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Charting two centuries of transformation in a coastal social-ecological system: A mixed methods approach

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ABSTRACT

Oyster reef ecosystems used to form significant components of many temperate and subtropical inshore coastal systems but have suffered declines globally, with a concurrent loss of services. The early timing of many of these changes makes it difficult to determine restoration targets which consider interdecadal timeframes, community values and shifted baselines. On the Australian continent, however, the transition from Indigenous (Aboriginal) to Westernized resource use and management occurred relatively recently, allowing us to map social-ecological changes in detail. In this study, we reconstruct the transformations in the Sydney rock oyster (*Saccostrea glomerata*) wild commercial industry of central and southeast Queensland, and by extension its reef ecosystems, as well as the changing societal and cultural values related to the presence and use of the rock oyster through time. By integrating data from the archaeological, anthropological and fisheries literature, government and media accounts, we explore these transformations over the last two centuries. Before the 1870s, there was a relative equilibrium. Aboriginal peoples featured as sole traders to Europeans, supplying oysters and becoming a substantial component of the industry's labour pool. Effectively, Australia's commercial oyster industry arose from Aboriginal-European trade. During this initial phase, there was still a relative abundance of wild oyster, with subtidal oyster reef structures present in regions where oysters are today absent or scarce. By contrast, these reefs declined by the late 19th century, despite production of oysters increasing due to continued large-scale oyster recruitment and the expansion of oyster cultivation in intertidal areas. Production peaked in 1891, with successive peaks observed in regions further north. During the 1890s, flood events coupled with land-use changes introduced large quantities of silt into the system, which likely facilitated an increase in oyster pests and diseases, ultimately decreasing the carrying capacity of the system. Today oyster production in this region is less than one-tenth of historical peak production. Many cultural heritage components have also been lost. Indigenous management is now very minor due to the massive decimation of Aboriginal populations and their respective practices. Yet, we found strong cultural attachment to midden remains and oyster production continues within Indigenous communities, with considerable broader community support. This study highlights the value of conducting thorough analysis of early media accounts as a means for reconstructing historical resource decline and management. It further demonstrates the application of historical information and context for contemporary management, protection and restoration of much-altered coastal social-ecological systems.

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1. Introduction

Increasing awareness of the highly degraded state of many estuaries and coastal ecosystems around the world has led to heightened interest in the potential for their restoration (Lotze et al., 2006; Gillies et al., 2015). Informing recovery targets for these systems, however, requires an understanding of historical conditions and ecosystem dynamics prior to large-scale human-induced perturbations (Jackson and Hobbs 2009). Despite our long associations with coastal ecosystems, ecological monitoring data rarely span more than a few years or decades (Pandolfi et al., 2003; Roberts 2007). A comprehensive understanding of the magnitude and patterns of past change thus requires an approach that incorporates deeper historical perspectives (Rick and Lockwood 2012).

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 (Engelhard et al., 2016). Without an understanding of the history of human resource use and intervention, we may mistakenly label past system dynamics as natural, when in fact these conditions are the result of human pressures, or vice versa. Furthermore, 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; Hicks et al., 2016), and thus how community engagement might be best leveraged for restoration or conservation initiatives (Garibaldi and Turner 2004; Wortley et al., 2013). Interdisciplinary approaches that incorporate the natural sciences, social sciences, anthropological and humanities disciplines can thus provide valuable information for contemporary resource management (Rick and Lockwood 2012).

Oysters form an important component of shellfish reef ecosystems throughout many regions of the world, although some oyster species do not strictly form biogenic reefs, instead existing in scattered aggregations as single or small clumps of individuals (Beck et al., 2011). Research is increasingly demonstrating the extent of oyster population declines (Beck et al., 2011), including quantitatively examining changes in habitat extent, density, size harvested and production trends over centuries to millennia (Erlandson et al., 2008; Rick and Lockwood 2012; zu Ermgassen et al. 2012; Blake and zu Ermgassen 2015; Alleway and Connell 2015; Ford and Hamer 2016; Rick et al., 2016; Pogoda 2019). However, few studies have comprehensively integrated this information with the archaeological, anthropological and popular literature to further explore the drivers and timings of change, and to understand the values and benefits gained from past oyster presence and use through time.

Using central and southeast Queensland and the commercial or Sydney rock oyster (*Saccostrea glomerata*) as our case study, this study attempts to answer the following questions: 1) What was the historical distribution, abundance and structure of oyster populations prior to (or near) pre-European times? 2) What type and scale of benefits did Aboriginal peoples and early European settlers gain from oysters and the oyster industry? 3) Which drivers were primarily responsible for the decline of oysters in central and southeast Queensland estuaries? While prior work has debated the biological mechanisms responsible for the decline of oyster production in Queensland during the 20th century (e.g., Nell 2001; Kirby 2004; Ogburn et al., 2007; Diggles 2013), we adopt a more interdisciplinary approach than previous studies, integrating ecological, social, economic and cultural data from a wide array of sources, including archaeological reports, government accounts, local history reports, popular media articles and interviews.

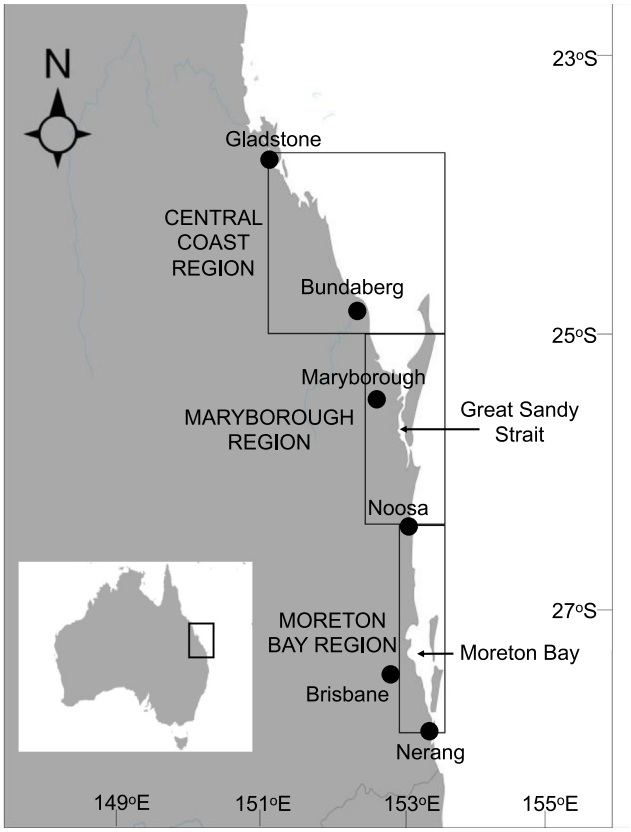

Fig. 1. Map of study area highlighting the locations of commercial oyster-production and the northerly and southerly boundaries of the three major oyster-producing regions referred to throughout the text: Moreton Bay, Maryborough and the Central Coast region.

