Reconstructing Ecological Baselines: Toward Improved Management in Aquatic Ecosystems

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Abstract

Human disturbances that alter ecosystems are distinct from natural disturbances that drive variation, and are critical to separate in the study of ecological change. Patterns created by a combination of anthropogenic and natural drivers are often ambiguous so that existing patterns can be mistakenly considered a function of natural or anthropogenic processes. Consequently, a notable challenge in ecology and in natural resource management is not only to recognise 'change', but also its causes. This thesis explored shifts in ecological patterns, and human perception of them, in aquatic ecosystems across historical time scales of decades to hundreds of years. Particular emphasis was given to the activities of fishing and European colonisation, which are renowned drivers of alterations. Research methods encompassing ecology, fisheries science and history, were used to generate time series for select hypotheses of change. Fisheries production and catch data were combined with historical data from the Adelaide Fish Market to reconstruct several baselines for fisheries in South Australia from colonisation in 1836 through present. Using the conceptual models of fishing down and 'neo-Europe' to account for change, key shifts in fisheries were identified. These were the modern addition and expansion of fisheries at lower trophic levels and the historical predilection of European settlers toward exploiting inland species. Though there is strong evidence of critical changes in ecosystems due to resource extraction, the addition or introduction of new species to ecosystems can also be influential. The effect of contemporary concern of society toward a cryptogenic oyster species and its management was assessed from a historical perspective. Field experiments were used to evaluate the impact of this species as an epibiont on a native bivalve. These established that the species might bring positive benefits, which contrasted the negative societal perception of unwanted 'invasion'. A factor contributing to this negative perspective was diminished general memory of the past presence of oyster reefs, which have been lost from that locality. A baseline of lost oyster reefs across the South Australian coastline was reconstructed through recovering fisheries catch and effort data and building a time line of change, including declines in perceived and actual abundance of this habitat due to overexploitation during the 1800s and early- to mid-1900s. The past distribution of oyster reefs was established, along with their eradication across more than 1,500 km of the

nearshore environment and loss of this knowledge through intergenerational amnesia. To account for such shifts scientists and managers can incorporate past baselines into their practice and to test this approach historical data were used to inform several aspects of planning for aquaculture. This thesis demonstrated that ecological baselines in temperate aquatic ecosystems have shifted and that more accurate representations of past states can be retrospectively reconstructed. Also, it illustrated the influence that change can have on societal and administrative perspectives and, accordingly, advocates for wider consideration of the shifting baseline syndrome. Without better representation of the past we risk misinterpreting change, negative and positive, which could perpetuate reduced expectations for the environment and its deterioration.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university of other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Heidi Katya Alleway

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Chapter 1: Introduction

1.1 Shifting baselines

Change in ecosystems has occurred over multiple time-scales, from tens of years to tens of thousands of years, which can be studied from the perspectives of palaeoecology, archaeology, history and ecology (Lotze and Worm, 2009). These disciplines can assist us to discern shifts in ecological states and natural disturbances that drive cyclical patterns of variation or long term ecosystem change. Discerning change that has occurred as a result of human activity, however, as opposed to change that has occurred naturally, can be challenging (Dayton et al., 1998, Willis and Birks, 2006). For example, natural patterns of climatic variability can be a driver of population structure in fish stocks (Finney et al., 2002), but climate change has induced alterations in their distribution, recruitment success and growth (Rijnsdorp et al., 2009). Coral reefs have experienced major episodic changes throughout geological time, but have also been impacted by climate change, and additionally overexploitation and pollution (Pandolfi et al., 2011).

The human use of natural resources has especially resulted in substantial declines in species and habitats. Exploitation began when humans first colonised new areas (Erlandson et al., 2009, Erlandson and Rick, 2010), but their persistent and more recent industrial scale utilization means that many ecosystems are now fundamentally different because of overfishing as well as habitat degradation and the incidence of invasive species (Jackson et al., 2001, Pauly et al., 1998, Mooney and Cleland, 2001). However, even profound to changes to ecosystems, such as habitat shifts or the regional extinction of species, can go unnoticed (Dayton et al., 1998, Turvey et al., 2009).

Alongside ecological change cognitive baselines can change over time when an accurate basis for comparison is not available (Papworth et al., 2009). Scientists and managers sometimes accept their own recent experience as their benchmark for ‘natural’ and where well-defined or documented baselines are not known or readily available they may use this perspective as their basis for comparison (Jackson, 2001, Willis and Birks, 2006, Connell et al., 2008). Measuring change against this contemporary benchmark can result in an intergenerational decline of the past and more accurate baseline through the shifting baseline syndrome (Pauly, 1995). Losing knowledge of the past can contribute to the loss and acceptance of further ecological change, including unobserved declines in species and potentially species extinction (Dulvy et al., 2003, Sadovy and Cheung, 2003, Sáenz-Arroyo et al., 2006). Thus, whilst ecological baselines are used in contemporary management they may not adequately characterise a more natural state of the ecosystem of interest or draw attention to the changes that have occurred. Through a ratchet-like action targets that poorly reflect past states of species or habitats can perpetuate declines (Dayton et al., 1998, Pitcher, 2001).

1.2 Change in temperate aquatic environments

Temperate aquatic ecosystems have been impacted by overfishing, pollution and the alteration of habitats through destructive fishing practices or changes in environmental flows. Worldwide more than 85% of oyster reefs – a highly valuable and engineering habitat – have been lost due to overexploitation, declines in water quality and disease (Airoldi and Beck, 2007, Beck et al., 2011). Overfishing has reduced abundances of higher trophic guilds such as marine mammals, sharks and billfish and these animals now represent some of the oceans most impacted species (Pauly et al., 1998, Baum et al., 2003, Worm et al., 2005). In some instances the loss of higher trophic level species has induced broader ecosystems shifts, for example, the incidence of regime shifts in kelp forests where the removal of predators enables increased abundances of sea urchins leading to the creation of urchin barrens (Jackson et al., 2001). Land-based activities have also contributed to impacts including pollution from runoff, which has led to declines in water quality and the loss of habitats such as seagrasses and wetlands (Lotze et al., 2006, Marbà et al., 2014).

Southern Australia is regarded for having extensive areas of remote, 'untouched' coastline that supports marine biodiversity and a high degree of biological endemism (Edyvane, 1999b, Fitzsimons et al., 2015), which is consistent with other isolated temperate regions, such as New Zealand (Gordon et al., 2010). But this region has been inhabited and affected by humans for tens of thousands of years. Aboriginal communities have occupied coastal areas of southern Australia for millenia and developed fishing techniques that have enabled them to exploit marine resources and to adapt to periods of regional stress to continue fishing (Luebbers, 1978). The more recent period of European colonisation and occupation also relied on fisheries resources and has precipitated landscape-scale transformations through other ‘imperial’ behaviours such as the introduction of exotic species to “renovate the biota” (Crosby, 1986, Griffiths and Robin, 1997, Osborne, 2001). Extensive harvesting of *Arctocephalus forsteri* (fur seals) began with the arrival of settlers and the impacts of this resource use have been so substantial that conservation measures have only recently realised a recovery in the population (Shaughnessy et al., 1995). Industrial fishing has brought on catastrophic declines of nearshore shellfish species (Edgar and Samson, 2004) and affected species stocks and assemblage structures offshore, within remote areas of the Southern Ocean (Ainley and Blight, 2009).

Throughout New South Wales, Victoria and South Australia the adjustment of freshwater environmental flows through river regulation has greatly reduced the viability of inland fishing (Humphries and Winemiller, 2009). *Argyrosomus japonicus* (mulloway), a large-bodied and late-maturing species, were historically a dominant part of estuarine fish assemblages and important to Aboriginal subsistence (Disspain et al., 2011) and European settlers (Duffield, 1909), but the implementation of weirs in 1940 and long term overfishing has since led to significant declines in their abundance (Ferguson et al., 2013). Commercial exploitation has also led to changes in the stock structure of some species. For example, Fowler and Ling (2010) compared the age of samples of *Hyporhamphus melanochir* (southern sea garfish), inferred from otoliths obtained 50 years apart, finding severe truncation in current South Australian populations as a result of fishing.

Estuaries, in particular, have been impacted by land-based anthropogenic pressures (Creighton et al., 2015, Fitzsimons et al., 2015). In the large, inverse estuary of Gulf St. Vincent pollution from wastewater treatment plants, stormwater, and agricultural runoff, together with prawn trawling, has transformed benthic habitats. Substantial changes to *Malleus malleus* (hammer oyster) and *Pinna bicolor* (razorfish) beds have occurred along with an 80% decline in byrozoan communities (Shepherd and Sprigg, 1976, Tanner, 2005).

Broadscale loss of seagrasses have been identified (Bryars and Rowling, 2009) and wetlands formed by mangroves and salt marshes have been degraded (Edyvane, 1999a). Connell et al. (2008) examined long term patterns of change in canopy-forming algae to test contemporary versus historical patterns of their occurrence at successive regional and biogeographical scales. In the past, areas along the metropolitan coastline of Adelaide were indistinguishable from contemporary unaffected sites, but as much as 70% of algal cover is now gone (Connell et al., 2008).

1.3 Historical ecological research

Since anthropogenic impacts can occur over considerable periods of time there is value in constructing data sets to have a temporal span commensurate with that of their influence (Baum et al., 2003, Willis and Birks, 2006, McClenachan, 2009). In the past, explicit evaluation of temporal scales of measurement have been somewhat limited by availability of methods and a perceived lack of availability of data. Focus on the ecology of the past has recently contributed a unique, multi-disciplinary approach to address this gap through historical ecological research (e.g. Rick and Lockwood, 2012). An agenda for historical ecology is growing, driven by a growing body of knowledge and evidence that a wide range of information sources can be drawn upon to generate quantifiable data sets and time series, from present through past (McClenachan et al., 2012, Schwerdtner Máňez et al., 2014).

The ‘historical’ element to historical ecology denotes data spanning hundreds of years, usually aligned to written sources such as diaries and fisheries catch returns, or illustrated material including maps and photographs (Pinnegar and Engelhard, 2008, Lotze and Worm, 2009). Whilst these sources have often been documented or archived, they can also be used to retrospectively evaluate past ecosystem states and patterns of change. Fisheries occurring in the past can be measured by modeling production, catch or market data (e.g. Klaer, 2001). Notably, fisheries data already in use can still contribute ‘new data’ because a different lens, through the method or model used, can be applied (Rosenberg et al., 2005, Josephson et al., 2008). For example, Baum et al. (2003) used log book data from the U.S. pelagic longline fleet in the Northwest Atlantic to resolve that the majority of recorded shark species have declined by more than 50% over the last two decades. The authors used well-known logbooks and simple empirical models, but the data had not previously been used to assess non-target species, in this case sharks.

Qualitative information can be a further source of data and forms a unique but challenging part of historical ecology. The dismissal of qualitative or historical records as “methodologically naïve” and not for scientific application is mistaken (Pitcher, 2001), because historical records and anecdotes are in fact early interpretations of data (Pauly, 1995, Pitcher, 2001, Pinnegar and Engelhard, 2008) and can contribute quantitative series to evaluate changes in species, ecosystems and human activities (Holm, 2003, Pinnegar and Engelhard, 2008, MacKenzie et al., 2011). These data can also detail important or anomalous environmental events and provide much needed context to anthropological influences and their consequences. Qualitative data can stem from information within diaries or reports of the accounts of early explorers, settlers, fishers or communities, as well as photographs and artwork (Sáenz-Arroyo et al., 2006, Pinnegar and Engelhard, 2008) and a precedent for its use in ecology has recently been set through the development of novel methods. Rigorous data sets can now be generated from qualitative sources through the use of methods that enable anecdotal statements to be coded and converted into semi-quantitative or quantitative measures of species abundances (Sáenz-Arroyo et al., 2005a, Sáenz-Arroyo et al., 2006). More alternative sources, such as newspaper articles (Thurstan et al., 2014) and interviews with fishers (Sáenz-Arroyo et al., 2005b, Thurstan et al., 2015), can also be used in this way. However, historical sources of data cannot always be accessed through conventional literature searches and are not always easily found, and a cross-disciplinary appreciation for this type of research is valuable, because it can inform identification of data and the choice and design of the methods to be used. An approach that incorporates perspectives from the discipline of history can also provide context to cultural aspects of change that might otherwise be lacking (Bolster, 2006, Szabó, 2010).

1.4 Reconstructing shifted ecological baselines

Using synopses or analyses that do not accurately reflect an ecosystem can lead to erroneous or misleading targets being applied to management. Incorporating historical data into management practices usually increases estimates of past maximum population abundances and indicates that ecosystems can have higher productive capability than is often presumed (McClenachan et al., 2012). Despite the fact that fisheries species in Australia have been commercially exploited for more than 150 years (Duffield, 1903a, Wallace-Carter, 1987), and there is knowledge of anthropogenic impacts and long term change in ecosystems (e.g. Connell et al., 2008, Humphries and Winemiller, 2009, Fowler and Ling, 2010), the ecological baselines used as the basis for management are disparagingly short. In particular, fisheries statistics and reference limits (targets) for fisheries management are based on data beginning in the 1980s (Fowler et al., 2014). Hence, there is a need to address this gap, between the onset of fishing and contemporary ecological baselines. Measuring species and habitats over longer periods of time will take greater account of natural cycles of variability as well as long term change induced by human activity. It is likely that this will generate more accurate points of reference, which could predicate the need for alternative management regimes or assist to overcome barriers to ecological restoration (Pitcher, 2005, Manning et al., 2006, Higgs et al., 2014).

Returning ecosystems to former or 'original' states through conservation or restoration is challenging where multiple shifted baselines interact to create complex trajectories (Duarte et al., 2009a) and, in fact, it may be impossible to fully recover past losses under a future of non-analogue environments (Hobday, 2011). But a future of complexity could make the definition of accurate historical baselines more important. Accurate definitions of past ecological states could assist us to predict and interpret future states (Pandolfi et al., 2011) and guide our choices for the historical legacies that must be protected, such as critical ecological processes or cultural values (Higgs et al., 2014). Historical baselines could also assist us to confront uncertainty, adding confidence to decision-making (Ludwig et al., 1993), and establish a stronger mandate for the repair of species or habitats to rebuild lost productivity (Worm et al., 2009).

1.5 Aims of research

The aims of this research were: to ascertain whether aquatic ecological baselines have shifted, using the temperate region of Australia as the focus; and to reconstruct more representative measures of past ecosystem states that can be used in ecology and management. To differentiate between natural versus anthropogenic effects I explicitly focused on measurement of human activity, testing whether fisheries and European colonisation have induced shifts in ecological states. I also examined the influence that these activities and societal perspectives have had on our definition of contemporary environments and the means through which historical baselines could be effectively integrated into management.

Each data chapter (two to six) is written in the form of a stand-alone scientific manuscript suitable for publication in a peer-reviewed journal. Therefore, each chapter includes a separate introduction, methods, results, discussion and supplementary material; references for unpublished manuscripts are appended at the end of the thesis. All chapters are co-authored, hence there is a use of plural, and a statement of authorship is included preceding the chapter. All tables and figures are embedded within the text and the numbering of figures and tables begins at one for each chapter, however, all are tied to the overarching aims of this research, the development of which I discuss in the Discussion (chapter seven). The following is a brief synopsis of each chapter.

In chapter two historical fisheries production data were used to reevaluate calculations of the mean trophic level (MTL) of fisheries catches in South Australia. Previous calculations had been indeterminate (Pauly et al., 1998, Watson et al., 2004, Pauly and Watson, 2005) but the use of disaggregated, regionally specific data enabled a more accurate interpretation of change, since 1936, to be made. This chapter also fitted a novel source of data to the model, this being quantities of fish sold at the Adelaide Fish Market, to consider whether alternative data that extends further back in time could be more widely applied to calculations of MTL, which predominantly start at 1950.

Chapter three used the model 'neo-Europe' (Crosby, 1986), from the discipline of history, to lengthen the time series used to evaluate changes induced by fisheries to 1900. A latent source of historical data from the Adelaide Fish Market was identified, through which a pattern of societal preferences for species was observed. Patterns of change and the influence of expectations of European settlers were substantiated through qualitative anecdotal statements contained within government reports at that time, then compared to the earlier experiences of fisheries in Europe.

