., 'Charting two centuries of transformation'.

[86] A. Brearley and F.E. Wells, 'Reappearance of Eumarcia fumigata (G.B. Sowerby II, 1853) (Bivalvia: Veneridae) into the Swan River, Western Australia', *Molluscan Research* **39** (2) (2019): 110–117.

to reconcile similar temporal perspectives, framing reference points for reconstruction efforts that account for wholesale ecological destruction commencing with colonial settlement, at the same time as recognising that, from the standpoint of geological time, 'oyster habitats are ephemeral, appearing and disappearing as sea-level rises and falls across tens to hundreds of thousands of years'.[87] Higgs and colleagues address the shifting role of historical knowledge in restoration ecology by pointing to its contribution to guiding scientific interpretation of altered environments, recognising key ecological legacies, influencing choices in ecosystem intervention and enriching cultural connections to the environment.[88] For us as well, the Swan-Canning case-study embodies a shift away from historical fidelity in restoration objectives, and towards historical knowledge as an information source on past environmental conditions and a reference point for rehabilitating a degraded ecosystem to restore lost amenity and function, employing strategies and approaches adapted to the conditions of today's Estuary.

The destruction of the Swan-Canning's subfossil assemblages provides an important new perspective on global shellfish ecosystem decline, in a context shaped by reconstruction programmes such as TNC's Australian 'Reef Builder' initiative. Not all historical declines were driven by commercial exploitation for human consumption, and in contrast, not all deep-time histories are defined by sustainable indigenous harvests across millennial timescales, despite the significance of these fisheries as components and indicators of resilient coastal and estuarine ecosystems in North America, eastern Australia and elsewhere.[89] Our case-study demonstrates how extractive industry can drive ecological decline through habitat destruction in a major urban waterway, suggesting the exploitation of shellfish deposits as a source of lime and building materials warrants further atten-

[87] Lockwood and Mann, 'A conservation paleobiological perspective on Chesapeake Bay oysters'.

[88] Higgs et al., 'The changing role of history in restoration ecology'.

[89] Reeder-Myers et al., 'Indigenous oyster fisheries'.

tion.[90] Environmental change along the Gulf Coast of the United States provides one case in point, as fossil and subfossil shell deposits were used extensively to construct roads and buildings in Texas and other states during the twentieth century.[91] Mining of phosphatic sandstone, guano, rock phosphate and coral from the islands, cays and reefs of the Great Barrier Reef offers a second and comparative example, as these activities are implicated in extensive habitat transformation through declining coral diversity, increasing turbidity and sedimentation, decreases in fish abundance and greater vulnerability to tropical cyclone impacts, among other ecological effects.[92] Uncovering further histories of extractive industries in estuarine, coastal and inshore environments is essential to understanding the full scale of ecological destruction since the early nineteenth century and, as we suggest, for refining strategies and approaches for restoring lost ecological amenity and maintaining or rebuilding cultural relationships to functional and resilient ecosystems.

[90] Gillies et al., 'Australian shellfish ecosystems'.

[91] Doran, 'Shell roads in Texas'.

[92] B. Daley and P. Griggs, 'Mining the reefs and cays: Coral, guano and rock phosphate extraction in the Great Barrier Reef, Australia, 1844–1940', *Environment and History* **12** (4) (2006): 395–433.

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