2. Methods

2.1. Study area and species

Oysters historically occurred, and were consumed, around coastal Australia (Gillies et al., 2018). This study focuses upon the southeast and central Queensland regions, from the New South Wales border to Gladstone (Fig. 1). Oysters referred to within this study are predominately the Sydney rock oyster (*S. glomerata*), but see Appendix 1 for other species that contributed to Queensland oyster production. Our geographical focus aligns with the vast majority of Queensland commercial production, and where the bulk of archival records were sourced. Prior to European settlement, Aboriginal groups of southeast Queensland shared cultural and kinship ties to north coast New South Wales and exhibited similarities to groups further north. Hence, where data from the pre-European period are lacking from central and southern Queensland sources, we utilize information from northern New South Wales and northern Queensland to inform our understanding of past oyster uses and values.

2.2. Data sources

Much of the historical data on Queensland fisheries and coastal ecosystems exist in disparate and fragmented archival collections. To minimize the likelihood of missing information, we undertook a broad search of the primary and secondary literature available in state and local library catalogues, archaeological databases and digitized collections. The locations of archaeological midden sites were sourced from databases held by the Queensland State Department of Aboriginal and Torres Strait Islander Partnerships (DATSIP) and Turnstone

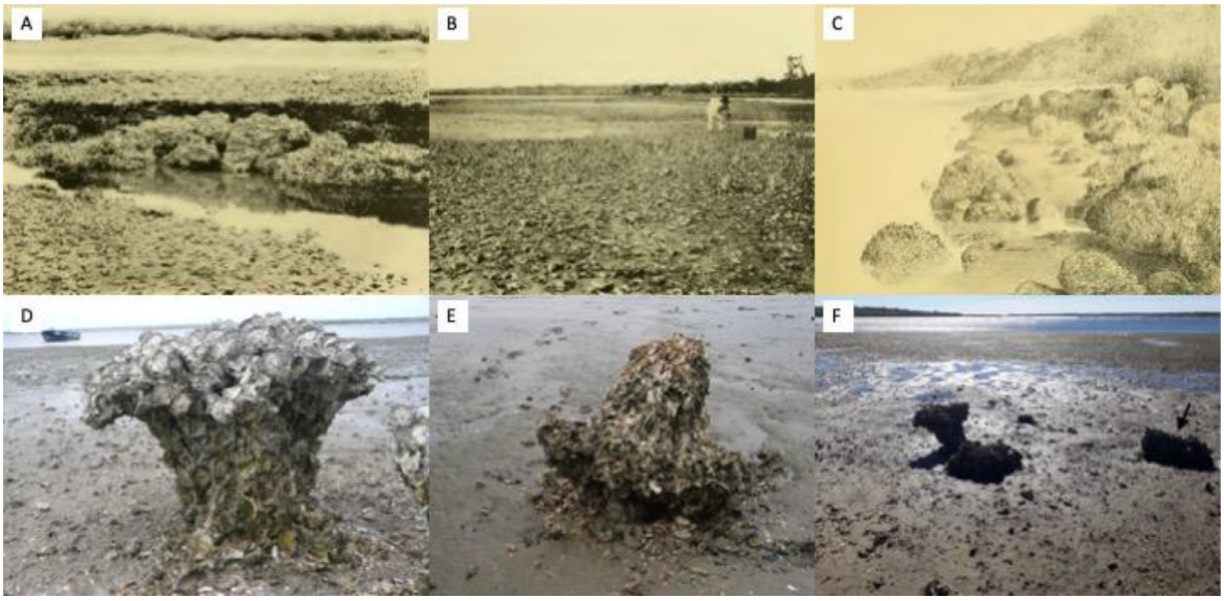

Fig. 2. A) An oyster (*S. glomerata*) reef, situated between Port Curtis and Keppel Bay, northern Central Coast region (ca. 1890). B) A typical cultivated oyster bank, situated in Bribie Passage, Moreton Bay region (ca. 1890). C) Rock oysters at Burleigh Heads, Southport, southern Moreton Bay region (ca. 1890). D) Degraded oyster clump photographed in January 2011, Pumicestone Passage, Moreton Bay region. The same clump is shown after breakage due to a lack of oyster recruitment and subsequent undermining in E) January 2012 and F) July 2019 (clump highlighted by black arrow). Sources: A-C) Saville-Kent 1891, D-F) Ben Diggles.

Archaeology (see Appendix 1). Relative abundance and composition of individual middens were sourced from the archaeological literature. Archival data were sourced from state government and regional library archives (see Appendix 1). Transcriptions and recordings of interviews with Queensland residents from libraries and media archives were identified and comments relating to oyster fisheries and ecosystems were collated, transcribed and coded.

2.3. Analysis

Descriptive data from the printed and digitized materials, and the interview responses, were transcribed and the text categorized into themes. We took a combined approach to thematic analysis (Braun and Clarke 2006), commencing with several previously derived themes driven by our research questions and what we expected to find in the literature, followed by identifying additional emergent themes as we began to collate and analyse the data. The final themes were based around 1) descriptions of oyster reefs (e.g., physical structure, abundance and distribution); 2) the uses of, benefits and values ascribed to these reefs (e.g., ecological benefits, activities and economies related to oyster gathering and harvesting, cultivation, social-cultural activities and coastal identities); and 3) observations of ecological change and potential/ascribed drivers (e.g., siltation, disease, dredging).

Quantitative data were sourced from annual reports produced by the government department charged with collating oyster production and effort (Department of Ports and Harbours, n.d.; Marine Department 1890–1928; Department of Harbours and Marine 1929–1970). Market oyster quantities were recorded in 'bags', which held 120 dozen oysters (Lergessner 2006). Smaller oysters (known as 'culture') were also transported in bags to be laid down in locations that were more conducive to faster growth. Trends in oyster production were split into three geographic regions corresponding to how returns of oysters were reported in annual reports: the Moreton Bay region (from Nerang in the South to Noosa in the North), the Maryborough region (incorporating the Great Sandy Strait) and the Central Coast region (from Bundaberg in the south to Gladstone in the north; Fig. 1). Further information on how trends in oyster production were calculated are provided in Appendix 1.

Fishing effort trends were recorded using the number of banks and dredges licensed each year, and the number of men and boats licensed. In the absence of alternative continuous effort data, production per unit effort (PPUE) was calculated by dividing the total quantity of market/cultivated oysters by the number of banks and dredges licensed that same year, per region. We use the term PPUE rather than the more standard measure of CPUE because 'production' more accurately represents how the fishery was conducted (e.g., in many regions oysters were not just removed for market, but also re-laid from other regions to encourage spat-fall and faster growth). The first-sale value of oysters was adjusted to 2015 $ (AUD) using the Consumer Price Index (Measuring Worth 2017) (see Appendix for a detailed breakdown of the methods). Contemporary quantities of oysters produced are reported in dozens, and were sourced from annual aquaculture production summaries sourced from the Queensland Department of Agriculture and Fisheries (2005–2016). Contemporary effort data were not found.

3. Results

3.1. Habitat characteristics

Qualitative descriptions of the habitat characteristics of oyster beds in southern Queensland during the early years of European colonization occur sporadically in the literature. These describe large quantities of oysters and extensive oyster beds (Table A1, quotations 1–2, 4, 6–9), although the physical characteristics often lack detail. Large oyster reefs are described on occasion, "*This day we saw something like a reef of rock about 3 feet out of the water and 300 yards long […] we found it to be a huge and apparently solid bed of oysters, large enough to load several large ships*" (Archer, 1862 in: Lergessner 2006) and *"solid masses of oysters that may be several feet in thickness, raised to a higher level than the banks […]"* (Saville-Kent 1891), while bank oysters were described as occurring *"side by side in the same cluster"* and *"attached to stones or dead oyster shells"* (Saville-Kent 1891).