Over the past 50 years our appreciation and understanding of the impacts of non-native species has grown and ‘invasion ecology’ is now widely studied (Richardson and Pyšek, 2008, Caluya, 2014). Chapter four assessed the concern of a community toward a cryptogenic oyster species and its management, which happened to be within a locality of oyster reef loss. The effect of the new species on a native bivalve and associated epifauna was quantified using field and experimental data. Potential ecological gains were identified which contrasted the community perception that the population was driving environmental degradation. The implications of this for management of the species were explored through the development of a decision-making model.

Chapter five further investigated oyster reef loss through the use of archival material to reconstruct the past occurrence, distribution and abundance of native oyster reefs formed by *Ostrea angasi* across the South Australian coastline. This evaluation recovered a shifted baseline, which indicated oyster reefs were historically characteristic of much of the coastline but have been extirpated by commercial fishing and overexploitation. Oyster fishing hastened the state’s first fisheries legislation, including the implementation of seasonal and spatial closures and reserves to protect declining oyster beds, but there was little contemporary knowledge or consideration of this species, oyster fishing, or oyster reefs.

Integration of historical data into contemporary assessments is needed and can ensure the best data available is used to establish baselines, rather than it being lost in the future (McClenachan et al., 2012, Ban et al., 2015). In chapter six, the use of historical data to prescribe management actions was tested and demonstrated. Past catch data from the fishery for *O. angasi* and anecdotal records of activity associated with this fishery were used to inform contemporary aquaculture planning. Aspects of spatial planning and ‘zoning’, non-native species risk assessment and consultation with industry and government were informed by the data, the conclusion being that historical information and past ecological baselines can be integrated into contemporary planning and used effectively to assist the prescription of management actions.

Chapter 2: Historical changes in mean trophic level of southern Australian fisheries

2.1 Preface

'Fishing down of food webs' can occur when fishing pressure is disproportionately applied to higher trophic level species leading to a lowering of the overall mean trophic level (MTL) of fisheries catches. Underlying patterns of ecosystem change, however, can be obscured by the use of over aggregated catch statistics or the voluntary expansion and sequential addition of fisheries for lower trophic level species. This chapter uses disaggregated catch statistics to calculate annual MTL of catch in South Australian fisheries and evaluate patterns and drivers of change. The analysis illustrates that the model of MTL must be interpreted with care because declines may not always be the result of 'fishing down', i.e. disproportionate declines in higher trophic level species. This chapter has been published in *Marine and Freshwater Research* and is reprinted here with permission from CSIRO Publishing (Appendix A). The original manuscript can be sourced from the publishers website: http://www.publish.csiro.au/?paper=MF13246.

2.2 Statement of authorship

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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
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Historical changes in mean trophic level of southern Australian fisheries

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Abstract. Decreases in the mean trophic level (MTL) of fishery catches have been used to infer reductions in the abundance of high trophic level species caused by fishing pressure. Previous assessments of southern Australian fisheries have been inconclusive. The objectives of the present study were to provide more accurate estimates of MTL using disaggregated taxonomic and spatial data. We applied the model of MTL to fisheries catch statistics for the state of South Australia from 1951 to 2010 and a novel set of historical market data from 1936 to 1946. Results show that from 1951 to 2010, MTL declined by 0.16 of a trophic level per decade; a rate greater than the global average of 0.10 but equivalent to similar regional investigations in other areas. This change is mainly attributable to large increases in catches of sardine, rather than reductions in the catches of high trophic level species. The pattern is maintained when the historical data is included, providing a time line from 1936 to 2010. Our results show a broadening of the catch of lower trophic levels and suggest care in interpretation of MTL of catches because reductions do not necessarily reflect change in high trophic level species by fishing pressure.

Additional keywords: fisheries, fisheries catch, 'fishing down' marine food webs, South Australia.

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Introduction

Fisheries can generate reductions in stock biomass or distribution (Baum and Myers 2004; Christensen *et al.* 2003; Poulsen *et al.* 2007), alterations in species composition and trophic cascades (Benoît and Swain 2008; Daskalov 2002; Pinnegar *et al.* 2000), even extinction (Dulvy *et al.* 2003; Roberts 2003). Predatory species can be disproportionately affected by exploitation (Christensen *et al.* 2003; Jackson *et al.* 2001; Ward and Myers 2005) and the systematic fishing of these species can also indirectly induce other impacts, including a lowering of the overall catch-related trophic level. The 'fishing down' of marine food webs was identified when Pauly *et al.* (1998) observed an average decline of 0.05–0.10 of a trophic level (TL) per decade since 1950 in global fisheries within the Large Fishing Areas (LFAs) of the Food and Agriculture Organisation (FAO). This pattern was attributed to repeated overfishing of higher trophic levels and a reduced contribution from these species to overall fisheries production (Pauly *et al.* 1998; Pauly *et al.* 2002).

Subsequent development of this model suggested that a portion of the decline may reflect the expansion of catch of lower trophic level fisheries and the sequential addition of new fisheries (Caddy *et al.* 1998; Essington *et al.* 2006). Discussion has focused on whether reductions in the mean trophic level (MTL) of catch, also referred to as the marine trophic index (MTI) (Butchart *et al.* 2010; Pauly and Watson 2005), is as widespread as initially thought and whether it accurately reflects underlying trends in the ecosystem structure (Branch *et al.* 2010). High trophic level species may not always be more vulnerable to fishing than low trophic level species (Pinsky *et al.* 2011) and concern about the effectiveness of catch-based MTL as an indicator of ecosystem structure is ongoing (Branch 2012; Hornborg *et al.* 2013; Pauly and Froese 2012).

Continued application has also demonstrated there are challenges to achieving a sound picture of estimates of MTL due to a lack of accurate data. Inaccuracies in reporting (Jacquet *et al.* 2010; Watson and Pauly 2001; Zeller *et al.* 2011) coupled with over aggregation of catch data spatially and taxonomically (Pauly and Palomares 2005; Watson *et al.* 2004) may have affected the accuracy of estimates of MTL. As a result, investigations of MTL are being repeated at more refined scales using source data, including the Exclusive Economic Zones (EEZs) of individual countries (Watson *et al.* 2005) and Large Marine Ecosystems (LMEs) (Watson *et al.* 2004), as well as regional units, for example: the states and territories of India (Bhathal and Pauly 2008) and Brazil (Freire and Pauly 2010); areas of the Mediterranean (Pinnegar *et al.* 2003); coastal and inland waters

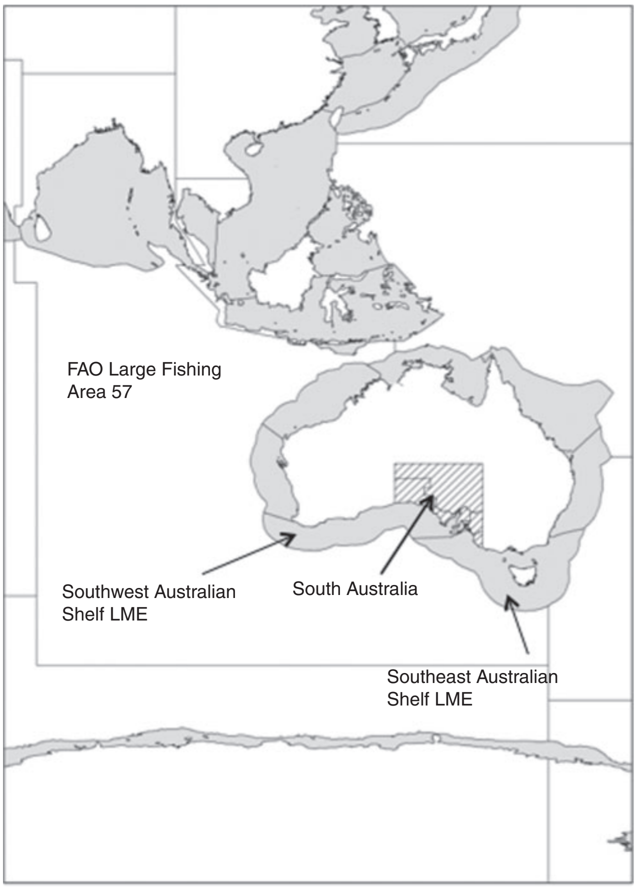

Fig. 1. Reporting zones for fisheries catch along the southern Australian coastline: Australia's Exclusive Economic Zone (EEZ); Food and Agriculture Organization (FAO) Major Fisheries Areas; Sea Around Us Large Marine Ecosystems (LMEs); and the Australian State Government boundaries (shape files courtesy of Food and Agriculture Organisation of the United Nations, Fisheries and Aquaculture Department (http://www.fao.org/fishery/area/search/en); National Oceanic and Atmospheric Administration (http://www.lme.noaa.gov/); and the Australian Government (http://data.gov.au/data/).

of Canada (Pauly *et al.* 2001); and the Gulf of Thailand (Christensen 1998) (comprehensive list provided by Freire and Pauly (2010)).

The sheer size of Australia's tropical and temperate marine environments mean that the scale at which the MTL of catches has previously been investigated in Australia has been coarse. It is also likely that for southern Australia the current estimates are ambiguous because the LFA encompassing this region (LFA 57) also spans the eastern Indian Ocean, north to the southern extent of Asia (Fig. 1). Previous assessments for this LFA, which covers an area of 31 100 000 km^2, and the south-west and south-east Australian Shelf LMEs, 1 046 368 km^2 and 1 199 787 km^2, respectively, have indicated no clear trends over time, with some periods of increasing MTL (Pauly *et al.* 1998; Pauly and Watson 2005; Watson *et al.* 2004). In comparison, the jurisdictional waters of South Australia, which extend to 3 nautical miles offshore, covers an area of 60 282 km^2. Several fisheries, including those for *Sardinops sagax*, *Chrysophrys auratus* and crustaceans, operate over a larger area through access to the Commonwealth waters adjoining South Australia. Previous results may reflect the broad fishing areas used to assess fishing down in southern Australian waters.

Using finer scale geographic and taxonomic data from 1951 to 2010 for the jurisdictional state of South Australia, we hypothesise that the phenomenon of fishing down can be demonstrated in fisheries along the southern Australian coastline. Because catch-based estimates can be influenced by mechanisms other than variations in stock, including regulatory changes, market preferences, technological improvements and attributes related to potential for profit (Branch *et al.* 2011; Sethi *et al.* 2010), we also sought to understand the potential causes of changes in MTL over time. South Australia has jurisdictional responsibility for the central southern coastal margin of Australia. Catches of several offshore species are included but nearshore and continental shelf fisheries are the focus of reporting. Changes in MTL have been found apparent at the spatial scale of 'state' (units within a country) but not when a country was treated as a whole (Bhathal and Pauly 2008; Freire and Pauly 2010).

In the present study, we emphasise that patterns in MTL may not just reflect changes in the underlying ecosystem MTL (Branch *et al.* 2010; Hornborg *et al.* 2013), but show that these patterns are useful in understanding how fisheries change over time. This is relevant to recent suggestions that a greater focus is required on how components of ecosystems are fished in relation to one another; i.e. that fishing a broad range of species from a range of trophic levels may be preferable to selective fishing of a few species (Pinsky *et al.* 2011; Smith *et al.* 2011; Zhou *et al.* 2010). Modelling changes in the MTL of southern Australian fisheries across a longer time period than previously investigated may provide important insights into patterns within this region that would have previously been obscured.

Using this refined spatial scale may mean that changes to fisheries through management have greater effects on trends in MTL than would otherwise be observed. As a result, we combine the model with a more explicit investigation of key taxonomic groups and also test the use of an alternative data source. Identifying whether alternative datasets can be included when calculating MTL may increase both the available information through which profiles could be built and the time series over which they are interpreted. A set of data comprising quantities of fish passing through a local market from 1936 to 1946 are combined with contemporary catch and production statistics to provide two time series for comparison. Market data are not catch based, but it is assumed that market data reflect the proportions of species caught; i.e. the preference for certain types and amounts of fish would in part be proportionate to the quantities caught in the fishery. Identifying whether alternative datasets can be included when calculating MTL may increase the time series of information that is available to build profiles of MTL, which would improve the comprehensiveness of the model and the time series over which it can be interpreted.

Materials and methods

Fisheries Statistics

Commercial wild-caught production statistics recorded and reported by the Department of Fisheries for the State of South

Australia (Fig. 1) were sourced from publicly available production reports. Contemporary catch quantities of individual taxonomic groups from 1986 to 2010 were translated from electronic copies of the fisheries reports of the South Australian Research and Development Institute (Knight and Tsolos 2011; Knight *et al.* 2006), South Australia's fisheries research provider.

For the period 1973 to 1985, annual production statistics for taxonomic groups were translated from hard copies of the 'Magazine of the Department of Fisheries and the Fishing Industry Council in South Australia', retained in the State Library of South Australia. Mandatory returns for species specific fisheries were variously introduced through the mid-1900s and voluntary catch statistics were available in a raw statistics book of the Department of Fisheries, which recorded annual quantities of commercially important species from 1951 to 1971. This information represented the only source in the dataset that is not publicly accessible and the South Australian Research and Development Institute made these statistics available. It was recognised that, being based on voluntary submission, these data, and potentially a portion of reporting for minor species from 1973 to 1985, may not have represented complete production quantities for all species caught across the state but the length of time over which the statistics were considered was believed to be appropriate for patterns of variability to override short-term inconsistencies in reporting.

It was also assumed that catch quantities that were voluntarily reported would represent the largest portion of overall production because the most popular and highly sought after species would be reported first and in more detail. Catch of marginal or commercially less significant species may have been under-reported, but voluntary data were considered valid for the purposes of assessing MTL because the process of fishing down is driven by changes in the greatest proportions of total catch; that is, the largest quantities of species caught. Variation in species that contribute a small portion to the total catch will have minimal influence on MTL from year to year, but the long-term patterns of change will remain.

Across the full data period, there was a significant alteration in the reporting of 'tuna', specifically *Thunnus maccoyii* (southern bluefin tuna). Although caught within South Australian waters through Offshore Constitutional Settlement (OCS), the management of this species was transferred to the Commonwealth (Australian Government) in 1979 and the catch of tuna was then reported through the Australian Bureau of Agricultural and Resource Economics – Bureau of Rural Sciences (ABARE-BRS) (ABARE 1993; ABARE 1994; ABARE 1997; ABARE 2004; ABARE 2006; ABARE 2010). Catch quantities of tuna from 1951 to 1986 were translated from the state-based reporting sources and, from 1991 to 2010, the Commonwealth reporting source. Inconsistencies in the reporting of tuna are known to induce a 'masking effect', obscuring underlying or more subtle patterns of change (Bhathal and Pauly 2008; Pauly and Palomares 2005). Masking was tested by treating tuna as a key driving species, retaining and removing catch quantities from analyses of MTL.

A similar situation existed in some trawl-related fisheries with an OCS also impacting several other species, in particular *Galeorhinus galeus* (school shark) and *Mustelus antarcticus* (gummy shark). The various OCS were negotiated in 1997 and 2000 (Noell *et al.* 2006) and apportioned management, and therefore reporting, to the Commonwealth fisheries agency. This transfer was not as clear as that of tuna and a portion of shark legally retained as by-catch remained reported through state-based statistics from 1997 onwards. Commonwealth data for species caught within each state are not available through ABARE-BRS public reports and because the transfer of responsibility was comparatively recent, shark quantities were not re-adjusted. The restructure of shark management and reporting in 1979 induced a drop of state-based catch quantities of 1200 tonne, followed by a further 100 tonne in 2000. Influence of this variation was tested for by also treating shark as a key driving species and quantities of shark were included and removed from analyses of MTL.

Adelaide Fish Market quantities

Prior to 1951, catch statistics for fisheries were not available. Parliamentary Papers of the Government of South Australia, archived in the State Records of South Australia and open to the public, provided annual reports on the 'Operations of the Fisheries and Game Department'. For the financial years 1936 to 1946, a contiguous set of papers reported 'Quantities of Fish Passing through the Adelaide Fish Market'. During those years, the Adelaide Fish Market was the pre-eminent market and outlet for fish sales in the region (Wallace-Carter 1987).

Fish market statistics were not comparable with catch statistics and were known to be significantly lower than total production quantities as the papers also tabled sizeable consignments of total quantities of fish by railway to New South Wales and Victoria. These figures and catch quantities for the regional sale of fish to processors, canneries or at the wharf were not available and we applied the equivalent assumption to these data as that applied to voluntary fisheries statistics. It was considered that fish market quantities represent favoured species caught at that time and the proportions of species sold would therefore reflect the proportions of species caught.

The use of these types of data (non-catch or production quantity) was an extension of existing fishing down models. The data were included here to test its ability to maintain the same patterns in MTL observed through contemporary fisheries production statistics and its potential as a further data type for use in fishing down analyses.

Taxonomic trophic level

Trophic levels (TL) of taxonomic finfish groups were taken from FishBase (the global online database listing specific biological and ecological traits of species, Froese and Pauly 2012), which has previously been used to calculate profiles of MTL (e.g. Bhathal and Pauly 2008; Watson *et al.* 2004). For invertebrates, the equivalent database, SeaLifeBase (Palomares and Pauly 2012), was used and where data were not available, the aggregate family TLs used by Watson *et al.* (2005) and available through the Sea Around Us Project (http://www.seaaroundus.org/) were applied.

Significant disaggregation of common groupings was achieved through the state-based catch statistics, which provided specific lists of the species caught. These lists were reconciled across the various data sources, correcting for

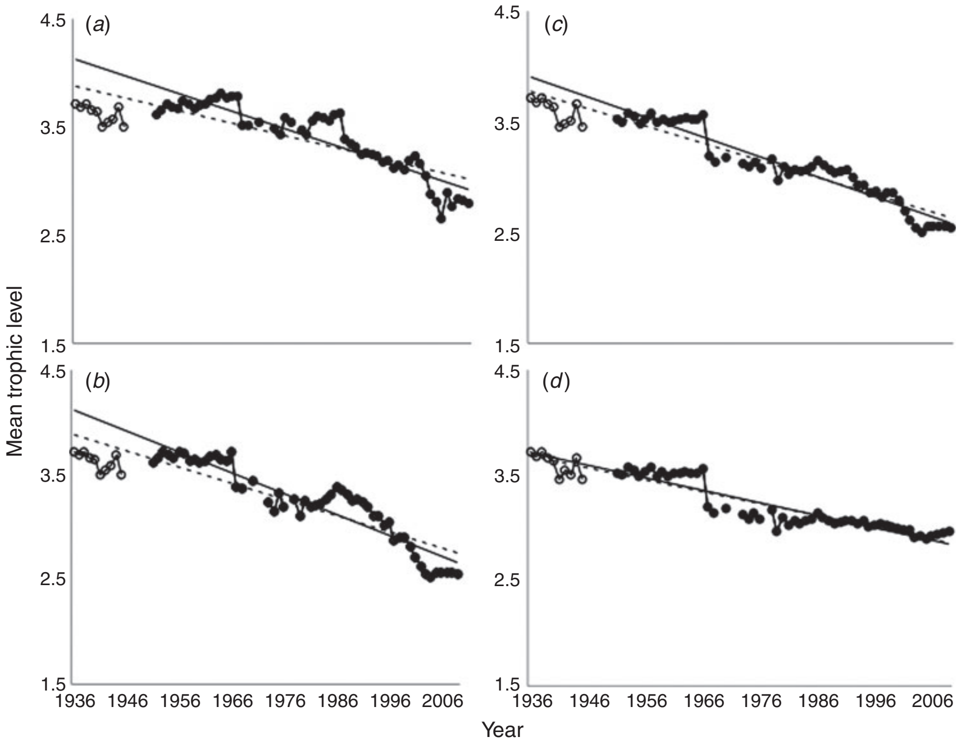

Fig. 2. Trends in mean trophic level (MTL) for (*a*) all species (*b*) all species excluding tuna, (*c*) all species excluding tuna and shark, and (*d*) all species excluding tuna, shark and sardine in South Australian fisheries catch and production statistics, 1951 to 2010 (●) and quantities of fish passing through the Adelaide Fish Market, 1936–46 (○). Linear regression lines extrapolated for comparison.

changes in synonymy and common names, to identify the most appropriate TL across the time series. Several generic groupings remained and where more than one species was included in a grouping, or where a grouping could not confidently be separated to species or genus, the average of all available TLs was used (see Supplementary Material).

Mean trophic level

The MTL of fisheries catch and market data for each year *y* was calculated using the original method of Pauly *et al.* (1998):

$$MTL_y = \sum_i (TL_i \bullet Y_{iy}) / \sum_i Y_{iy}$$

where TL_i is the trophic level of the taxonomic group, determined as described above, and Y_{iy} is the catch of the species or taxonomic group *i* in the year *y* (Pauly and Palomares 2005). MTL quantifies the contribution of a specific taxonomic group to the total catch for a specified time, in this case a fiscal year.

We assessed the model to determine if the voluntary addition and expansion of new low trophic level fisheries can drive declines in MTL of a magnitude similar to the systematic depletion of high trophic level species (Caddy *et al.* 1998; Essington *et al.* 2006) by assessing only species with a TL > 3.25 (Pauly and Watson 2005). MTL was also calculated excluding all invertebrate species, and then invertebrates as well as *Sardinops sagax* (sardine), because the expansion of these fisheries in recent years may represent an alternative scenario, including 'fishing through' food webs rather than 'fishing down' (Branch *et al.* 2010; Essington *et al.* 2006). The sardine also had the potential to mask trends in MTL through its contribution in recent years of over 70% to the State's total wild catch production (Knight and Tsolos 2011) and using the same approach as that of tuna and shark, the sardine was retained and removed from all analyses of MTL to test this influence.

Trends in MTL were quantified through linear regression and an assessment of the goodness of fit through the coefficient of determination, R^2. For each assessment of MTL, a trend line was fitted to fisheries production statistics (1951 to 2010) and a trend line extrapolated for comparison to the second trend line of fisheries statistics and fish market data (1936 to 2010). R^2 was not used as an absolute measure of fit but as a guide to the appropriateness of a linear trend across time. The statistical significance of trends was also analysed (*P*-value).

The contribution of the most important species (catch volume) to total annual catch was further investigated for their individual pattern of change over time. The percentage that a species contributed to overall catch was calculated and displayed as a 2-dimensional area graph, for species with a TL > 3.25 and for species with a TL < 3.25, to illustrate a more detailed profile for understanding the variation that occurred to drive the patterns observed.

Results

MTL all species

The MTL of South Australia's fisheries has declined through time by an average of 0.14 of a trophic level per decade (Fig. 2*a*).

Table 1. Measures of patterns in mean trophic level (MTL) over time, in fisheries data (1951–2010) and with the inclusion of market data (1936–2010), R^2 values of linear trend lines, and the significance of the trend, *P*-value

Analysis	1951–2009			1936–2009		
	Per decade TL change	Linear trend R^2	*P*	Per decade TL change	Linear trend R^2	*P*
All	−0.14	0.8226	0.000	−0.11	0.6896	0.000
All (no tuna)	−0.18	0.8694	0.000	−0.15	0.8010	0.000
All (no tuna or shark)	−0.16	0.9161	0.000	−0.14	0.9027	0.000
All (no tuna, shark or sardine)	−0.10	0.8285	0.000	−0.09	0.8730	0.000
TL > 3.25	−0.01	0.1307	0.007	−0.01	0.0080	0.480
TL > 3.25 (no tuna or shark)	−0.01	0.0173	0.339	−0.04	0.3525	0.000

This rate of decline increased to 0.18 per decade when tuna was removed (Fig. 2*b*) and 0.16 when both tuna and sharks were removed (Fig. 2*c*). All three relations showed a good level of fit to a linear model, with $R^2 = 0.8226$, 0.8694 and 0.9161, respectively (Table 1). When the sardine was removed from the data, a drop in the rate of decline to 0.10 per decade was observed (Fig. 2*d*) ($R^2 = 0.8285$). All trends for MTL of all species were statistically significant ($P < 0.001$) (Table 1).

Tuna was not found to mask trends in the present study but MTL excluding tuna and shark was considered to be more accurate because of inconsistencies in reporting and difficulties in obtaining good estimates from historical fisheries. A levelling out of MTL from ~2002 onwards was seen, which may have reflected no new development in low trophic level fisheries since that time, and drops in trophic level were observed for the years around 1966, 1985 and 2000 (Fig. 2*a–d*), a reflection of the recalibration of the species reported against. Each recalibration generally expanded the list of species being reported, leading to greater resolution in taxonomy and catch quantities.

MTL in trophic levels > 3.25

When calculations were restricted to species with a TL > 3.25, a stable and comparably unchanged trend was observed (Fig. 3*a–b*). MTL from 1936 to 2010 decreased 0.01 per decade on average for all species or decreased 0.04 when tuna and shark were removed. A negligible portion of this pattern fitted the linear trend, $R^2 = 0.0080$ and 0.3525, respectively, and the trend only became significant when tuna and shark were excluded, $P < 0.001$ versus $P = 0.480$ for all species (Table 1).

MTL excluding invertebrate species

Removing invertebrate species, and then invertebrates as well as sardines (tuna and shark removed for both calculations), indicated that a small portion of the overall decline reflected the addition and expansion of fisheries for these species but that the greatest portion of change in MTL was still driven by the inclusion of quantities of sardine (Fig. 4). When invertebrate fisheries were removed, the rate of decline in trophic level was 0.18 per decade, with a significant trend ($R^2 = 0.7043$, $P < 0.001$). With the removal of both invertebrates and sardines, the rate of decline dropped to 0.05 per decade, but the significance of the trend remained ($R^2 = 0.6259$ and $P < 0.001$). The influence of catches in sardines was particularly noticeable from the early 1990s onwards when there was a divergence in the

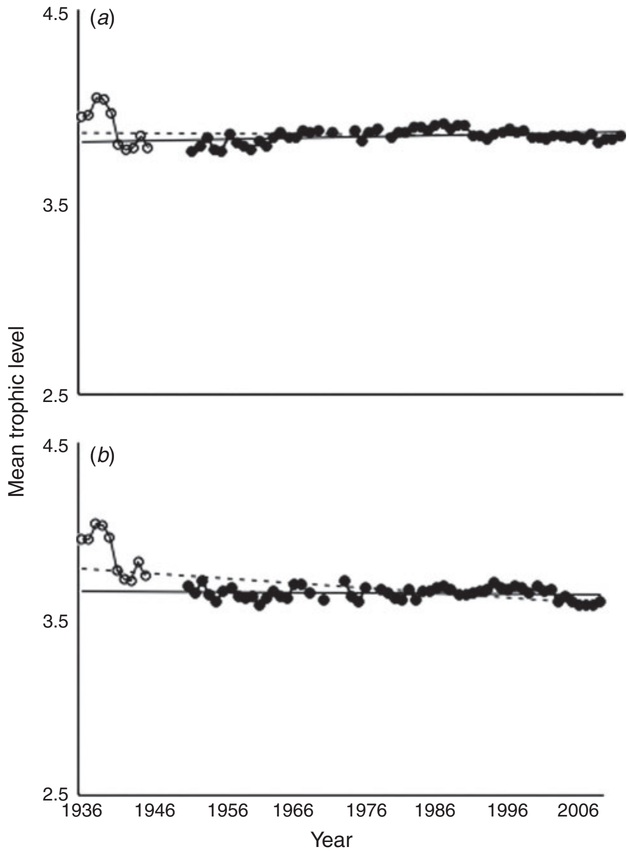

Fig. 3. Trends in mean trophic level (MTL) for (*a*) all species with trophic level > 3.25 and (*b*) species > 3.25, excluding tuna and shark, in South Australian fisheries catch and production statistics, 1951 to 2010 (•) and quantities of fish passing through the Adelaide Fish Market, 1936–46 (○). Linear regression lines extrapolated for comparison.

patterns of MTL excluding invertebrates, either including or excluding sardine (Fig. 4).

Proportions of significant species

Key species contributing to total annual catch were illustrated through their percentage contribution across time. In species with a TL > 3.25, the contribution of several species, including *Jasus edwardsii* (southern rock lobster), *Pseudocaranx georgianus* and *Pseudocaranx wrighti* (trevally), *Chrysophrys*

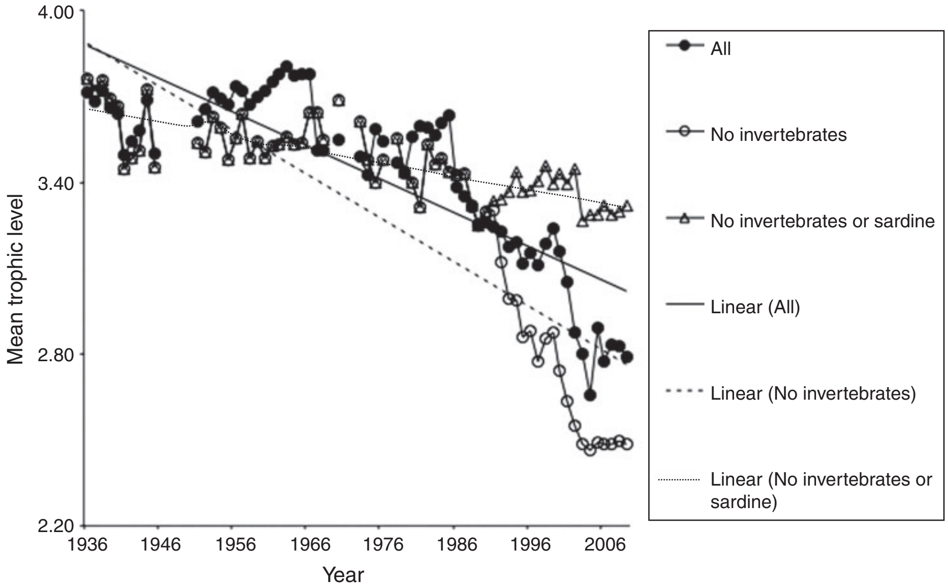

Fig. 4. Trends in mean trophic level (MTL) for all species (●), all species except invertebrates (○), and all species except invertebrates and excluding catches of sardine (△).

auratus (snapper), and *Sillaginodes punctatus* (King George whiting), was relatively stable through time (Fig. 5*a*). Market data (1936 to 1946) was more evenly apportioned across the suite of species than the catch and production data, which might have resulted from market preferences for species.

Species with a TL < 3.25 displayed a pattern of high variation and transitions between species contributing the greatest percentage to catch (Fig. 5*b*). The transitions may have reflected inconsistencies in reporting, but the recent addition of new, low trophic level species such as *Haliotis* spp. (Abalone) and *Penaeus (Melicertus) latisulcatus* (Western King prawn) to total catch, and the rapid expansion of *Sardinops sagax* (sardine) quantities, was noticeable.

Use of fish market quantities

Analyses including all species indicated the inclusion of fish market data to extend the time series maintained much the same pattern of MTL as those observed in fisheries production statistics (Fig. 2*a–d*, and Fig. 3*a–b*). In all variations of MTL, the time series of 1936 to 2010 reflected the pattern observed when only the contemporary fisheries catch statistics from 1951 to 2010 were calculated and these trends remained statistically significant (Table 1).

Discussion

Patterns of change in MTL in South Australian fisheries identify a declining trend at a 'per decade' rate greater than the global average attributed through early investigations (Pauly *et al.* 1998). This pattern differs from previous descriptions of change for the region, which were unclear, with increases in MTL observed in some periods (Pauly *et al.* 1998; Watson *et al.* 2004). Our estimated rate of decline in fisheries along the southern Australian coast is 0.16 of a trophic level per decade and this trend appears robust due to increased resolution of the data used both geographically and taxonomically. What is much less clear is what this change infers about ecosystem structure, specifically the abundance of high trophic level species.