Photographs of cultivated and non-cultivated beds were published in 1891, several decades after the commencement of the oyster industry (Fig. 2). By this time, oyster reefs were reported to have severely declined in abundance in southern Queensland (Saville-Kent 1891), although the abundance of bank oysters remained considerable. No quantitative estimates of living oyster reefs were found, although these

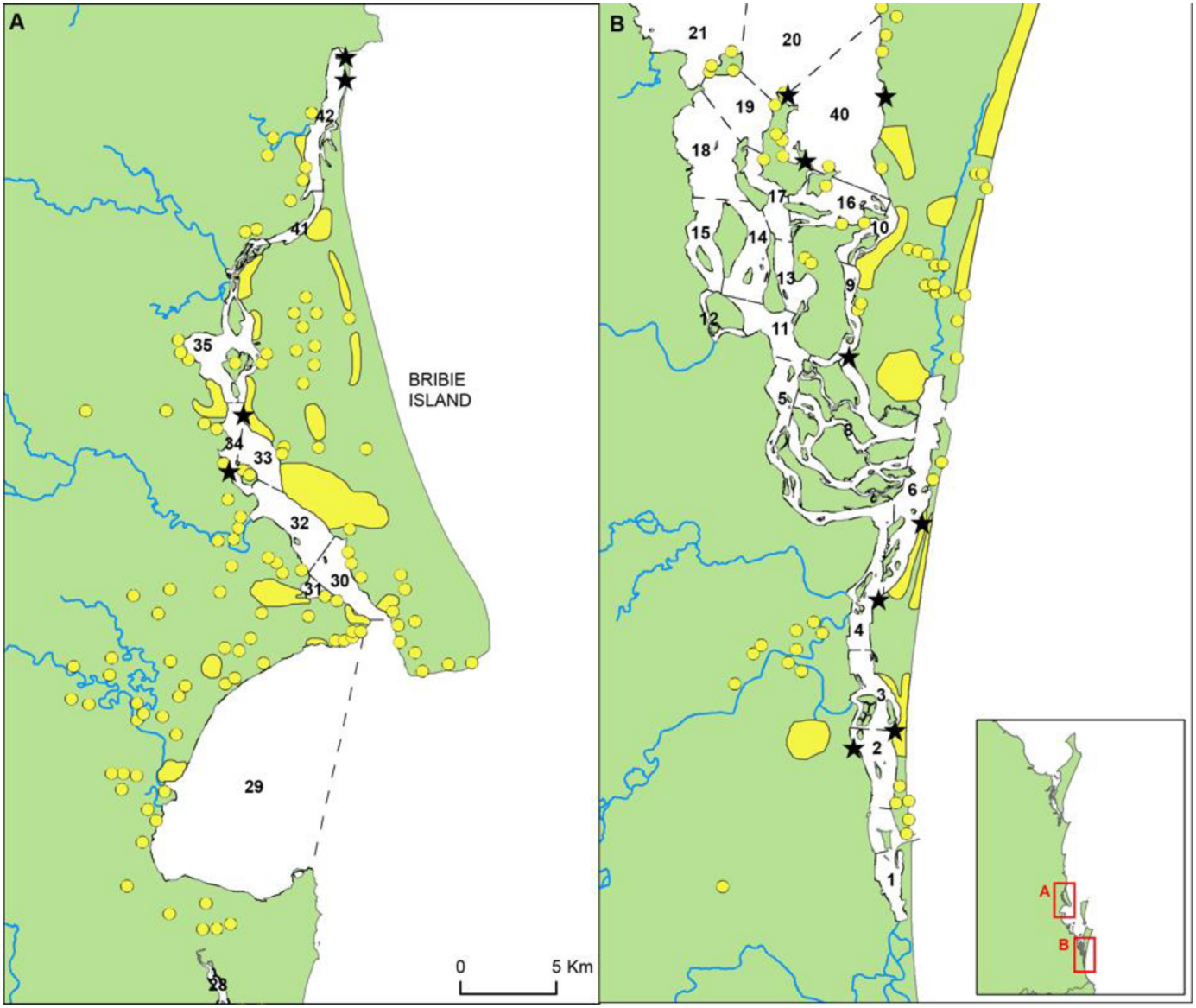

Fig. 3. Known midden locations and extent (in yellow) surrounding northern and southern Moreton Bay. See Figure A1 for known coastal midden locations across the whole study site. Licensed dredge sections are numbered and their boundaries highlighted by dashed lines (for additional sections see Figures A2 and A3). Stars indicate locations of permanent oyster camps referred to in Smith (1985). Midden location maps provided by Turnstone Archaeology.

exist for oysters reefs in nearby New South Wales, which were reported to vary in area from 10m^2 to 100,000m^2 and were described as "*close set clumps of five or six oysters and two to four clumps thick all over the bed, averaging 18 mature oysters besides spat of every 5 square inches (5570 oysters per m^2) over an unbroken bed of shell on a tolerably hard bottom*" (Oyster Culture Commission 1877; Ogburn et al., 2007).

3.2. Historical distribution and composition

Approximately 2500 known shell midden sites have been recorded along the Queensland coast (Fig. 3; Fig. A1). The pre-European tally was undoubtedly greater as most middens observed during early settlement were destroyed or greatly diminished through land clearance, building, and the industry of mining and burning midden shells for mortar and road base (Smith 1985). For middens where surveys were undertaken, the percentage of oyster remains relative to other species varies amongst sites. Oyster remains tend to be dominant in middens situated in sheltered bay waters, or on the leeward side of islands (Ulm 2002). For example, south of our study area, in the Richmond River in New South Wales, *S. glomerata* makes up 98% by weight of molluscan shell remains (Bailey 1975). In contrast, at the Toulkerrie middens on the southwest coast of Moreton Bay, *S. glomerata* composed just 6–11% (by number of individuals) of midden shell taxa, with the majority of shells being surf-dwelling pipis or eugaries (*Plebidonax deltoides*) (Hall and Bowen 1989). Along the central coast region, coastal shell middens are generally dominated by mud ark (*Anadara trapezia*) and/or *S. glomerata* (Ulm and Lilley 1999).

Even such recorded middens only provide a limited indication of the original quantity of oyster shells within the middens. 19th and early 20th century accounts from southeast Queensland describe middens so large they formed ridges extending 40 miles along the coast, and local, named landmarks (e.g., "The Lions of Tewantin", Table A2, quotations 18, 20). Almost none of these giant middens survive. Along the Richmond River in northern New South Wales, the largest midden sites are 400 m in length and up to 4 m high, and contain an estimated 23,100t of oyster shell (Bailey 1975).