By refining the suite of species used for the calculation of MTL, we showed that the observed decline is largely attributable to the establishment of a fishery for the sardine in 1991 and its rapid growth in the late 1990s and early 2000s. The influence of key species on trends in MTL is well known, in particular large catches of tuna have previously been shown to mask underlying patterns of MTL because they are a high trophic level and caught in large quantities (Bhathal and Pauly 2008; Pauly and Palomares 2005). Similar impacts on patterns have also been observed by lower trophic level species, such as clupeoids (e.g. India, Bhathal and Pauly 2008; and the Mediterranean, Pinnegar *et al.* 2003) and the influence of changes in high production quantity fisheries was also observed in the original pattern of fishing down through fluctuations in extremely large catches of Peruvian anchoveta (Pauly *et al.* 1998).

Tuna was not found to mask trends in the present study but MTL excluding tuna was considered to be more accurate because of inconsistencies in reporting and difficulties with obtaining good estimates from historical fisheries. Identifying data that would enable the inclusion of tuna and shark, which was removed for the same reason, would improve the accuracy of this profile, particularly for MTL for species with TL > 3.25.

Sardine currently constitutes over 70% of the South Australian state total catch (Knight and Tsolos 2011) and, although the fishery has grown rapidly since it began in the 1990s, the spawning biomass remains above the target reference point (Goldsworthy *et al.* 2013). This quantity is greater than the global average for lower trophic level forage fish of 30% (Alder *et al.* 2008; Smith *et al.* 2011) and the large proportion of this catch to overall production may not be reflected in the broader-scale statistics that have previously

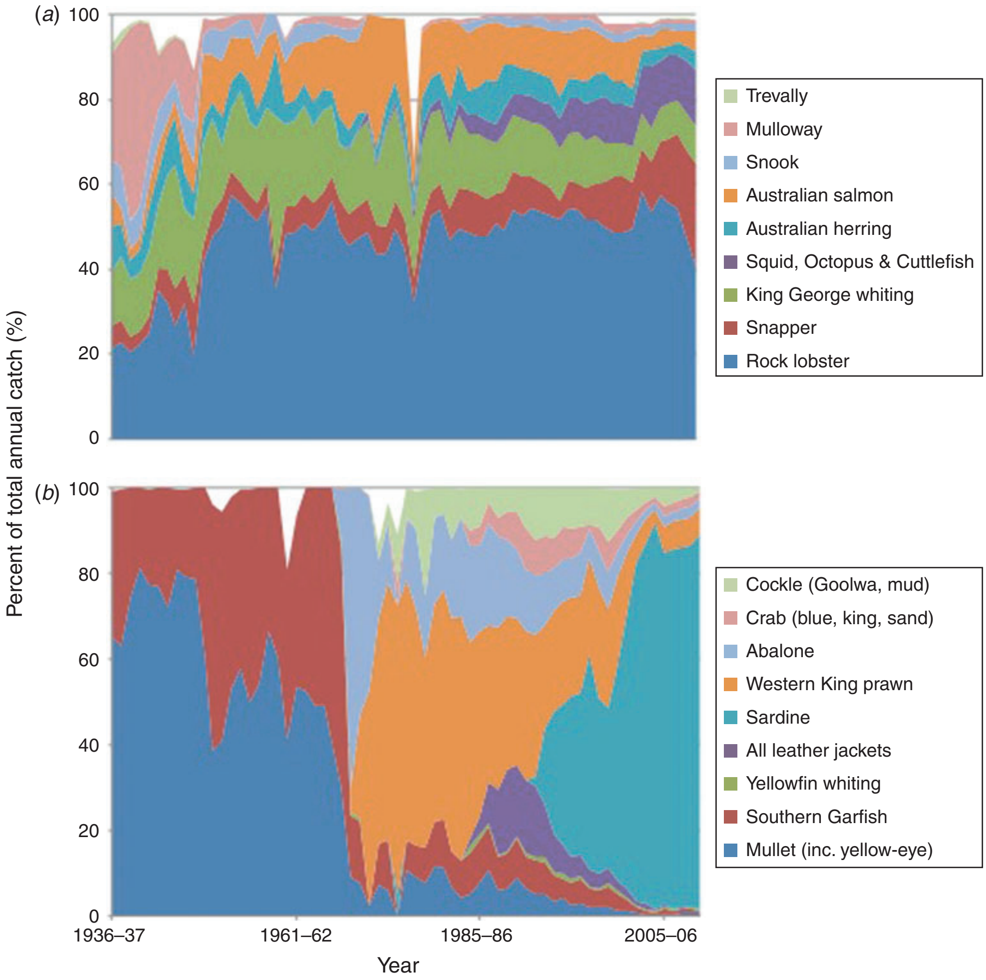

Fig. 5. Species contributions (%) to total annual fisheries catch and production (1951 to 2010) and quantities of fish passing through the Adelaide Fish Market, (1936–46), for main species (*a*) with a TL > 3.25, and (*b*) with a TL < 3.25.

been used to model fishing down in the southern Australian LMEs (Watson *et al.* 2004).

As is the case with sardine, there has been an emergence and augmentation of new fisheries in South Australia that has also contributed to a decline in MTL. For example, the growth of an extensive fishery for *Penaeus (Melicertus) latisulcatus* (Western King prawn), crab fisheries for *Portunus pelagicus* (blue crab), *Pseudocarcinus gigas* (king crab) and *Ovalipes australiensis* (sand crab), and the catch of cockles *Donax deltoides* (the Goolwa cockle) and *Katelysia* spp. (mud cockle), has contributed to the reduction in MTL. This trend in expanding low trophic level fisheries, especially for invertebrate species, is consistent with a worldwide growth in these fisheries (Alder *et al.* 2008; Anderson *et al.* 2011). There is no evidence to suggest that the growth of these new South Australian fisheries reflects an overall decline in the abundance of high trophic level species.

The trend in higher trophic level species remained stable across time. Unlike Bhathal and Pauly (2008), who found the process of fishing down to only be identifiable when lower trophic level species were excluded, and Pauly and Watson (2005), who used TL > 3.25 to indicate greater rates of decline in higher order species than when considering all species, our results do not show a prevailing pattern of fishing down of higher trophic levels. The influence of the expansion in the fisheries for low trophic level species was recognised by investigating MTL only for species with a TL > 3.25, which remains constant, while MTL for all species declines. We suggest that the MTL of fisheries catches does not always reflect declines in high trophic levels within the ecosystem, and that more explicit calculations testing the influence of key driving species and the addition of new fisheries are required to understand the causes of changes in MTL.

Broader consideration of the drivers of change also provide necessary context to patterns observed in MTL. In our example, the expansion of the sardine fishery has been voluntary and in part based on an increase in demand for this species as fodder for the aquaculture of *Thunnus maccoyii* (southern bluefin tuna) (Shanks 2005). The development of tuna aquaculture is driven by export markets in Asia, specifically Japan, and catches of sardine have been influenced by multiple external drivers rather than variation in the underlying ecosystem (Goldsworthy *et al.* 2013). Changes in the catch quantities of the high value marine species rock lobster and abalone, for which the majority of product is exported to Hong Kong and China, can also be influenced by market access and demand. Western King prawn was previously a key export fishery but has most recently been sold increasingly within domestic markets. Although management controls regulate catch quantities, anticipated growth in the export of Australian seafood products to Asia may continue to drive changes in existing fisheries and the addition and expansion of new fisheries. Evaluation of broader and non-ecosystem-based drivers of change might be essential for future models of MTL.

The geographical scale of 'state'

Averaging occurs when catch data are pooled across large spatial units, such that patterns may be masked or emerge as a function of a few highly variable or abundant species. In the present study, we reduced this potential bias by focusing the geographic and taxonomic scales at units that were more representative of the local fisheries and fish stocks, these being the state of South Australia and the classification of species. A consequence of focusing investigations at smaller spatial scales may be the increased influence of catches in dominant species, as well the impact of management and regulatory controls.

The influence of changes in large fisheries was observed in the original pattern of MTL when extremely large catches of Peruvian anchoveta occurred (Pauly *et al.* 1998) and this effect is likely exacerbated at small spatial scales. Management controls aim to regulate species-specific catches, which contributes to the absence of reductions in MTL of high trophic level species and a recent levelling out of MTL, particularly because there has been no contemporary development of new fisheries. The addition of small bodied and invertebrate species are not reflected well in global, industrial fisheries data (Pinsky *et al.* 2011) and using small scale, regional calculations of MTL may be more appropriate for some areas rather than relying on global estimates.

State-based data also reflects periods of recalibration. When the list of species reported against changes, the modification leads to greater resolution, specificity or accuracy in the taxonomic groups reported against and the MTL may noticeably differ from the previous year. We identified three observable recalibrations impacting upon periods around 1966, 1985 and 2000, but while these drops were noticeable, the long-term pattern of decline remained because of the length of the dataset and the ongoing development of new fisheries for low trophic level species. This suggests that taxonomy can be retrospectively refined in the existing or historical data with minimal impact on the long-term trend of MTL (Jacquet *et al.* 2010).

The use of alternative data

Future investigations of the MTL of catches may be assisted by broadening the types of data used in the model, particularly where there is a strong influence from large catches of few new species, short timelines for conventional fisheries data or long-term changes to fisheries through alternative management arrangements. A novel extension of previous work was the successful inclusion of an alternative data source, namely quantities of fish passing through a commercial fish market, which increased the timeline of observation back to 1936. In analyses of MTL for all species, market data were evenly distributed across a trend comparable to that of the fisheries statistics. We suggest that this approach needs further assessment and that, at least initially, alternative data should run alongside contemporary and already validated sources (fisheries statistics). However, this method addresses the need for the inclusion and acceptance of a broader range of information to reconstruct fisheries catch identified elsewhere (e.g. Hardt 2009; Jackson *et al.* 2001; Jacquet *et al.* 2010).

We redress a knowledge gap in southern Australian fisheries by identifying a declining trend in the MTL of fisheries at a rate of 0.16 of a trophic level per decade. However, this reduction in MTL does not appear to be driven by declines in the abundance of high trophic level species, which have sustained important fisheries throughout the study period, but by the development of new fisheries for low trophic level species that are also providing sustainable catches, in particular sardines. Over-aggregation of data, which has obscured patterns of fishing down in other areas, is considered to be the reason that this reduction in MTL has been unobserved previously and the spatial scale used should be taken into account when interpreting calculations. We also show that historical market information, which is not always treated as a useful or valid source of data, may be important in continuing to reconstruct changes in fisheries, particularly where the data may be able to extend the timeline before 1950; the current starting point for most investigations. Our results not only show a broadening of the catch of lower trophic levels, but also reveal care is necessary when interpreting the MTL of catches because reductions do not necessarily reflect change in the abundance of high trophic level species by fishing pressure.

Acknowledgements

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Supplementary Material: *Marine and Freshwater Research*

Supplementary Material

Historical changes in mean trophic level of southern Australian fisheries

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Table S1. Taxonomic groups used for calculating mean trophic level, including historical common names, misapplied or no longer used species synonyms, trophic levels (TL) and standard error of the TL (s.e.), and explanations of any assumptions or derivations for the TLs used

Functional group or species	Common name	Previously used misapplied names	Trophic level (TL)	Assumptions and comments
Haliotis rubra and *Haliotis laevigata*	Abalone		2.0	TL for *Haliotis rubra* available through Sea Around Us Project.
Thunnus alalunga	Albacore tuna		4.31 ± 0.73	
Arripis georgianus	Australian herring	Tommy Rough, Ruff	4.31 ± 0.76	
Arripis truttacea	Australian salmon	Salmon, *Arripis truttaceus*, *Arripis trutta*	4.20 ± 0.70	
Centroberyx affinis	Bight redfish	Red snapper	3.81 ± 0.59	
Acanthopagrus butcheri	Black bream		3.47 ± 0.53	
Portunus armatus	Blue Crab	*Portunus pelagicus*	2.60	TL for Brachyura available through Sea Around Us Project.
Scomber australasicus	Blue mackerel		4.2 ± 0.74	

Nemadactylus douglasii	Blue morwong		3.46 ± 0.49	
Multiple unknown Nemipteridae spp.	Bream, including tarwhine		3.72	TL for Nemipteridae available through Sea Around Us Project.
Katelysia spp.	Cockles (mud)		2.0	Basic TL for Molluscs available through Sea Around Us Project.
Pseudaphritis urvillii	Congolli		3.27 ± 0.47	
Multiple unknown Brachyura spp.	Crabs		2.60	TL for Brachyura available through Sea Around Us Project.
Sepia apama	Cuttlefish		3.60	TL for Sepiidae available through Sea Around Us Project.
Multiple *Platycephalus*, *Leviprora* and *Thysanophrys* spp.	Flathead		3.95 ± 0.64	TL of known species of Platycephalidae in South Australia averaged (*n* = 7 spp.).
Multiple *Lophonectes*, *Ammotretis* and *Rhombosolea* spp.	Flounder		3.13 ± 0.24	TL of known species of Plueronectiformes in South Australia averaged (*n* = 5 spp.).
Hyporhamphus melanochir	Garfish	*Hyporhamphus intermedius*	2.65 ± 0.27	
Trachurus declivis	Jack mackerel		3.93 ± 0.61	
Seriola lalandi	Kingfish	Yellowtail, *Seriola grandis*	4.07 ± 0.34	
Pseudocarcinus gigas	King crab		3.0	Basic TL for Crustacea, available through Sea Around Us Project.
Sillaginodes punctatus	King George whiting	Whiting, Spotted whiting	3.28 ± 0.42	Although two species *Sillaginodes punctatus* (King George whiting) (TL 3.28 s.e. 0.42) and *S. bassensis* (silver whiting) (TL 3.31 s.e. 0.47) are referred to in papers on 1936–46 data the greatest portion of catch is known to be King George whiting. For consistency TL for King George whiting used for all 'whiting' references.
Multiple Monacanthidae spp. (coastal and ocean)	Leatherjacket		2.96 ± 0.37	Generic 'leatherjackets' of the Monacanthidae family are listed in recent Production Statistics, TL of known coastal and ocean Monacanthidae in South Australia is averaged (*n* = 5 spp.).
Scomber australasicus and *Trachurus declivis*	Mackerel		4.07 ± 0.68	A species for 'mackerel' is not listed in 1936–46 data and could be either *Scomber australasicus* (blue mackerel) (TL 4.2 s.e. 0.74) or *Trachurus declivis* (jack mackerel) (TL 3.93

				s.e. 0.61). Although *S. australasicus* is reported in small quantities in recent Production Statistics the TL of both possible species is averaged for all references to 'mackerel' for consistency.
Dactylophora nigricans and *Nemadactylus douglasii*	Morwong		3.18 ± 0.44	'Morwong' is listed in recent Production Statistics with two species names provided *Dactylophora nigricans* (dusky morwong) (TL 2.89 s.e. 0.38) and *Nemadactylus douglasii* (blue morwong) (TL 3.46 s.e. 0.49). There is no determination of which species contributes what component of a catch and the TL of both species is averaged.
Aldrichetta forsteri, *Liza argentea*, *Upeneichthys vlamingii* and *Mugil cephalus*	Mullet	*Upeneichthys porosus* and *Upeneichthys lineatus*	2.75 ± 0.33	Three species of mullet are listed in 1936–46 data and 'mullet' may also refer to *Aldrichetta forsteri* (yellow-eye mullet), this species has therefore been included, TL of all four species averaged for historical references to 'mullet'.
Argyrosomus japonicus	Mulloway	Butterfish, *Sciaena antarctica*	4.48 ± 0.72	
	Mussels		2.0	Basic TL for Molluscs available through Sea Around Us Project.
Octopus spp.	Octopus		3.58	TL for Octopoda available through Sea Around Us Project.
Multiple Labridae spp.	Parrotfish		3.46 ± 0.50	Generic 'parrotfish' of the Labridae family are listed in the recent Production Statistics. The TL of known coastal and ocean Labridae spp. in South Australia is averaged (*N* = 10 spp.)
Donax deltoides	Pipi		2.0	Basic TL for Molluscs available through Sea Around Us Project.
Multiple unknown Rajiforme spp.	Rays & skates		3.61	TL for Rajiformes available through Sea Around Us Project.
Pinna bicolor	Razor fish		2.0	Basic TL for Molluscs available through Sea Around Us Project.
Upeneichthys vlamingii	Red mullet		3.46 ± 0.54	
Jasus edwardsii	Rock lobster	Crayfish, *Jasus lalandii*	3.50	TL for *Jasus novaehollandiae* only available through Sea Around Us Project, TL of *J. novaehollandiae* applied as surrogate TL for *J. edwardsii.*
Ovalipes australiensis	Sand crabs		2.60	TL for Brachyura available through Sea Around Us Project.
Sardinops sagax	Sardine	Pilchard, *Sardinia*	2.43 ± 0.12	

		neopilchards		
Pectinidae spp.	Scallops		2.0	TL for Pectinidae spp. available through Sea Around Us Project.
Multiple species	Shark		4.31 ± 0.53	Species of shark are not listed in 1936–46 data. ‘Sweet william’ (gummy shark) and ‘shark’ are reported against, but never in the same year. It is therefore assumed that in the years reporting under ‘shark’ a majority of the catch was in fact sweet william, although it is likely that large quantities of other species were also marketed. For consistency across time, without knowing all species caught, the TL for sweet william (TL 4.31 s.e. 0.53) is applied to all references of ‘shark’. This has negligible impact on overall TL as 4.31 s.e. 0.53 is a relative median for other shark species, e.g. *Carcharhinus* spp. (bronze whaler) (TL 4.49 s.e. 0.76) and *Galeorhinus galeus* school shark (TL 4.21 s.e. 0.65).
Katsuwonus pelamis	Skipjack Tuna		3.75 ± 0.61	
Chrysophrys auratus	Snapper	*Pagrus auratus*	3.32 ± 0.47	
Sphyraena novaehollandiae	Snook		4.50 ± 0.80	
Thunnus maccoyii	Southern bluefin tuna		3.93 ± 0.53	Although three species of tuna *Thunnus maccoyii* (Southern Bluefin Tuna) (TL 3.93 s.e. 0.53), *Thunnus alalunga* (Albacore) (TL 4.31 s.e. 0.73), and *Katsuwonus pelamis* (Skipjack tuna) (TL 3.75 s.e. 0.61) are referred to in papers on 1936–46 data the statistics more often list ‘bluefin’ or ‘southern bluefin’ quantities. For consistency TL for southern bluefin tuna used for all ‘tuna’ references.
Sepioteuthis australis	Southern calamary	Squid	4.13	TL for Teuthida available through Sea Around Us Project.
Octopus spp. and *Sepia apama*	Squid, octopus & cuttlefish		3.77	Aggregate of three TLs.
Pelates octolineatus	Striped perch		2.59 ± 0.14	
Multiple *Scorpis* spp.	Sweep		3.32 ± 0.41	*Scorpis georgianus* is listed in 1936–38 data; however, generic sweep of the Scorpididae family are listed in recent Production Statistics. For consistency TL of known *Scorpis* spp. in South Australia is averaged (n = 3 spp.).
Mustelus antarcticus	Sweet William		4.31 ± 0.53	Gummy shark
Pseudocaranx georgianus	Trevally		3.64 ± 0.58	Trevally is the common name for *Pseudocaranx georgianus*

and *Pseudocaranx wrighti*				(silver, or white trevally) (TL 3.92 s.e. 0.68) and *Pseudocaranx wrighti* (skipjack trevally) (TL 3.35 s.e. 0.48). There is no determination of which species contributes what component of catch, TL of both species is averaged.
Achoerodus gouldii	Western blue groper	Groper, Blue groper	3.78 ± 0.59	
Penaeus (Melicertus) latisulcatus	Western king prawn	Prawn	2.70	TL for *Penaeus* spp. available through Sea Around Us Project.
Aldrichetta forsteri	Yellow-eye mullet		2.51 ± 0.26	
Sillago schomburgkii	Yellow fin whiting	Western sand whiting	3.21 ± 0.38	

Chapter 3: 'Neo-Europe' and its ecological consequences: the example of systematic degradation in Australia's inland fisheries

3.1 Preface

Societal expectations can underpin the nature and scale of human activities and, as a result, the influence they have on the environment. The colonisation of new lands by European settlers established behavioural patterns that provide an explanation for change in ecosystems, such as the intentional introduction of plants and animals that are now widespread invasive species. In this chapter historical fish market data are used to illustrate that inland fisheries species were traditionally favoured by European settlers. Inland species were highly popular and large quantities were supplied to market, however, their popularity contributed to their overexploitation and eventual deterioration; a pattern that mirrors a demand driven transition from inland to marine-based fisheries in Europe Consequently, the chapter proposes the systematic overexploitation of inland fisheries species in the 'neo-Europes' was, in part, predicated on the societal expectations of European settlers. This chapter has been submitted to *Biology Letters* as an opinion piece, based on invitation, with the co-authors Bronwyn M. Gillanders and Sean D. Connell.

3.2 Statement of authorship

Title of Paper	'Neo-Europe' and its ecological consequence: the example of systematic degradation in Australia's inland fisheries		
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Principal Author

Name of Principal Author (Candidate)	Heidi K. Alleway		
Contribution to the Paper	Conceptualised and designed the research and model used, collated and analysed the data, interpreted the results and wrote and edited the manuscript.		
Overall percentage (%)	80%		
Signature		Date	24/07/2015

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

iv. the candidate's stated contribution to the publication is accurate (as detailed above);

v. permission is granted for the candidate in include the publication in the thesis; and

vi. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Bronwyn M. Gillanders		
Contribution to the Paper	Assisted with the interpretation of the model and results, and editing the manuscript.		
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Name of Co-Author	Sean D. Connell		
Contribution to the Paper	Assisted with the interpretation of the model and results, and editing the manuscript.		
Signature		Date	15/07/2015

‘Neo-Europe’ and its ecological consequences: the example of systematic degradation in Australia’s inland fisheries

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3.3 Abstract

The antiquity of human impact on ecosystems is increasingly understood, though the arrival of settlers to new lands remains a defining period. Colonisation of the ‘neo-Europes’, a reference from the discipline of history, precipitated changes in aquatic ecosystems through modification of waterways and introductions of non-native species. We considered historical fisheries records and fish market data from South Australia (1900-1946) against contemporary production statistics (1987-2011) and described patterns of change in the species fished over time. Native inland species historically contributed large quantities to market but have deteriorated such that fishing is now limited and conservation regulations exist. This pattern mirrors the demand-driven transition from freshwater to marine fisheries in Europe, hence, we propose this pattern was predicated on societal expectations and that European settlement led to systematic overexploitation and degradation of native inland fisheries species in Australia, reflecting a further consequence of neo-European colonisation to ecology. Accurate interpretation of ecological change, its drivers and implications can support appropriate management intervention. Models from alternative disciplines, such as neo-Europe, can enable these descriptions at regional and global scales.

3.4 Introduction

Human domination of ecosystems after the arrival of people to new lands often set the foundation for the ecosystems we study today (Erlandson and Rick, 2010). Change induced by human activity has been pervasive, for example, the effects of overfishing have been widespread and protracted (Jackson et al., 2001). Between 1820 and 1930, more than 50 million European people migrated to distant colonies – the United States, Canada, Australia, New Zealand, Argentina, Uruguay – which have been called the 'neo-Europes' (Crosby, 1986). When settlers arrived they initiated unprecedented changes in ecosystems, including the intentional introduction of exotic species (Piper and Sandlos, 2007, Lightfoot et al., 2013, Crawford and Muir, 2008) to "renovate the biota" (Osborne, 2001). The behaviours of settlers have been shown to have been vested in their ability to acclimatise to new surroundings (Piper and Sandlos, 2007, Crosby, 1986). For example, formal acclimatisation societies were established to contribute 'colonial science' (Osborne, 2001) toward the successful establishment of plants and animals, but these societies introduced exotic diseases and species (Moorhouse, 1938).

Where ecosystems have been irreparably altered 'Anthropocene Baselines' may provide a more representative basis for management (Keller Kopf et al., 2015). Neo-Europe is a model for widespread European colonisation of geographically distinct areas across the world, the behaviours that settlers displayed, and the ecological changes they initiated (Crosby, 1986). We considered changes to fisheries in South Australia, from 1900 to 2011, and describe the influence of societal expectations on native inland fisheries species, which mirrored those that occurred in Europe. The reference neo-Europe (Crosby, 1986), well known in social sciences is little known in ecological sciences, can assist description of why ecosystems look and function the way they do today. Its wider use in ecology could provide a more rigorous basis for evaluating change associated with European agency (Lightfoot et al., 2013), reconciliation of the ongoing disparity between history and ecology (Szabó and Hédl, 2011), and identification of appropriate baselines and management in human-dominated ecosystems (Keller Kopf et al., 2015).

3.5 South Australian fisheries, 1900-2011

In the early 1900s, native inland fisheries species were highly popular and proportionately larger quantities from distant inland ports supplied the Adelaide Fish Market. Adelaide, the capital of South Australia, a coastal settlement, had ready access to marine resources and a range of species (table 1). But archival fisheries records (annual quantities of fish sold at the Adelaide Fish Market held within the State Records of South Australia, State Library and Adelaide City Council) illustrate that proportionately larger quantities of inland species contributed to market sales. Although total quantities of inland species have increased over time (figure 1*a*,*b*) the contribution of inland species relative to all fisheries species has decreased (figure 1*c*,*d*). Between 1900-1946 the contribution of inland fisheries to market sales fluctuated from 23-57 %, but quantities, of the same species, declined from 17 % in 1992 to 2 % from 2004 onwards.

Table 1. Number of marine and inland species sold at the Adelaide Fish Market, 1900-1946, and statewide production, 2000-2011, and the average ratio of marine to inland species.

Time Series	Min N	Max N	Min N	Max N	Average N Marine spp : N Inland spp
	Marine Species		Inland Species		
1900 - 1946	13	21	4	5	3.25 : 1
2000 - 2011	33	38	6	8	5.50 : 1

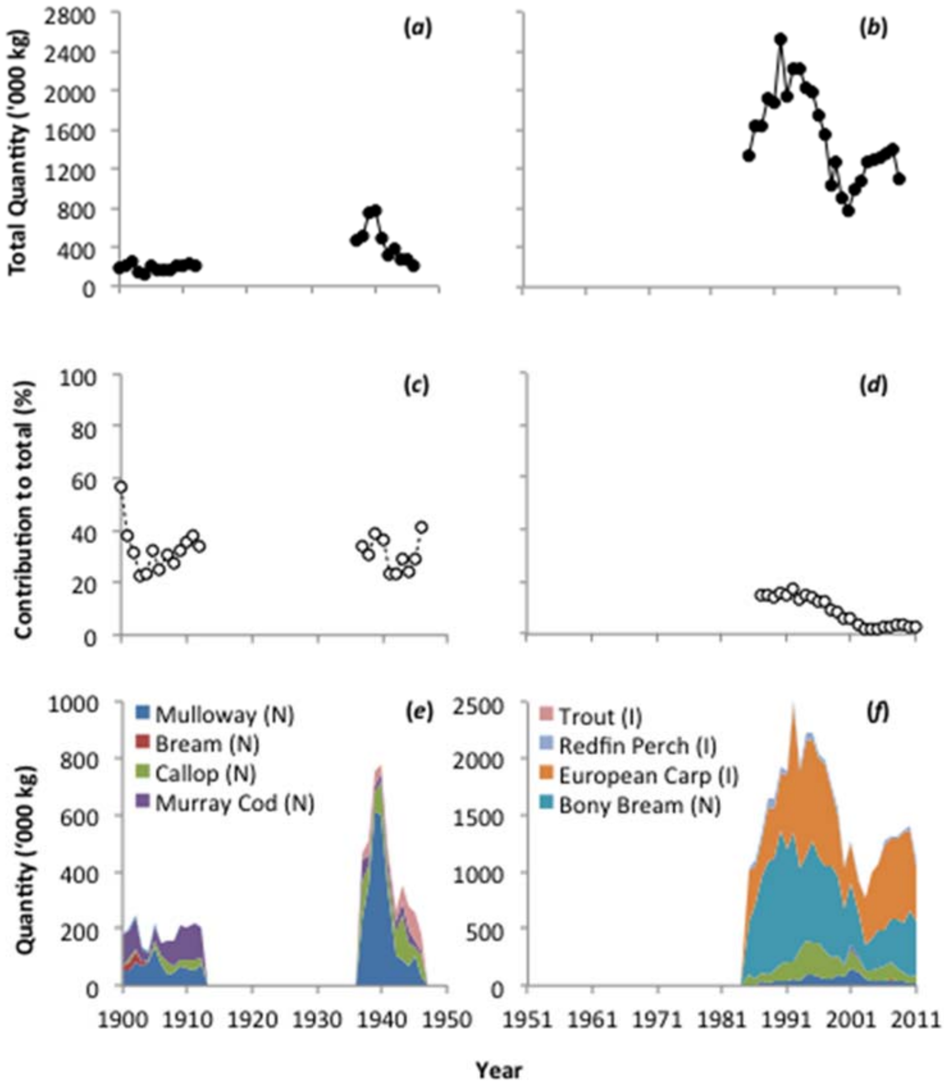

Figure 1. Quantities from inland fisheries (a) sold at the Adelaide Fish Market, 1900-1946 and (b) statewide production, 1987-2011; the contribution of fisheries (c) to total sales and (d) total production; and individual quantities of native (N) and introduced species (I) to (e) market sales, and (f) fisheries production.

Historical governmental reports and photographs attest to the popularity of native inland fisheries species, and that this popularity influenced their overexploitation and degradation. Murray cod (*Maccullochella peelii peelii*) historically supplied large quantities to market (figure 1*e*, figure 2*a)*, but in 1996 the species was listed as critically endangered on the 'Red List' of Threatened Species and has recently supported a spatially and temporally limited catch and release recreational fishery only (table 2). Catches of 'butterfish' (mulloway, *Argyrosomus japonicus*), bolstered sales after cod declined, but deteriorated in the mid-1900s (figure 1*e*, figure 2*b*) through overfishing and weir construction in 1940 along the states principal waterway, the River Murray, which reduced flow to estuarine areas (table 2) (Ferguson et al., 2013). Golden perch (*Macquaria ambigua*) also supplemented sales from 1937 onwards, but has recently supported limited commercial production (figure 1*e*, figure 2*c*,*d*, table 2). Bony bream (*Nematalosa erebi*) has most recently contributed large catch quantities to production from native species (figure 1*f*), possibly because it has not declined since flow regulation (Ferguson et al., 2013), but historically this species was unpopular and not sold at market. Since 2003, commercial fishing of native species has been prohibited in the South Australian section of the River Murray and catches have been dominated by introduced species, particularly European carp (*Cyrpinus carpio*) (figure 1*f*).

Increased production of sardine (*Sardinops sagax*) since 1991 has contributed to a recent pattern of decreasing inland fisheries production, however, declines in native species occurred prior and their current degraded status indicates deterioration has been absolute, not due to changes in reporting (table 2). Implementation of regulations can indicate when governments first became concerned about overexploitation and declining populations (Kirby, 2004). Legislation was introduced to regulate inland fishing by the early 1900s. It did not, however, preclude fishing and it is possible the decline of highly valued species, such as cod, was exacerbated by opportunistic exploitation because fishing for co-occurring lower value species continued (Branch et al., 2013).

Figure 2. Historical photographs of inland fishing in South Australia: (a) two men holding a large Murray cod ca. 1925 (State Library of South Australia (SLSA), PRG 1258/2/2508); (b) mulloway caught at Milang, 1938 (SLSA, B 19128/4); (c) catch at the Goolwa Wharf 1939 (SLSA, B 44307); (d) and a large golden perch 1931 (SLSA, PRG 1258/1/4007).

Table 2. Largest per annum quantities sold at the Adelaide Fish Market, 1900-1946, or caught statewide, 1987-2011, of native and introduced inland species in South Australia, current regulation or management, and historical anecdotes regarding past status.