3.3. Social and cultural significance

3.3.1. Pre- and early-European settlement

Using the midden site at Richmond River, Bailey (1975) derived an estimated mean annual consumption in the pre-European period of 17t of oysters live weight, the same as the mean annual output of oysters from this locality during the mid-20th century (Bailey 1975). Given the site's close proximity to southeast Queensland and historical references to large, oyster-dominated middens (Table A2), it is not inconceivable that similar quantities of oysters could have been extracted in Queensland localities during the pre-European period. Bailey (1975) postulates that oysters sourced from the Richmond River, some of the region's largest known midden remains, were unlikely to compose more than 10% of coastal Aboriginal peoples' diet in this region. Studies of stable-carbon isotope analysis on Aboriginal peoples' remains from coastal southeast Queensland suggest that fish and shellfish composed a maximum contribution of 50% to the overall diet, and possibly much less (Hobson and Collier 1985; Collier and Hobson 1987). Midden scatters excavated in the Maroochy River area showed substantial exploitation of riverine oyster beds and other shellfish species at particular times. Three identified major shell layers were dated and were found to have been deposited during the late 15th, mid-18th and 19th centuries, suggesting a transient use of these particular sites and their coastal resources (McNiven 1989).

Despite uncertainty surrounding the relative significance of oysters in coastal Aboriginal diets in pre-European times, the historical record highlights the social and cultural significance of oysters to some coastal communities. In deconstructing middens for lime making or during land clearing, ancient stone tools, usually axe heads, choppers and grinders (indicating an active industry of processing shellfish, dates unknown), were sometimes found buried amongst the stratified layers of oyster shells, as were – occasionally – partial and full burials of Aboriginal people (Table A2, quotations 17, 28, 49, 52, 57, 58). In Redcliffe, middens were sometimes accompanied by special hearths of hot rocks used for cooking oysters (Sunday Mail, 4 June 1939).

Oysters were a totem for coastal tribes in northern Queensland (The Telegraph, 11 April 1938) and probably held similar significance in southeast Queensland. One Aboriginal clan from southeast Queensland called themselves 'Ningy Ningy', which meant oysters (Steele 1984), while an annual 'oyster corroboree', an intertribal social gathering, occurred in the Noosa region of southeast Queensland up until the 1910s. This was an opportunity for different tribes to gather together to socialize and hold ceremonies. At least part of this gathering consisted of feasting on locally collected oysters (Table 1; Table A2, quotations 25, 28). These oyster corroborees were a regular event and involved groups from all over northern New South Wales and southern Queensland (The Queenslander, 29 May 1897; Brown 2000). A similar annual inter-tribal shellfish feast was held 15 kms to the south, at Maroochy Heads. In the early 20th Century, a midden the size of a 'small hill' pertaining to this gathering was destroyed (Uhlmann 2014).

In southern Queensland, the work of gathering oysters usually fell to the women and children, who waded out at low tide with dilly-bags and short spears, or used small canoes to conduct this work (Table A2, quotations 1, 6, 32). However, adults of both genders and children were recorded as diving for oysters. Aboriginal communities also relayed oyster shell to build new substrate and translocated small oysters to areas where they would grow faster and larger (Frawley 2017). The farming of oysters by Indigenous peoples has been confirmed by recent archaeological excavations, showing the Kabi Kabi people deliberately chose and placed suitable rocks along creek banks for oyster attachment, and created stone arrangements in intertidal zones to support and facilitate oyster production (archaeologist Michael Strong, unpublished data, 3 December 2019). Fishhooks made from oyster shell have been sourced in New South Wales (Ogburn et al., 2007), while in Queensland oysters were sometimes cultivated in fish traps to entice the fish in at high tide, or used as bait to catch finfish (Table A2, quotations 44, 45, 69; see Pascoe 2018 for evidence of wider pre-colonial Indigenous aquaculture practices).

The main characteristic of this mode of oyster-management was its sustainability over thousands of years, as Joondoburri/Kabi Kabi Elder Fred Palin explained:

> "Aboriginal people were great communicators and astute people… and travelled vast distances for ceremonies. They never exhausted their food source like the white people do. Much would have been the same at Noosa… the oyster midden sites at Tewantin and Wallace Road indicate a thriving marine ecosystem that had been existing for a long period of time. Both sites were major camping grounds… You could say that for thousands of years the oysters were never extinguished". Fred Palin, 10 December 2019.

3.3.2. Post-European settlement

European occupation of Queensland commenced in 1824 with the establishment of a penal colony, with free settlement permitted in 1841 (Diggles 2013; Table 1). Almost as soon as settlement in Queensland began, convict workers and free settlers exploited oyster middens around Brisbane for 'quicklime', once one of the main ingredients for bricks, mortar and road material (Table A1, quotations 3, 7; Table A2, quotations 2, 8, 47). As sources of dead shells became less accessible, the focus turned to extracting and burning live oysters, which were believed to produce a higher-quality cement (Smith 1985; Lergessner 2006). Concerns about local extinction led to the Oyster Act of 1863 being established, halting the practice of lime burning (Smith 1981).

Upon European settlement, Aboriginal peoples continued to be involved in harvesting and producing oysters, both for their own subsistence and as free-traders (Kerkhove 2013). Aboriginal people were the first to commercially sell or trade fish and oysters in the region's towns and cities (Kerkhove 2013; Table A2, quotations 5, 11, 13, 19). After the Oyster Act of 1863, members of the public were allowed to continue harvesting oysters for personal consumption from public reserves. Outings to oyster banks became a popular recreational entertainment, sometimes involving Aboriginal guides or boat pilots (Table A2, quotations 15, 22). The gift of an oyster boat to the Noosa Aboriginal community upon their capture of a wanted criminal highlights the continued significance of oysters to Aboriginal communities during European settlement (Table A2, quotation 23).

The harvest industry gained momentum in the mid-1860s when subtidal reefs of "dredge oysters" (*S. glomerata*) were discovered in Moreton Bay (Fig. 3; Fig. A2). By the 1870s, interstate trade with Sydney and Melbourne had commenced, which promoted the expansion and development of the Queensland commercial oyster fishery (Smith 1981; Table A1, quotation 32). Queensland's first oyster saloon (an eatery which primarily or solely sold oysters) opened in Brisbane in 1860 (Carpenter 1991; Smith 1985) and outings to oyster saloons became a popular recreational activity until the decline of the oyster fishery in the mid-20th century (Carpenter 1991).

Upon commercialization of the fishery, Aboriginal peoples were commonly employed as oyster harvesters, as were South Sea Islanders, in some cases as indentured labour (The Queenslander, 9 December 1916; Dickson 1980) or through enforced relocations to Aboriginal-only missions (Anderson 2001). Although it is unknown how many people the early oyster fishery employed, these labourers and their families often lived in established 'oyster camps' alongside the worked oyster beds (Fig. 3; Table A2, quotations 34, 36). Myora Aboriginal Reserve (on North Stradbroke Island) became one such foci of the emerging commercial industry, involving Aboriginal families, some of whom bought oyster leases and worked their own banks (Anderson 2001). By the late 19th century, more permanent 'oyster camps' were encouraged as part of advancing the commercial fishery (Smith 1985; Fig. 3). Through subsidized building of houses and schools, these soon became distinctive multi-racial communities along Queensland's coast (Table

Table 1
Timeline of major changes and their social-ecological outcomes.