	Largest quantity (1,000 kg)	Year of largest quantity	Current status (fisheries and conservation)	Example historical qualitative statements regarding species (additional statements in supplementary material)
Native Species				
Acanthopagrus butcheri (bream, black bream)	32.01	1902	Commercial fishing permitted and occurring. Recreational fishing permitted, with size and bag limits.	Inspector Furler reports that bream fishing at Noarlunga in the Onkaparinga River has been exceptionally good, and in one week over 2,000 fish were taken by a few anglers. This stream is at present splendidly stocked above the suspension bridge, where on calm days large shoals can be seen (1914).
Euastacus armatus (Murray crayfish)	0.76	1907	Fully protected species (state legislation), must be returned to the water.	*Lobsters, etc.*—Great falling off from Morgan to the corner this year, although a number were caught higher up the river. Lobsters generally appear in May and go away in August; they are not sent to market; personally prefer them to salt-water lobsters (1903).

Maccullochella peelii peelii (Murray cod)	128.02	1911	Commercial fishing not permitted in SA River Murray; catch and release recreational fishing only; listed as ‘critically endangered’ on IUCN Red List.	Nine years ago men could make a good living with crosslines and springers. “No unusual thing for a man to catch half a ton a week” (Mr. McIntosh’s evidence). … With a cycle of normal river levels and judicious fishing therein, is there any reason why those good times should not come again? Since those prosperous times netting has been introduced, and though doubled during the last few years, a precarious living only can be made. IMPERATIVE RESTRICTIONS. The precautionary measures recommended may trench upon the means of livelihood of a certain number of fishermen : but better inflict this necessary hardship, and save the industry, than allow the present decimation to go on till all those now engaged in the trade (about 500) find their occupation gone (1903).
Tandanus tandanus (catfish)	2.03	1911, 1912	Fully protected species (state legislation), must be returned to the water.	… personally prefer them to salt-water lobsters (Murray crayfish). The same thing applies to catfish and callop, both of which are excellent food, but very little in demand (1903).

Argyrosomus japonicus (butterfish, mulloway)	608.99	1939	Commercial fishing permitted and occurring. Recreational fishing permitted, with size and bag limits.	Butterfish, the most important fish passing through the Adelaide market also reached a production peak not noted for many years, with the result that its price fell to as low as 1 ½d. per lb (1939).
Pseudaphritis urvillii (congolli)	50.44	1942	No management ascribed.	Fortunately, congollis appeared again in the Lakes during the winter and helped the market carry on through this difficult season. These fish have not occurred in big numbers this winter (1943).
Macquaria ambigua (callop, golden perch)	299.00	1994	Commercial fishing not permitted in SA River Murray; commercial fishing occurring in Lakes and Coorong. Recreational fishing occurring, with size and bag limits.	The Adelaide market regularly receives considerable quantities of River Murray fish (cod and callop). When flooding of the river occurs these supplies are often so large as to over-tax the market (1942).
Nematalosa erebi	1,172.00	1990	Commercial fishing	This fish is a member of the herring family, and is known in New

(skipjacks, silver fish, bony bream)			occurring in the Lakes and Coorong.	South Wales as the "Bony Bream", this name having reference (the former portion, at least) to the large number of bones which it contains, and which are the means of preventing many people from using it for edible purposes (1903).
Introduced species				
Oncorhynchus mykiss and *Salmo trutta* (rainbow and brown trout)	92.97	1945	Introduced exotic species (state legislation); recreational fishing occurring; stocking permitted within 5 waterways.	It is exceedingly pleasing to note the success obtained by stocking waters with rainbow trout, which have spread to the various streams; also the enterprise of the Gawler Fish Protection Society and Anglers' Club, who continue to stock their waters with fish supplied from the Ballarat Acclimatization Society (1914).
Perca fluviatilis (redfin perch)	92.00	1989	Introduced noxious species (state legislation), must not be returned to the water. Commercial and recreational fishing	English perch, which are good sporting fish and very palatable, have been liberated in many privately-owned dams in South Australia. Many orders for these fish could not be supplied last year. It is known that so long as such food as shrimps, yabbies, and minnows is present the perch thrive and multiply. Many

			permitted and occurring.	farmers now enjoy not only the relaxation of fishing on their own properties, but also the consuming of palatable fresh fish (1948).
Cyprinus carpio (European carp)	1,154.00	1992	Introduced noxious species (state legislation), must not be returned to the water. Commercial and recreational fishing permitted and occurring.	During recent years immense shoals of carp and goldfish have been reported in the waters of both the lakes and the river. This variety is of no edible value to man, yet it appears to supply the wants of the cod, and also affords pastime to the pelicans and cormorants (1909).

3.6 Connections to Europe; fishing and ecological imperialism

Ecological changes influenced by European societal preferences are a recurring phenomenon around the globe. When settlers arrived in the neo-Europes they precipitated transformations of landscapes altering vegetation histories (Bjorkman and Vellend, 2010) and introducing exotic species (Osborne, 2001). In inland aquatic ecosystems fish, including Salmonids, were introduced and their spread encouraged and facilitated (table 2) (Moorhouse, 1938). Many events reflected ‘seed’ introductions, having the intent of establishing populations in new ecosystems (Crawford and Muir, 2008). Trout were introduced to South Australia around 1900 (Duffield, 1903a) and the Inspector of Fisheries reported in 1909 the occurrence “of immense shoals of carp and goldfish in waters of both the lakes and the river” (Duffield, 1909).

To assist acclimatisation European settlers carried mechanisation to generate food surpluses from agriculture (Crosby, 1986). Tools, which were often destructive, were likewise introduced to South Australia to generate food surpluses from inland fisheries. For example, the most destructive fishing gear to freshwater species, because of its indiscriminate nature, “grab-alls”, were drum nets (Duffield, 1903b, Duffield, 1903a). These nets were introduced in about 1886 by a Norwegian fishermen who used a similar tool on a larger scale sea-fishing in Norway (Dannevig, 1903). The “cross-line”, another device common in Europe, was “probably introduced by the many Europeans who gradually settled along the Murray (River)” (Dannevig, 1903) (supplementary material).

Behaviours associated with ecological imperialism are also prominent in historical records. Fishermen believed native animals were pests and had a negative impact on fish species and supplies. Their treatment of these animals was emblematic of this ethic (Crosby, 1986, Piper and Sandlos, 2007), for example, legislation was introduced in 1903 permitting destruction of fish enemies, including native shags and turtles as neither were considered to “possess any redeeming features” (Duffield, 1903a). A bounty was paid for their heads, and for pelicans, because “beyond the sentiment of their being a fine Australian bird, there appears to be no reason why they should be protected” (Duffield, 1903a).

3.7 Shifting baselines in aquatic ecosystems

South Australian fisheries have experienced a 'transition', from fisheries historically focused on inland species to contemporary industries focused on marine species. Several distinct changes through history have characterised European fisheries, including a demand-driven transition from freshwater to marine species partly because of declines in freshwater populations (Barrett et al., 2011). Inland fisheries in other neo-Europes have also been systematically depleted; Pacific salmon in the United States and Canada have deteriorated dramatically since settlement and inland populations have been disproportionately more impacted than those in coastal areas (Gustafson et al., 2007).

Over one hundred years ago there was concern for shifting baselines and what this meant for expectations of fisheries. During inquiries into Murray cod fisheries in 1900, the Australian fisheries superintendent evaluated the number of years' experience of fishermen against their response to the question was the supply of cod the "same as before" or "falling off". He observed fishers with a greater number of years' experience more often considered stocks to be declining, describing their perspective as "drifting" (Dannevig, 1903), i.e. the shifting baseline syndrome (Pauly, 1995). This shift is reflected in loss of detail in government reporting and erosion of knowledge. Historically, government was mindful of inland fisheries, for example there were inquiries into fisheries circa. 1900 (Dannevig, 1903) and the impact of destructive fishing gears (Duffield, 1903b, Duffield, 1903a), but the detail of information declined between 1938-1959 (supplementary material). Though not all regions have been impacted equally (Piper and Sandlos, 2007), our interpretation is that historical preferences for inland fisheries species and their subsequent declines, were, to a degree, predicated on societal expectations of settlers. Hence, we propose the systematic overexploitation and degradation of native inland fisheries species in Australia reflects the model neo-Europe and is a further consequence of colonisation.

Since human activity, including colonialism, has had impact over long periods of time detailed descriptions of ecosystem change are needed to accurately interpret natural versus human mediated variation (Lightfoot et al., 2013, Jackson et al., 2001). We illustrate how models from the social sciences could assist identification of past baselines, including Anthropocene Baselines (Keller Kopf et al., 2015), and reconciliation of history with ecology (Szabó and Hédl, 2011). Scientists and managers could move beyond specialist methodologies in fields of fisheries and ecological sciences to use such models to quantify patterns of change. The perpetuated poor state of aquatic ecosystems has contributed to a forgotten past prodigiousness (Humphries and Winemiller, 2009). The model neo-Europe especially, could establish and motivate more accurate baselines for management intervention.

3.8 Acknowledgments

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3.9 Supplementary material

'Neo-Europe' and its ecological consequences: the example of systematic degradation in Australia's inland fisheries

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Historical records of South Australian fisheries

Table 1. Historical statements made in relation to the fishing of inland fisheries species in South Australia, their status, management, observations about these species, and the introduction of non-native species.

Topic	Year	Record
State of inland fisheries in South Australia	1903	But this river system (the Murray River) is also possessed of still another source of riches that deserves the full attention of the adjoining States, viz. : the fisheries. Generally speaking, this industry has been left to itself, or the individual states have formulated regulations out of harmony with one another. In all cases little supervision has been provided, and the consequence result has been lawlessness, abuses, and friction.

		No industry can thrive under such conditions, and the fisheries are at present in what may be termed a sickly and straggling state. The climatic conditions are said to have an influence on these matters, but, if, this is only another reason why the most should be made of the existing possibilities, which in themselves are great ; and in regard to this, as to fisheries generally, it is, for obvious reasons, highly desirable and much easier to maintain an abundant supply rather than allow the latter to dwindle away through neglect, and the start the necessarily slow and difficult task of replenishing against heavy odds (Dannevig, 1903).
Importance of Murray cod	1903	Of the fishes on the western river system the Murray cod is by far the most important. … The cod appears to be hardy and prolific ; it occurs in quantities in all the principal tributaries to the extensive system of rivers, as well as the large lakes, etc., … All the year through fishing operations are carried on, and the greater part of the catches despatched from various centres to Adelaide, in South Australia, Melbourne and Ballarat, in Victoria (Dannevig, 1903).
Distribution of fish for market	1903	From Tables II. and III. the following particulars may be observed :- 1. That about two-thirds of the fish caught are sent to Adelaide. 2. That the total quantity sent away from the five railway stations for the three years averages about 422 tons per year. … But these tables are by no means exhaustive. Apart from the three centres stated, it is obvious that a certain—perhaps considerable—quantity of fish sent is direct to other townships along the railway lines in South Australia, Victoria, and even New South Wales, and fish is probably received in Adelaide, Melbourne, and Ballarat, also from other parts of the river than the five

		quoted. And when the local consumption in the small and large townships along the river itself, as well as by the surrounding country population along the hundreds of miles of fish-carrying water is taken into account, it is clear that a considerable quantity of fish has been omitted from the Inspector's tables (Dannevig, 1903).
Perceptions of fishermen in relation to Murray cod supply	1903	In regard to the important question of natural supply of fish on the Murray, opinions differ considerably. ... it will be seen that about one-half of the witnesses think the supply is the same as before, while the other half holds the opposite view. … While numerically the whole body of men are about equally divided, it is seen that those who think the supply is unaltered are the men with less experience, who can only compare a few seasons with one another. Their evidence does not, therefore, carry the same weight as that of the men who have been fishing for a longer period, and are able to judge from longer experience. The remarkable evenness in the gradual change of opinion from the younger to the older precludes the idea of accidental coincidence. It brings out very plainly how matters are drifting in regard to the natural supply of the Murray cod, whatever the cause may be (Dannevig, 1903).
Status and supply of inland fisheries	1903	SUPPLY. In regard to the important question of natural supply of fish on the Murray, opinions differ considerably. From the tabulated evidence it will be seen that about one-half of the witnesses think the supply is the same as before, while the other half holds the opposite view (Dannevig, 1903).
Inland fishery	1903	Residence permits is a matter of considerable interest to the fishermen. They appear in many instances to be

		obliged to camp along the river banks, and come occasionally into conflict with the residents. The men move up and down the river in accordance with seasons and other circumstances, and are unable to live with their families. … The majority now catch what they can in one place and then go onto another (Dannevig, 1903).
Introduction of trout (non-native species)	1903	ACCLIMATISATION. The Sydney Fisheries Department has kindly given us 1,000 rainbow trout fry, which are to be distributed to persons who have agreed to receive same and release them in running streams in various localities throughout the State. Beyond this, I think our energies will be better directed to the conservation of our local varieties than in attempting to acclimatise foreign species. Later, when we know more about the habits of our own fish, we may well seek to acquire an acquaintance with those of other waters (Duffield, 1903a).
Closed season for Murray cod	1903	CLOSE SEASON. The close season on the Murray has now been made uniform in New South Wales, Victoria, and this State, viz., from the 1st September to December 20th of each year. During this period no fishing whatever can be carried on, except with rod and line, or hand line. Crosslines, springers, and all description of nets are absolutely prohibited … (Duffield, 1903a)
Fisheries and conservation management	1903	OLD METHODS SUCCESSFUL. Nine years ago men could make a good living with crosslines and springers. “No unusual thing for a man to catch half a ton a week” (Mr. McIntosh’s evidence). … With a cycle of normal river levels and judicious fishing therein, is there any reason why those good times should

requirements		not come again? Since those prosperous times netting has been introduced, and though doubled during the last few years, a precarious living only can be made. IMPERATIVE RESTRICTIONS. The precautionary measures recommended may trench upon the means of livelihood of a certain number of fishermen : but better inflict this necessary hardship, and save the industry, than allow the present decimation to go on till all those now engaged in the trade (about 500) find their occupation gone (Duffield, 1903a).
Types of gear used	1903	… there is not the slightest doubt that these devices (drum nets) have depleted the river of an enormous quantity of fish. Thousands of small fish, not fit for marketable purposes, taken out of these nets have been thrown on the bank of the river to die. In the interest of all kinds of fish the use of traps of all descriptions should be strictly prohibited (Duffield, 1903b).
Status of Murray cod	1903	The falling off is not all due to the use of improper devices—the prolonged drought and low water claim a share ; but I find that at Tailem Bend, where the objectionable nets are not used, the fish taken during the years 1897-8, 1898-9, and 1899-1900 were respectively 69 tons, 93 tons, and 73 tons ; while at Morgan, during the same periods, 164 tons, 131 tons, and 93 tons respectively were taken, despite the fact that the number of drums was almost doubled. The drought had not then reached an acute stage, and the alarming falling off must be largely attributed to the use of improper devices. Be the cause of decimation what it may, it is imperative that active steps be taken to save our prime fish from annihilation (Duffield, 1903b).
Importance of Murray	1903	Of the fishes in the western river system the Murray cod is by far the most important. … All the year

cod and distribution of fish for market		through fishing operations are carried on, and the greater part of the catches despatched from various centres to Adelaide, in South Australia, Melbourne and Ballarat, in Victoria (Dannevig, 1903).
Little demand for freshwater crayfish and callop (golden perch)	1903	(Evidence submitted by Mr. Samuel MacIntosh, Expert, Village Settlements, also Chief Assistant Inspector of Fisheries) *Lobsters, etc.*—Great falling off from Morgan to the corner this year, although a number were caught higher up the river. Lobsters generally appear in May and go away in August ; they are not sent to market ; personally prefer them to salt-water lobsters. The same thing applies to catfish and callop, both of which are excellent food, but very little in demand (Dannevig, 1903).
Destruction of turtles	1903	(Evidence submitted by Mr. Samuel MacIntosh, Expert, Village Settlements, also Chief Assistant Inspector of Fisheries) An advantage of drum nets is that they destroy enormous quantities of turtles, and if properly set in still waters can be utilised for catching turtles along. Have seen twenty-six turtles taken out of one drum in Benrock Creek, near Overland Corner, about three years ago (Dannevig, 1903).
Number of fishermen	1903	(Evidence submitted by Mr. Samuel MacIntosh, Expert, Village Settlements, also Chief Assistant Inspector of Fisheries) Number of settlers along the river during the last ten years increased very considerably. In 1891 not twenty settlers between Morgan and boundary, and now there are 500 (excluding station hands and Renmark. No caught fish crossed our boundary in 1891, and in that year there were practically no fish caught above Overland Corner (Dannevig, 1903).