Year	Social-cultural change	Environmental change	Social-ecological outcome
c. 5000 BCE-1824	Harvesting and low-impact cultivation of oysters and other shellfish by Indigenous peoples.	Stabilization of current coastline (5000–4000 BCE)	Large, numerous middens across Queensland; inter-tribal oyster feasts and other Indigenous cultural practices.
1824–1842	Small penal outposts established in southeast Queensland.	Some land clearance for crops resulting in first phases of increased sedimentation; mouth of Brisbane River deepened.	Earliest European harvesting and lime-burning; salinization of Brisbane River.
1842–1860s	Pastoral settlement: grazing and extensive timber leases cover southeast Queensland. Indigenous peoples trade oysters to settlers. Expansion of fishery.	Conversion of forest to pasture commenced, extensive deforestation.	Indigenous and non-Indigenous first (sole trader) oysterers; large-scale destruction of middens to manufacture materials for buildings and roads; harvesting of live oysters for lime.
1860s-1880s	Lands Act (1868) enforces extensive division of large properties into numerous small mixed-farming plots. Popularity of recreational fishing and seafood cuisine. First regulation of oyster industry (1863), first annual statistics (1870); licensing of oyster beds (1874).	Unprecedented levels of sediment deposited during flood events; pollution from farms; depletion of oyster reefs.	Beginnings of recreational oystering and oyster saloons; first large-scale oyster industries (oyster camps, interstate trade) and fishing villages populated by mixed Aboriginal, Asian and European families; regulation of oyster industry; rapid decline of Indigenous cultural practices.
1880s-1910s	Urban growth across southeast Queensland (many towns founded); rapid expansion of European population; large-scale recreational fishing and oystering; rapid decline of Indigenous populations.	Five major floods within 11 years, rapid sediment influx. Mudworm reported in Moreton Bay.	Initial zenith in oyster production followed by loss of oyster beds; closure of beds (1895–1903), economic loss, increased oyster mortality; decline in reported size and health of oysters; cessation of Indigenous cultural activities concerning oysters.
1910s-1950s	Suburban growth; 'monoculture' farming (pesticides and fertilizers); economic depression (1930s), labour/material shortages. Increased competition.	Increase in pollutants; decline in mangroves.	Job losses in oyster industry, declines in oyster production; extinction of riverine oyster beds.
1950s-1970s	Vast urbanization and population growth; 'canal estates' developed along coasts and bays; watersports (motor boats); annual statistics ceased (1969).	QX disease detected (1968).	Major oyster mortality events, continued economic losses; Fishery dynamics unknown (from 1969).

A2, quotations 16, 24, 30, 34, 36, 38).

Today, some European Australian and Aboriginal families still hold oyster leases in Moreton Bay, while the collection of wild oysters and other shellfish for subsistence continues (Russell et al., 2015). Midden remains, oral histories and contemporary harvest activities maintain cultural and spiritual links to past generations (Table A2, quotations 63–69). Despite the decline of oyster production, aspirations amongst Aboriginal peoples to be employed and involved in the management, education and/or restoration of shellfish reefs remain (Table A2, quotations 63–69). However, according to Joondoburri/Kabi Kabi Elder Fred Palin, Aboriginal families often feel current measures are little more than a "bandaid." Palin notes that his family (the Turners) encountered many obstacles in trying to hold on to their leases and perpetuate their cultural practices:

> "The Turner family were an Aboriginal family who had several oyster leases in the Pumicestone Passage… they settled there in 1872 on what was later to be deemed crown land, but at the time everyone thought the land belonged to James Clark. When the last Turner died in 1961 the land was taken back by Government […]. They were forced to relinquish the leases in 1976… Any questions on why Aboriginal people don't maintain Cultural oyster banks is answered by the persistence of Government in dispossessing them from their land/oyster leases." Fred Palin, 10 December 2019.

3.4. Production trends

Annual records of oyster production began in 1870. The data do not differentiate between harvested (e.g., dredged) and cultured (e.g., relaid) oysters, and because many lease holders sold their oysters through private channels, these records likely underestimate the true extent of the industry (Table A2, quotation 62). Recorded Queensland oyster production peaked in 1891, at 3.65 million dozen oysters (Fig. 4a). The earliest and greatest quantities of commercial production occurred in Moreton Bay, closest to Queensland's population centre and the New South Wales border. Moreton Bay production peaked in 1891, at 2.9 million dozen oysters. From the 1880s production expanded north (Maryborough peak = 1902; Central coast peak = 1959; Fig. 4b-d; Fig. S3). While production in each region peaked successively, the rate of decline post-peak production was swiftest in the Maryborough and Central coast regions (% decline in the 10 years following production peak: Moreton Bay = −38%; Maryborough = −82%; Central coast = −53%). Today, the majority of commercial quantities of *S. glomerata* are again cultivated in Moreton Bay (Dexter, 2015). However, in 2016, the numbers of oysters produced from Moreton Bay was >96% less than the peak of oyster production. Remaining oyster reef ecosystems have been reduced in vertical height while the vast majority of subtidal oyster reefs have been rendered extinct (Diggles 2013; Fig. 2).

Production effort follows different patterns depending upon whether effort is measured by the number of licensed areas, men or boats licensed (Fig. 5). The number of sites leased peaked in 1907 but for Moreton Bay a second peak occurred in 1924, with smaller peaks after WWI and WWII (Fig 5a), although these peaks are not reflected in the total landings (Fig. 4a-d). The numbers of men recorded as employed change markedly each year and are certainly an underestimate (Smith 1981), but indicate a peak in employment in 1895 for Moreton Bay (Fig 5b). A later employment peak occurs in the early 1960s but this is not reflected in the areas leased or boats licensed (Fig 5c). The rate of increase in the total number of licenses granted per year was most rapid during the 1880s, when an average of 37 additional banks or dredges were licensed each year. The rate of decline in the number of licenses granted was greatest in the 1950s, when an average of 31 fewer licenses $year^{-1}$ were granted. Production per unit effort (PPUE), calculated using numbers of licensed banks and dredges, peaks earlier than total oyster production (peak PPUE Moreton Bay: 1882 vs peak production 1891; Maryborough: 1899 vs 1902; Central Coast: 1941 vs 1959), and declines more rapidly than production alone (Fig. 4e-h).

Natural production of oysters was supplemented by the removal and relaying of small oysters in areas where they would grow faster. In Moreton Bay, trends in the quantity of cultured oysters laid down declined from the first year of data recording (1884), when 41,000 bags (relative to 4.9 million dozen oysters at market size) were recorded as moved from various locations. The source of this culture was probably young oysters transported from within Moreton Bay and more northerly regions. In later years, large but unknown quantities of culture were removed from the Maryborough region to Moreton Bay. While

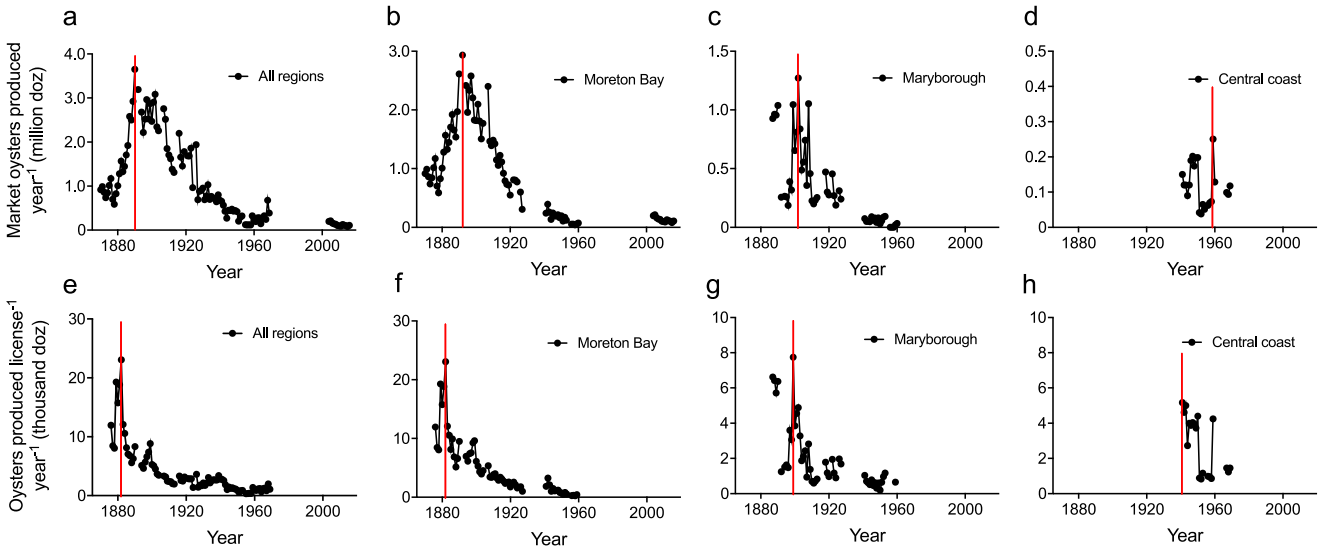

Fig. 4. Numbers of market-size oysters produced year^{-1} (a-d) and numbers of market-size oysters produced licensed area^{-1} year^{-1} (e-h) for the whole of southeast Queensland and by region. Red lines highlight the year of maximum production. Sources: Department of Ports and Harbours, n.d., Marine Department (1890–1928), Department of Harbours and Marine (1929–1970), and Department of Agriculture and Fisheries (2005–2016). Production data from 1970–2003 could not be found.

cultivation continued to be a common practice, the quantity of re-laid culture from Queensland beds declined over the years (Fig. 6a,b), and the Queensland industry became increasingly reliant upon the purchase of spat from New South Wales beds to supplement local collection (Witney et al., 1988).

The first-sale value of locally-sold oysters was rarely recorded in the official statistics, hence the recorded prices during the first 50 years of record-keeping (1870–1919) were derived from the first-sale earnings of oysters shipped to interstate markets (Fig. A4a). After 1920, the recorded values include both locally-sold and interstate oyster sales (Fig. A4b). During the late 19th century oysters were relatively cheap to buy. Prices rose in the late 19th but stabilised during the early 20th century, before rising steeply (Fig. 6c). Today, oysters continue to be cultivated and harvested in commercial quantities in Moreton Bay, albeit at a smaller scale than historically, but still with a value that is the highest in history (Queensland Department of Agriculture and Fisheries, 2016).

3.5. Drivers and timings of change

A number of drivers have been highlighted as contributing to the decline of Queensland's oyster production during the 20th century, including overexploitation, excessive siltation due to changing land-use and coastal development, and the increased prevalence of disease and oyster pests (Kirby 2004; Ogburn et al., 2007; Diggles 2013). The pre-1880s decline of large oyster reefs was reported to be due to harvesting pressure (Saville-Kent 1891). The conditions on the shallow banks presented an environment far more conducive to fast growth compared to the oyster reefs: hence extant oyster reefs were commonly broken apart and the individual oysters spread upon banks in the Moreton Bay region to be cultivated to marketable size (Saville-Kent 1891).

Major environmental changes have also occurred over the last 120 years. Contemporary reports suggest that prior to the 1889–1893 La-Niña wet period, commercial oyster harvesters could extract large numbers of oysters from a bank or dredge section, at which point one to three years of no harvest would allow wild spatfall to recruit to the beds and replace the harvested oysters (Fison 1884, 1889). In some areas it was considered that if dredging was not undertaken, large mortality events would occur due to the overcrowding of spat.

After European settlement in the Brisbane region, vegetation clearance for agriculture commenced almost immediately (Kemp et al., 2015). Land policies introduced during the 1860s aimed to quickly convert forest to pasture, resulting in rapid rates of vegetation clearance (Kingston 1965), coinciding with increased rates of sedimentation within Moreton Bay. Several major floods occurred during the first half of the 19th century but there were no reports of widespread sedimentation resulting from these events (Coates-Marnane et al., 2016). In contrast, flood events from the 1850s onwards (when widespread land clearance and the dredging of major rivers commenced (Richards 2019)) led to unprecedented amounts of sediment being deposited downstream. The 1887 flood event was reported to have "*killed all the oysters in the southern part of the Bay, the rivers bringing down immense deposits of mud which simply smothered the bivalves*" (The

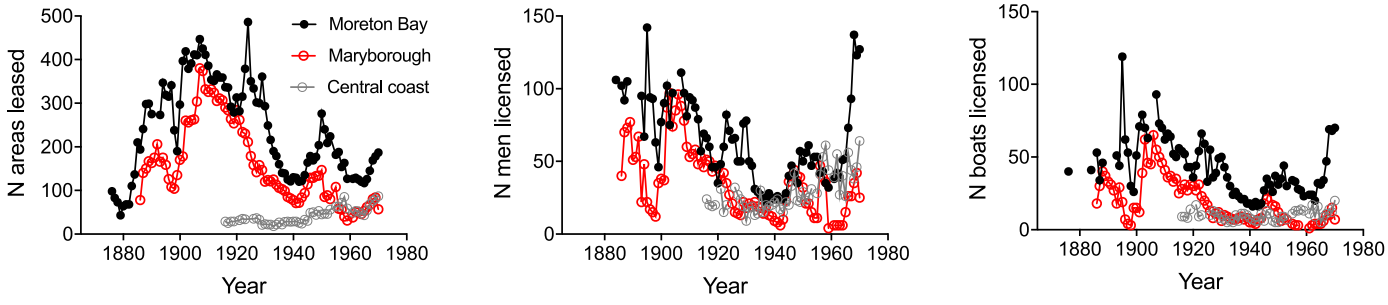

Fig. 5. Number of bank and dredge sections leased (a), number of men licensed (b) and number of boats licensed (c) in each region year^{-1}. Sources: Department of Ports and Harbours, n.d., Marine Department (1890–1928), Department of Harbours and Marine (1929–1970).