Number of fishermen and types of gear used	1909	RIVER MURRAY FISHERIES. The register shows that 246 licensed fishermen and licensed servants are employed on these waters, added to which almost as many amateurs find more or less enjoyment in using the drum-net, crossline, sideline, springs, rod and line, hand line, or mesh net in contributing to the total annual catch, which is estimated to exceed 400 tons per annum. The principal fish in the waters in question are mulloway or butterfish (*Sciaena Antarctica*), known in New South Wales as jewfish, in Queensland as dewfish, and in Victoria as kingfish ; Murray cod (*Oligorus macquarium*), callop, gold or Murray perch, black bream, and mullet (flat-tailed, sand, and jumping). The more unimportant fish include silver bream, tookery or piwhiree, catfish, kongolley, carp (imported), and flounder (Duffield, 1909).
Crabs destructive to fishing gear	1909	The small common crab is a great pest in the lower waters in destroying nets and any meshed fish, wherever the nets are allowed to touch bottom. For some years past the necessity for some system of either checking their increase or, if possible, bringing about their practical extermination, has been looked for by the department. Mr. Dannevig (Federal Director Fisheries), Dr. Ramsay Smith, and others have been approached with a view of finding some effective and economical cure for the evil ; but up to the present no practicable theory has been suggested (Duffield, 1909).
Distribution of fisheries species along the Murray River	1909	From Wellington to Blanchetown, which constitute the permanently navigable portion of the river, cod and callop are the only catch worth recording, as far as market requirements are concerned. … This portion of our inland waters as far up-stream as Blanchetown is the only water in the States where the cod fisheries are

		open throughout the year. … Lakes Barmera (Bonney) and Victoria are kept closed against fishing, their waters being generally acknowledged to be the principal cod-spawning grounds in the Murray watershed. Quantities of Murray lobsters are trapped in baited wire cages on the river above Murray Bridge. This species (*Astacoides serratus*, McCoy) is one of the most delicate-fleshed crustaceans, and is held in high esteem by the majority of those who are acquainted with it (Duffield, 1909).
Carp and goldfish (non-native species) in the Murray River	1909	During recent years immense shoals of carp and goldfish have been reported in the waters of both the lakes and the river. This variety is of no edible value to man, yet it appears to supply the wants of the cod, and also affords pastime to the pelicans and cormorants (Duffield, 1909).
Destruction of shags and turtles	1909	Since the payment of a bonus on shags and turtles, the numbers of these fish enemies have been visibly decreased on the settled portions of the river, and no doubt the recent wonderful accession of codfish—nearly all under three years' growth—can with safety be adduced partly to the protection afforded by observing a close season on the recognised breeding-places and other protecting measures (Duffield, 1909).
Connection to European fisheries	1910	*Maintaining Supplies.*—The department is alert after increasing supplies, and is gathering information respecting the whereabouts of natural breeding grounds, with a view to making them a sanctuary for the rearing of young fish. It is believed that the reservation of these spawning places will replenish the supplies with more certainty and less expense than by artificial hatcheries. Nevertheless, when more is known of the character of our waters as a home for the well known edible fish of the North Seas, it may become

		incumbent upon us to establish a hatchery for the purpose of enriching our waters with the favorite species of fish so appreciated in the United Kingdom. The closing of certain waters for breeding grounds has had the effect of increasing the fish supply on certain parts of the coast and the River Murray (Duffield, 1910).
Impacts of low-flow and status of fisheries along the Murray River	1912	MURRAY RIVER.—The low state of the river was responsible for the falling off in fish supplies from the river districts, and the drying up of the backwaters has had a bad effect on these natural nurseries, millions of small fish were being destroyed by birds. During the early part of the season some large catches of fine cod were made all along the lower river, and reports from Renmark and Loxton show a plentiful supply in the upper portion, in fact, they were so plentiful that people were using them for food for fowls and pigs. With the advent of railway communication to these up-river towns fishermen will be able to send fish to market in one-third of the time now occupied, and if these fish are packed in ice during warm weather they should arrive in Adelaide in first-class condition (Duffield, 1912).
Impacts of low-flow and status of fisheries along the Murray River	1913	The Murray River fisheries showed a slight falling off, owing mainly to the low state of the River. The salt water killed many hundreds of fine cod in the lakes and lower sections of the river. On the other hand the finest cod fish seen for years were caught during May and June, and exhibited in the city shops ; several of these weighed over 100lbs. each. … It is pleasing to note the success obtained in stocking rivers with rainbow trout and English perch, some fine specimens of which have been taken by fishermen in various waters (McIntosh, 1913).

Impacts of low-flow and status of fisheries along the Murray River	1913	The lowness of the Murray has again been responsible for short supplies, but some very large cod from the upper river reached Adelaide in prime condition ; they were possibly the finest fish seen for years. Up river towns reported fair catches, but in the lower waters there was a great scarcity, particularly down stream from Murray Bridge, where the salt water played havoc with cod. Hundreds of fish were to be seen floating on the surface. For some months cod were exceedingly scarce in the lakes, probably due to the influx of salt water, but lately some good catches were obtained in Lake Albert and at Point McLeay. Line fishing at Murray Mouth has not been as successful as in former years, but netting in the Coorong and up stream from Goolwa was satisfactory (McIntosh, 1913).
Introduction and spread of trout (non-native species)	1913	Anglers in streams and rivers had good sport, particularly in the Upper Sturt, where some nice rainbow trout were taken. Some years ago these fish were liberated in a dam which overflowed and allowed the fish to escape, thus stocking the waters of the river. Some years ago rainbow trout were placed in the River Angus, near Strathalbyn, by Sir Lancelot Stirling, and have apparently done well, as fishermen report having caught these fish in Lake Alexandrina and up the Murray as far as Tailem Bend (McIntosh, 1913).
Introduction of redfin perch (non-native species)	1913	A number of English perch were obtained from the Ballarat Acclimatization Society for Mr. P. W. Bromfield, of Kangaroo Island. I personally accompanied these to Kingscote, and delivered them in excellent health. These fish were released in Birchmore's and Murray's Lagoons, the former being on Mr. Bromfield's property and the latter on the estate of Mr. F. W. Winch. The Gawler Fish Protection Society

		and Angling Club, which has been established by some local sportsmen, received another supply of fish from Ballarat for liberating in the North Para. The stocking of these waters last year has evidently been successful, as several fine trout have been noticed lately (McIntosh, 1913).
Good catches of mulloway	1914	It is pleasing to record the favourable season for mulloway (butterfish), large hauls being made at Goolwa, Milang, and Lake Alexandrina (McIntosh, 1914).
Impacts of low-flow and status of fisheries along the Murray River	1914	RIVER MURRAY AND LAKES' FISHERIES. Two dry seasons with a record low river have depleted the fish supplies in these waters ; some of the backwaters have dried up entirely, and to prevent the possible waste of valuable fish it was decided to open the natural hatchery at Lake Bonney to fishing, owing to the waters of the lake diminishing to such an extent that there is every possibility of its becoming dry. When the lake is again filled the fisheries will be again protected (McIntosh, 1914).
Impacts of low-flow and status of fisheries along the Murray River	1914	GENERAL. The drought conditions experienced during the period under review have very seriously affected the inshore and fresh water fisheries of the State generally, and the oyster fisheries in particular. The majority of our streams are rapidly drying up, consequently the greater portion of the trout, perch, &c., therein must of necessity be destroyed, while through the almost total absence of storm of flood waters such fish as are in the habit of frequenting the estuaries were not so abundant as usual (McIntosh, 1914).
Introduction and spread		It is exceedingly pleasing to note the success obtained by stocking waters with rainbow trout, which have

of trout (non-native species)		spread to the various streams ; also the enterprise of the Gawler Fish Protection Society and Anglers' Club, who continue to stock their waters with fish supplied from the Ballarat Acclimatization Society. One large consignment was received on their account by one of our officers, who gave instructions as to their handling and liberation. This was a most successful venture, as fully 99 per cent. were liberated in a health condition. During the coming winter we hope to be able to supply the orders for fish that were cancelled owing to the dry season, and restocking will be necessary in places as, unfortunately, the extreme drought conditions threaten to materially reduce the natural increase (McIntosh, 1914).
Stocking of Murray cod	1914	Lake Bonney, in the South-East, has been stocked with Murray cod ; a consignment of 48 of these fish were taken from Wellington West for the purpose, 40 of which were liberated in good condition. A strict watch is being kept by persons interested and the local inspector, and the protection of these fish will be strictly enforced (McIntosh, 1914).
Increase in the number of fishermen	1914	The number of fishermen has increased considerably, which is accounted for by farmers and others, who previously worked on the land, being forced to look for another occupation to assist in making a living (McIntosh, 1914).
Good catches of mulloway	1914	The season for mulloway has been an exceeding good one, large hauls being made at the various centres, particularly so at the Murray Mouth, where some fine fish were landed (McIntosh, 1914).

Impacts of low-flow and distributing fish to market	1914	MURRAY RIVER. With such dry seasons it was only natural that supplies from the river districts would be short, but, notwithstanding this, many good catches were made in the Renmark district, which were railed to Adelaide rom Paringa and Loxton. One enterprising fisherman has found that a motor car is a valuable addition to his plant and a quick means of transit to the railway terminus. Another great benefit to the men is that they can purchase ice in which they can pack their fish, and with these facilities the fish are marketed in prime condition, which compensates the fishermen for the additional expense (McIntosh, 1914).
Good catches of bream	1914	Inspector Furler reports that bream fishing at Noarlunga in the Onkaparinga River has been exceptionally good, and in one week over 2,000 fish were taken by a few anglers. This stream is at present splendidly stocked above the suspension bridge, where on calm days large shoals can be seen (McIntosh, 1914).
Status of Murray cod	1914	Two dry seasons with a record low river had depleted the fish supplies in these waters … (McIntosh, 1914).
Introduction of trout (non-native species)	1914	It is exceedingly pleasing to note the success obtained by stocking waters with rainbow trout, which have spread to the various streams ; also the enterprise of the Gawler Fish Protection Society and Anglers' Club, who continue to stock their waters with fish supplied from the Ballarat Acclimatization Society (McIntosh, 1914).
Spread of trout (non-native species)	1914	Rainbow trout are increasing in Lake Alexandrina, and it has been reported that some fish have been taken there. It is astonishing the number of creeks and streams that contain these fish, which must now suffer on

		account of the dry season ; but as they seem to be well established, and are prolific breeders, there is every reason to believe that with a return of normal conditions they will soon multiply (McIntosh, 1914).
Stocking of Murray cod	1914	Some years ago it was decided to stock Lake Bonney (near Millicent) with Murray cod, but owing to the scarcity of small fish it was postponed until last April, when through the kindness of Messrs. Stacey and Sons, of Wellington West, the Department was enabled to secure a supply. These fish were handed to me in excellent condition and placed in cans, in which they were confined during their long journey. I was met at Millicent Railway Station by a trap kindly supplied by Mr. Ross Gordon, of Stuckey and Sons, and driven to the lake. The fish were liberated in their new home, where it is confidently expected they will do well. This was the first experiment by the Department in carrying live Murray cod long distances. The fish were placed in the cans at 5.30 p.m. on the 14th April and liberated at noon on the following day ; yet, after 18 hours confinement they were little the worse for their journey, and when released swam quietly away—some of them at once starting to feed. At present there is a good supply of food, but I would recommend that some carp be placed in these waters, as they are an excellent fish food and prolific breeders (McIntosh, 1914).
Status of Murray cod	1938	It (Murray cod) is a very large species, specimens having been stated to reach a weight of over 150 lb., and it has played for very many years a conspicuous part in the fish trade—particularly Melbourne. In fact, considering the little that has been done either to protect or to propagate the species, it is a wonder that it

		has not been almost wiped out (Dakin and Kesteven, 1938).
Fluctuation in New South Wales catch of Murray cod	1938	A graph (2) of the production from the inland fisheries of New South Wales, so far as that can be constructed from statistics available, shows roughly a series of peaks at 1883, 1900, 1918 and 1934, which is approximately in seventeen years cycles, but whether such a periodic fluctuation has genuinely existed the nature of the statistics does not permit us to say, nor are we in a position confidently to assign the causes of such fluctuations (Dakin and Kesteven, 1938).
Freshwater fisheries and Murray cod	1938	For only one important marine fish, the tommy rough, was there a falling off in production for 1938, but there was a tremendous drop in quantities of fresh water fish marketed in Adelaide. The chief reason for the decline in cod and callop lies in the fact that there was a complete absence of floods during the past 12 months—in fact, in August, September, and October, the season of greatest production in previous years, the Murray River was lower, according to residents, than at any other time since locking was completed. The close season for cod during the months September and October, when none could be marketed, is another reason for the drop in production of that fish (Moorhouse, 1938).
Closed season for Murray cod	1938	For many years South Australia has permitted the marketing of Murray cod during the breeding season. It had been found in 1936 that most of the fish taken in September were so full roed as to be nearly mature. In order to save potential breeders, this State, after consultation with Victoria and New South Wales, during September, 1936, decided to impose a close season on the taking of this fish. Since so few of them were

		found full roed in November, 1936, it was considered sufficient for the moment to prevent their being taken during the months of September and October, but Victoria and New South Wales, both of whom had for many years had a close season during October and November, merely added September to that season. An intensive study of this fish was commenced by an officer of the New South Wales Fishery Department during the 1937 breeding season, and the very inconclusive results obtained by him were published in Bulletin No. 1, 1938, of the New South Wales Chief Secretary's Department (Moorhouse, 1938).
Status of inland fisheries	1938	The 225 licensed fishermen who have had allotted to them lengths of the Murray River in which to fish exclusively, experience a very difficult period during the past year, and the majority had to obtain exemption from fishing their reaches in order to take up temporarily some other occupation. However, in general, the prices for these fish have been much higher than in previous years, so that thought small quantities were taken, results obtained from a monetary point of view were reasonably good (Moorhouse, 1938).
Local sale of inland fisheries catch	1938	Numbers of Murray fishermen have decided to market their fish in the townships along the River Murray, and from this local trade, residents have benefited considerably. Large quantities, too, are marketed in Melbourne. No accurate information on the amounts so disposed of has been obtained (Moorhouse, 1938).
Status of freshwater crayfish	1938	A fresh water Crustacean, the Murray lobster, makes a delicate fish, and a ready sale is found for it in the various towns along the Murray River. Of course, no records of quantities marketed are available, but

		fishermen state that there was a very serious decline in the quantities taken by them this year (Moorhouse, 1938).
Difficulty of transporting fish	1938	CONDEMNED FISH. … The Bacterioloist attached to the Fisheries Section of the Council for Scientific and Industrial Research in a copy of his report on “The Marketing of Fish in South Australia” (not yet published) has commented adversely on the transport supplied to fishermen in the Goolwa-Milang area. Knowing what a very large amount of fish from those ports is condemned it would appear that a change in the transport facilities afforded this area is called for (Moorhouse, 1938).
Types of gear used	1938	TYPES OF FISHING GEAR. Mesh nets are in very common use in the Lakes and Coorong where large quantities of butterfish and mullet are being captured (Moorhouse, 1938).
Tagging of fish species for research	1938	In order to throw some light on the growth-rate and migration of our commercial fish, tagging experiments have been commenced. In this tagging of fish which has been carried out on two freshwater species, and two seawater types, many fishermen have given invaluable assistance. Murray cod and callop were the first to receive attention, but whiting and snapper have now been added to the list (Moorhouse, 1938).
Introduction of trout (non-native species)	1938	In 1937 the fish hatchery at Ballarat could not supply this State, but in 1938 some 7,000 advanced fry of brown trout, approximately 2 ½in. in length were obtained. With the co-operation of honorary inspectors these fish were liberated in the following streams:--Torrens, Onkaparinga, Angas, Finniss, Cox’s, and

		Gawler. Some few more, as an experiment, were liberated in dams and large waterholes and lakes. A report on the manner in which these fish will develop is eagerly awaited (Moorhouse, 1938).
Good catches of mulloway	1939	Butterfish, the most important fish passing through the Adelaide market also reached a production peak not noted for many years, with the result that its price fell to as low as 1 ½d. per lb (Moorhouse, 1939).
Tagging of fish species for research	1939	(*c*) TAGGING OF FISH. The tagging of whiting, snapper, Murray cod and callop was continued. … Six Murray cod were recaptured after tagging and liberation. Some had gone upstream, others had moved downstream, but the general migration was very slight distances. The greatest growth was noted in a cod liberated on 12th September, 1937, but Mr. J. F. T. Heinicke and recaptured by him on 1st July, 1938. It had grown 1in. which represented an increase in weight of approximately ½lb (Moorhouse, 1939).
Size limits and closed season for Murray cod	1939	On the Murray River, Murray cod may not be taken unless they are of over the prescribed length, viz., 15in. There is also a close season restriction on cod. This is fixed from September and October each year (Moorhouse, 1939). In our other freshwater streams, the imported trout (either brown or rainbow) may not legally be taken unless they are of over the minimum length, viz., 10in. There is, for this fish also, a close season which now extends from 1st May to 31st August (Moorhouse, 1939).