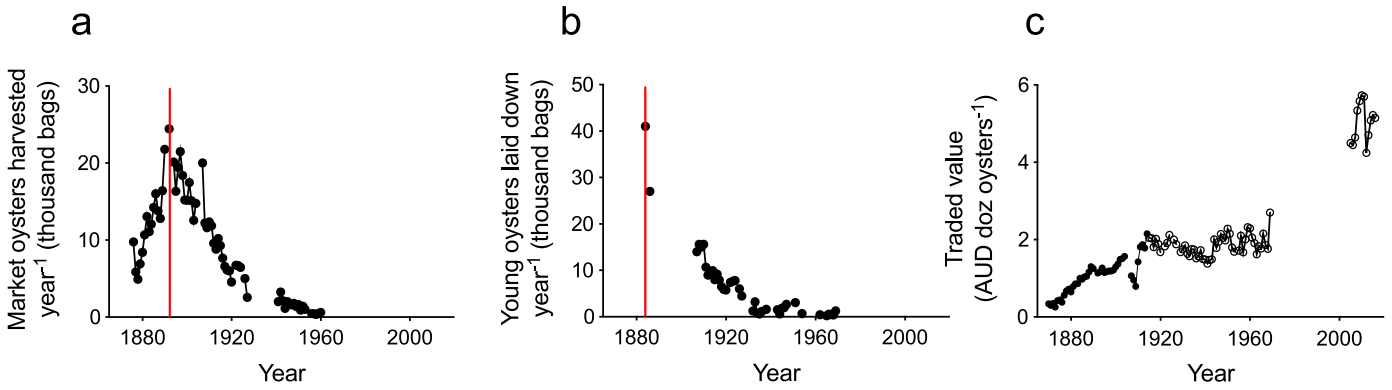

Fig. 6. Quantities of market-size oysters produced year^{-1} from Moreton Bay (a), quantities of young oysters sourced from Moreton Bay and other locations and laid down (cultivated) within the Bay each year (b), and traded value doz^{-1} year^{-1} after adjusting for inflation (base year: 2015; closed circles indicate period when the majority of recorded oysters traded were sold to interstate markets, open circles indicate when the majority of recorded oysters traded were sold to Queensland markets) (c).

Queenslander, 8 Sept 1906). This flood event also stimulated a burst of oyster recruitment (Fison 1888) due to nutrient loading. Despite a corresponding increase in production which peaked in 1891 (likely stemming from the 1887 recruitment event), multiple major floods in the following years led to increased sediment loading, ultimately rendering many of the subtidal oyster harvest sections unusable (Brisbane Courier, 1 Feb 1898). From 1895, mudworm (*Polydora* spp.), a polychaete which burrows into oyster shells increasing their vulnerability to environmental stressors, also began to be reported as problematic for the Moreton Bay oyster industry for the first time (Saville-Kent 1891; The Queenslander, 30 Nov 1895).

Further north in the Maryborough region, oyster beds were similarly damaged by a flood event in 1893, which was also followed by a large recruitment event (Erbacher and Erbacher 2011). During the 1880s large quantities of oyster culture from Maryborough were transported to Moreton Bay. Cultivation also commenced in the Maryborough region in the late 1880s, and by 1902 record numbers of oysters were being produced. In contrast to Moreton Bay, the oysters remained free of mud-worm during the early 1900s, although other oyster pests and predators were sporadically reported (Erbacher and Erbacher 2011).

This evidence suggests that during the late 1800s Moreton Bay transitioned from a relatively nutrient-limited system to an increasingly eutrophic system dominated by mud introduced via land-use change and periodic flooding (Diggles 2013; Diggles 2017). Loss of subtidal oysters and mudworm infections forced cultivation to be limited to the intertidal zone or away from the sediment. In 1928, a report on the oyster beds of Moreton Bay concluded: *"I can offer no better advice to the oyster growers than this; concentrate the cultivation and keep it off the bottom"* (Roughley 1928).

During the 1950s heavy mortality of oysters sporadically occurred in southern Queensland, but the cause remained unknown (Smith 1985). In the 1970s a disease called QX (Queensland unknown) caused by the endemic protozoan *Marteila sydneyi* was identified in the Maryborough and Moreton Bay regions, with up to 90% of infected oysters dying. It is possible that earlier reported mortality events were caused by this same protozoan (Smith 1985). The high levels of mortality forced many people out of the industry (Erbacher and Erbacher 2011) or required them to start purchasing culture and young oysters from New South Wales (Smith 1985). Subsequent research found a polychaete intermediate host for this parasite occurs in muddy sediments (Diggles 2013). In parts of Moreton Bay today, increased nutrient loading combine with siltation to form dense algal turfs that prevent oyster spat recruitment (Diggles 2013). In areas of western Moreton Bay, the zone suitable for natural oyster survival has been upwardly compressed to less than 5% of its original extent (Diggles 2013).

Social and economic drivers have also been responsible for changes in the production of Queensland oysters. Periods of economic depression sporadically stagnated the Queensland economy, halting or reducing growth in the oyster industry, particularly during the 1890s and 1930s (Erbacher and Erbacher 2011). Poaching of oyster banks also occurred, meaning smaller businesses were unable to expand oyster production beyond their line of sight (Table A1, quotations 33 and 34). The two World Wars made accessing supplies and manpower difficult, while labour costs and competition from other states and New Zealand increased after World War II (Smith 1985; Erbacher and Erbacher 2011).

4. Discussion

Archaeological and archival sources highlight more than a century of ecological changes in the central and southeast Queensland oyster fishery, providing baselines and an understanding of drivers of change for future restoration and management. Significantly, these sources also demonstrate the benefits of oysters and reef ecosystems to coastal communities through time: oysters did not just provide a provisioning service, oyster harvest provided a means of employment for rural communities and marginalized peoples (although some of this employment occurred via indentured labour); trade and annual oyster festivals promoted social interactions amongst different cultural groups (both amongst Aboriginal peoples and European settlers), and in some instances provided a means of empowerment and agency to Aboriginal individuals and peoples during a period characterized by dispossession and loss. Finally, oyster ecosystems and midden remains provided (and continue to provide) cultural heritage links to past generations.

4.1. Social and ecological significance

Oyster reefs were a major component of subtidal benthic communities until they began to decline from the mid-19th century onwards, firstly due to dredging and mining activities, and then from increased siltation and eutrophication. Given the known value of shellfish reefs for supporting high biodiversity, providing nursery habitats for fish and shoreline stabilization (Grabowski et al., 2012; Kent et al., 2016), it is likely that wider ecological impacts from the loss of these ecosystems, although not recorded, was significant. Notably, the loss of hard surfaces associated with oyster reefs is likely to have reduced the biomass of reef-associated fauna, reducing overall biodiversity. The loss of filter feeders (oysters and their epibionts) will have likely reduced biogeochemical cycling, since oyster reefs are known to facilitate drawdown of nutrients from the water column into sediments (Kellogg et al., 2013). The literature strongly suggests the system was far more oligotrophic than the sediment-dominated system observed today, hence it is

possible that ecological impacts extended to other ecosystems such as mangrove forests, which in the early 20th century began to be harvested for sticks (fascines), and seagrasses, as increased sedimentation and shoreline erosion would have created conditions unfavourable for seagrass growth.

Over the centuries, oysters have been valued by both Aboriginal peoples and non-Aboriginal Australians, providing sustenance to coastal and city populations, jobs and income, construction materials and contributing to cultural identity. At its height, the government sold over 200 licenses to individuals in the oyster industry. While a small number at face value, oyster production represented a source of employment in rural areas with otherwise limited opportunities, as well as a source of employment and license ownership for Aboriginal peoples. Far greater numbers of people – men, women and children – would have been employed in the harvesting, production, trade and selling of oysters, although the numbers are not recorded. Finally, while the oyster was not the only species to be harvested and to exist within middens, our results suggest that oysters and oyster reefs remain a highly visible and easily recognizable cultural link for Aboriginal peoples, and their traditional ecological knowledge could support current management, restoration and aquaculture.

4.2. Potential for informing modern estuary management

Understanding the previous extent, biomass and predominant oyster forms can help to inform their current protection. For instance, the process of nominating threatened ecosystems under the IUCN Red List of Ecosystems (https://iucnrle.org/) and Commonwealth Environmental Protection Biodiversity Act, 1999, both require an assessment of ecosystem decline from 1750 and a description of drivers to assess the risk of ecosystem collapse and category of protection (Act, E.P.B.C. 1999; Rodríguez et al., 2011). The extent to which oyster reefs were once dominant in southeast Queensland, as identified in this study, can also help to inform and potentially correct existing management policy. For instance, the main estuary habitat protection policy for the state of Queensland, Fish Habitat Areas, declared under the Fisheries Act, 1994 (Queensland Government 2015) does not explicitly classify oyster or shellfish reefs as fish habitat amongst the 14 identified inshore habitats. Whist the policy also doesn't explicitly exclude oyster reefs, their absence in state policies can potentially perpetuate shifting baselines (Alleway and Connell 2015) and lead to confusion when allocating permits for science or restoration (Authors Pers. Obs.). The results of this study clearly identify that oyster reefs were once common in central and southeast Queensland and their status as a distinct ecosystem type should be incorporated into future estuary management policy.

An understanding of historical baselines is valuable in strengthening the case for protecting remaining reefs and to build the case for restoration to the local community, managers and government (Brumbaugh et al., 2006; Creighton et al., 2015; Gillies et al., 2015) and can act as a conduit for encouraging community advocacy and interest in restoration. Historical Indigenous cultural values and practices surrounding oyster harvests in this region have been largely lost over the past century, but the extensive cultural heritage uncovered in the historical literature, together with the strong cultural values that continue to exist, provide strong evidence that oysters and oyster beds in this region provide, or have the opportunity to provide, services and value far beyond the economic. Indeed, Indigenous and non-Indigenous community interest and participation has been demonstrated in current restoration efforts of shellfish reef systems in southern Queensland estuaries (McLeod et al., 2018; The Nature Conservancy 2019; Restore Pumicestone Passage 2019). Historical description of reef biomass, structure, location, depth and drivers of reef decline can help guide restoration practitioners understand how and where best to restore oyster reefs. Modern restoration techniques call for the use of reference systems which can be used to obtain basic ecosystem traits (such as oyster density, patch size) and functions (such as shoreline stability) to help establish restoration targets and metrics (McDonald et al., 2016). In the absence of nearby reference systems, reference models, developed from historical and current literature and remnant patches can be substituted (Gillies et al., 2017).

An understanding of the drivers of decline – including, the removal of oyster biomass, loss of available substrate, increased sedimentation and disease – can help practitioners employ methods to overcome these such as the relaying of cultch, introduction of QX-resistant oysters and the reduction of sediment and pollutants into the system (Smith 1985; Diggles 2017). Maps of historical distribution such as those presented in Fig. 3 and information on local site attributes (such as reef depth, original sediment type, substrate) obtained from historical accounts (e.g. Table A1, quotations 8–10) can help practitioners identify more productive sites or estuary attributes (such as regions with greater tidal flow, estuary flats, suitable currents) that may facilitate reef growth and persistence.

4.3. Wider relevance

Previous studies have examined changes through time in coastal ecosystem structure, functioning and resource use, including oyster habitats (Jackson et al. 2001; Lotze et al., 2006; Kirby 2004; Alleway et al. 2015; Rick et al., 2016; Schulte 2017). These studies uncovered similar findings to ours; that extensive ecological changes have occurred, often as a consequence of direct and indirect human impacts including increased sedimentation, over-harvest, and/or introduced predators, competitors and diseases. We believe there are two main aspects of our study that make it stand out from the existing literature, and be of particular relevance for regions where interactions between Indigenous and Western cultures have resulted in dramatic social, cultural and/or ecological change over the last few hundred years. Firstly, the relatively recent nature of the dramatic changes observed in this social-ecological system align with the introduction of mass-produced printed media in the form of newspapers, popular literature and government reports. As such, we were able to map these changes in considerable detail by mining the ethnohistorical literature and collating formerly disparate data from a range of sources and disciplinary silos. We believe this approach offers an opportunity to support not only restoration of the ecosystem, but – by highlighting past cultural knowledge and cultural heritage – potentially support the revival of Indigenous and traditional values and practices and their integration into management. Significantly, the increasing accessibility of historical materials, largely due to digitization, make our approach of creating a detailed social-cultural narrative feasible for many other regions around the world that have similar recent histories of intense societal change or upheaval.

Secondly, unlike many other oyster fisheries around the world, including the more southerly Australian flat oyster (*Ostrea angasi*) fishery (e.g., the recent discovery of *Bonamia* spp., Buss et al., 2019), it is unlikely that the major infectious agents that affected the Queensland oyster fishery, mudworm and QX disease, were introduced from other regions (Diggles 2013). Mounting evidence suggests that the expression of these diseases is forced by environmental factors (Diggles 2013; Raftos et al., 2014; Adlard and Nolan 2015; Carrasco et al., 2015). Importantly, this suggests the diseases are the symptoms, not the primary cause of declines, and subsequently the emergence of these diseases provides robust information to pinpoint the timings of environmental and ecological decline. This is also one of the critical differences between this case study and the Chesapeake Bay oyster fishery, which was undoubtedly impacted by the introduction of the exotic *Haplosporidium nelsoni* (MSX disease) (Burreson et al., 2000; Schulte 2017). As such, our research provides important alternate perspectives on both the drivers of and social-cultural outcomes of change.

5. Conclusion

This study examined changes through time in a habitat-forming species that was once highly abundant and of significant commercial and cultural value to coastal communities across central and southern Queensland. Similar to many regions around the world, the actions of non-Indigenous people were undoubtedly the cause of the decline of the Queensland oyster fishery. For this case study, however, how these impacts interacted and affected the coastal ecosystem and the Indigenous peoples – whose history and culture is so strongly intertwined with the oyster and wider coastal resources – is notably detailed in the historical literature, albeit such customs were usually interpreted and communicated by settlers. While the coastal ecosystem has been transformed and many cultural values and practices have been lost, this study helps unravel some of the history and drivers of change which can be used to inform contemporary management, protection and restoration of these oyster reefs and associated traditional practices.

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CRediT authorship contribution statement

Ruth H. Thurstan: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **Ben K. Diggles:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **Chris L. Gillies:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **Michael K. Strong:** Methodology, Formal analysis, Investigation, Writing - original draft. **Ray Kerkhove:** Methodology, Formal analysis, Investigation, Writing - original draft. **Sarah M. Buckley:** Methodology, Formal analysis, Investigation, Writing - original draft. **Robert A. King:** Investigation. **Vince Smythe:** Investigation. **Gideon Heller-Wagner:** Investigation. **Rebecca Weeks:** Formal analysis, Investigation, Writing - original draft. **Fred Palin:** Investigation, Writing - original draft. **Ian McLeod:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2020.102058.

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