Impacts of flooding and status of inland fisheries	1940	MURRAY RIVER. Heavy flooding of the Murray river, which lasted through the months of Augusta, September, October and November, constituted favourable conditions for the capture of large quantities of river fish. September and October are a close season for Murray cod, so only callop and bream can be marketed during those months. Fishermen along several parts of the river often caught as much as 40lb. these two fish (besides quantities of cod which had to be release) in each drum net. The numbers of nets used therefore were often reduced to as few as six per man. A conservative estimate shows that 25 tons of callop and bream per week were caught during October. Despite the heavy production, the quantity of cod and callop which passed through the Adelaide fish market during the year did not constitute a record, mainly because a large proportion of the catch was sold at local markets, which this department has been urging fishermen to exploit. Some more enterprising fishermen even delivered their fish to towns as far removed from the Murray river as Jamestown, Peterborough and Wirrabara. Considerable quantities, as usual, were also consigned to Melbourne. While these large quantities of fish were being captured in South Australia's portion of the Murray river, the municipality of Albury (New South Wales) suggested that owing to the depletion of our fresh-water fish all commercial fishing the Murray river should be prohibited for two years. From this is may be inferred that conditions generally in South Australia's part of the river must be very different from those in the New South Wales portion. To-day the Murray in South Australia can be regarded as a river in magnitude only

		during flood periods. At other times it is merely a series of seven large narrow lakes, due to the locking system. In these lakes, each approximately 50 miles in length, and of varying depths, are found plankton (principally copepods), shrimps, yabbies, and small fish such as smelts and carp, upon which cod and callop are dependent for food. The 1939 floods disclosed vast numbers of Murray fish in our portion of the river. So numerous were they and so easily were they caught that many fishermen suggested a revision of the minimum weights. They considered the size of callop and of bream should be raised to 12in. and of cod to 18in. These suggested increases were strongly supported by the marketing proprietors, and by the Adelaide fishmongers, all of whom at times experience considerable difficulty in disposing of these fish and others which just come within the present prescribed minimum weight. The suggestions were not adopted (Moorhouse, 1940).
Tagging of fish species for research	1940	(*a*) TAGGING OF FISH. The tagging of whiting, snapper, Murray cod and callop, was continued, and much valuable assistance was given by various fishermen. One of the most interesting migrations was that carried out by a Murray cod which, three days after its liberation at Lock 15, Robinvale, was captured 65 miles upstream from its point of liberation. As has been previously found, migration can also be downstream. This was shown by a fish liberated near Blanchetown which, a week after liberation, was found 5 miles downstream (Moorhouse, 1940).

Migration of fish and operation of weir fish ladder	1940	(*c*) FISH MIGRATION. *Murray River Fish*.—From information supplied this year by the lock master at Lock 15, at Robinvale, the following fish passed up the fish ladder at that lock:--363 cod (176 of which were tagged), 1,510 callop, 1 Macquarie perch, 5,153 grunter or silver perch, 303 English perch, and 4 catfish. From July to December the Murray river was, according to the lockmaster's report, so high that the lock and weir were left open. During March, on the other hand, there was not sufficient water to flow over the weir. No check on fish using the ladder was made during those months. Of the fish mentioned above the cod were reported to have varied from 9in. to 28in. in length ; callop from 6in. to 20in. ; and the silver perch from 8in. to 16in (Moorhouse, 1940).
Poor catches of mulloway	1941	… it will be seen that, though the quantity of fish passing through the market this year was only slightly less than that of 1937-38, the value received was £1,000 more. Butterfish – the most important fish in the Adelaide fish trade – showed a big drop in production compared with the quantities taken during the last two years and returned to the 1937-38 level. Though the quantity marketed this year was almost the same as that for 1937-38, it reached only two-thirds of the value, due probably to the more even marketing noticed in 1937. In the early part of the year 1940-41 such large quantities were marketed (on some days as much as 10 tons arrived for distribution) that prices fluctuated violently … (Moorhouse, 1941).

	1941	*No mention of Murray cod (Moorhouse, 1941)*
Poor catches of mulloway	1942	GENERAL REMARKS—The decline in butterfish supplies not only from the Murray mouth and Coorong but also from all other fishing centres noted last year, continued and reached a very low level (Moorhouse, 1942).
Importance of inland fisheries	1942	The principal sources of Adelaide's supply are the Murray River, the Murray Lakes and Coorong, the ports of Gulf St. Vincent and the ports on the eastern side of Spencer Gulf (Moorhouse, 1942).
Importance of inland fisheries	1942	The Adelaide market regularly receives considerable quantities of Murray River fish (cod and callop). When flooding of the river occurs these supplies are often so large as to over-tax the market. On such occasions or when there is an excess of sea fish, the prices of all fish are generally low (Moorhouse, 1942).
Tagging of golden perch for research	1942	Owing to the presence of quite large numbers of small callop and small perch in Lake Alexandrina and Lake Albert hundreds have been meshed in nets set to capture mullet. One interested fisherman (Mr. D. Cremer) has already tagged a very large number of these callop in the hopes that some interesting discoveries will result (Moorhouse, 1942).
	1942	*No mention of Murray cod (Moorhouse, 1942)*
Large catches of	1943	Fish supplies were somewhat scarce during those stormy months and wholesale prices remained high.

congollis		Fortunately, congollis appeared again in the Lakes during the winter and helped the market carry on through this difficult season. These fish have not occurred in big numbers this winter, but ruffs which were taken in considerable quantities filled the demand for fish of small size. Large fish capable of supplying the requirements of the cutlet trade were also in rather short supply due mainly to the further fall this year in butterfish landings (Moorhouse, 1943).
	1943	*No mention of Murray cod (Moorhouse, 1943)*
	1944	*No mention of inland fisheries (Moorhouse, 1945)*
	1945	*No mention of inland fisheries (Moorhouse, 1945)*
	1946	*No mention of inland fisheries (Moorhouse, 1946)*
Breeding of trout (non-native species)	1947	BROWN TROUT. The breeding of trout was resumed on a small scale this year after a lapse of several years. Honorary Inspector Malpas, whose serious illness had prevented a continuance of the work begun by him in 1940, fortunately recover sufficiently to supervise the work of this son. Several thousand fish were hatched. A protozoan parasite, due to overcrowding, was discovered in the later stages. This took relatively heavy toll of the young fry. Approximately 2,000 fish were released (Moorhouse, 1947).
Discussion regarding	1947	DEPLETION. This is surely an inappropriate word to use in Australia where the fisheries are markedly

the status of South Australian fisheries	under-developed and have such a relatively short history compared with those overseas. When Dr. Thompson, Chief of the Fisheries Division of the C.S.I.R., who had expressed the opinion that South Australian in-shore waters were “probably depleted except possibly for the whiting fishery,” was asked why, it that were the case, the departmental beach netting tests on fish other that whiting has been so successful, he replied that my tests were made “in very shallow water which was more or less virgin ground.” I fail to see how a state of depletion by over-fishing can be reconciled with virgin waters. … When a fish that is normally plentiful becomes scarce of does not frequent its usual haunts the cause is often ascribed in some quarters to depletion, regardless of the fact that perhaps no adequate investigations of the position have been made. How easy it is to draw wrong conclusions about fish stocks is illustrated in the following. … Two other species have also been scarce, namely, the mulloway or butterfish, which is of great commercial important, and the silver whiting which is not so important. … The mulloway have also been capricious in their appearances. Years ago big hauls of them could be taken in the shallows and the “runs” to the north of Adelaide. They are not there now but in 1938 and 1939 they

		were present in very large numbers in the Murray Mouth, lakes, and Coorong. Today only a few are taken there. The coming into operation of the barrages was coincidental with the scarcity of the mulloway in the Coorong and many fishermen are convinced that the advent of the barrages actually caused the mulloway to leave the Coorong. But what reason can be advanced for the failure of this species to frequent the "runs" to the north of Adelaide where no barrages exist? It might be mentioned here that mulloway were once an important fish commercially in the Gippsland Lakes (Lakes Entrance) of Victoria ; they have almost disappeared from there also. Some fishermen there ascribed their disappearance to the opening of the Gippsland lakes to the sea. On the other hand these fish have appeared in numbers along the foot of Yorke Peninsula where no fresh water streams entre the sea (Moorhouse, 1947).
Introduction of redfin perch (non-native species)	1948	English perch, which are good sporting fish and very palatable, have been liberated in many privately-owned dams in South Australia. Many orders for these fish could not be supplied last year. It is known that so long as such food as shrimps, yabbies, and minnows is present the perch thrive and multiply. Many farmers now enjoy not only the relaxation of fishing on their own properties, but also the consuming of palatable fresh fish (Moorhouse, 1948).
	1948	*No mention of inland fisheries (Moorhouse, 1948).*
	1949	*No mention of inland fisheries (Moorhouse, 1949).*

	1950	*No mention of inland fisheries (Moorhouse, 1950)*
Impacts of flooding and status of inland fisheries	1951	MURRAY RIVER. This year, the second in succession, heavy flooding of the Murray River gave favourable conditions for the capture of large quantities of fresh water fish, but their wholesale price in Adelaide often fell so low as to make the catching unattractive to many fishermen. Again, as in previous floodings, the quantities reaching the Adelaide market did not constitute a record. There were, however, heavy sales at towns and villages along or near the river. Fishermen operating in the Murray Lakes (Alexandrina and Albert) also reported the presence of ever-increasing quantities of fresh water fish. These men are taking heart again after the loss of their salt water fishery which followed the closing of the barrages at Goolwa. For a period during the change-over from salt water to fresh water conditions in the areas became a "desert." Slowly fresh water life became established. Today the quantity of fish present makes fishing a profitable occupation once more. Amateur fishermen, too, enjoyed good catches. In 1939, while large quantities of fish were being capture in South Australia's portion of the Murray River, the Municipality of Albury suggested that all commercial fishing should be prohibited in the Murray River for a period of years. The suggestion was not adopted. Similar requests for the total prohibition of fishing or for the introduction of severe restrictions on the taking of Murray fish have been made by various interstate bodies from time to time since then. The most recent request for a complete closure, made in June, 1951,

		came from the Victorian Piscatorial Council. It, too, was not approved (Moorhouse, 1951).
	1952	*No mention of inland fisheries (Moorhouse, 1952)*
	1953	*No mention of inland fisheries (Moorhouse, 1953)*
Introduction of redfin perch (non-native species)	1953	LIVE FISH DISTRIBUTION. The liberating of English perch in privately-owned dams was continued and 15 applications were supplied. … (Moorhouse, 1953)
Issuing of location-based licences to fishermen	1954	RIVER MURRAY RESERVES. The River Murray is divided into reaches of lengths varying from half a mile to two miles. These were formerly allotted to fishermen who were the only persons permitted to use commercial fishing gear such as cross lines and drum nets in the capture of fish. All other persons were restricted to handlining for the fish they wished to catch. The towns were established along the river. Residents pressed for permissions to use cross lines and drum nets in the capture of their fish. Fishermen objected to this intrusion so it was decided that as soon as a reach-holder near a town gave up his area the reach would be declared a town fishing reserve. At present town fishing reserves are established at Wellington, Tailem Bend, Murray Bridge, Mypolonga, Caloote, Mannum, Bowhill, Cournamount, Swan Reach, Blanchetown, Murbko, Morgan, Cadell, Ramco, Waikeries, Kingston, Cobdogla, Loxton, Berri, Lyrup, and Renmark. This policy is giving general satisfaction (Moorhouse, 1954).

	1955	*No mention of inland fisheries (Moorhouse, 1955).*
Decline of inland fisheries catches	1956	The known production of fish (all species except crayfish) amounted to 6,530,000 lb. This represented an increase of 30,000 lb. over figures quote last year. There was a marked increase this year in the production of tuna, mullet, snook, whiting, and garfish. A serious decline in Australian salmon production due principally to fishermen turning their attention to other fish, and a big fall in fish from the Murray River, namely Murray cod, callop, and mulloway, due to heavy and continuous floods, almost outweighed those increases (Moorhouse, 1956).
Breeding and introduction of trout (non-native species)	1956	TROUT. Trout hatching was first attempted in 1939 when Honorary Inspector C. W. Malpas, of Unley, hatched thousands of locally obtained eggs in small trays in his backyard. The hatchery was moved to Upper Sturt so that the using of spring waters could supplant the somewhat expensive town supply. The spring water was impure so the hatchery, now in charge of the Fly Fishers' Association, was removed to Ovingham, where the town supply was again availed of. This year the size of the hatchery was more than doubled at a cost of £475. The Fisheries and Game Department met half this expense. Thousands of rainbow trout hatched from eggs imported from Western Australia are reported to have been distributed throughout the nearby streams. A considerable number of brown trout was also hatched and liberated. The South Australian Tourist Bureau made a film of the hatchery and of fishing for trout in the Torrens Gorge. This will be used for publicity and entertainment purposes (Moorhouse, 1956).

Discussion regarding fisheries management conference proceedings	1956	MURRAY FISHES. On 25th November a conference on Murray fishes convened by the Murray Valley Development league was held at Albury. The Fisheries Departments of Victoria, New South Wales, and South Australia were represented. Such proposals as the establishment of a fish hatchery at Albury and of fish ladders at the Hume Weir were matters of local concern. That amateur angling licence fees should be increased also held no interest for South Australia because amateur angling is free in this State. The principal subjects discussed were the appointment of more inspectors and the proposal that the sale of Murray fishes should be banned. The proposal to prohibit the selling of Murray fishes was defeated. The other was approved (Moorhouse, 1956).
	1957	*No mention of inland fisheries (Moorhouse, 1957).*
	1958	*No mention of inland fisheries (Moorhouse, 1958).*
	1959	*No mention of inland fisheries (Moorhouse, 1959).*

Chapter 4: Historical ecology changes the options for management of invading species

4.1 Preface

Invasive species can drive changes in ecosystems that have lasting legacies. The implications of such changes for society can be considerable where there is, for example, a loss of access to resources or environmental variation that is confronting. In this chapter, societal concern toward a cryptogenic species of oyster is assessed along with the options for its management. The population is considered from a historical perspective, using historical data obtained from archived fisheries records, and the contemporary effects of the species on a native bivalve and associated epifauna are quantified. A decision-making model is used to understand the management actions that could be assigned to the population based on community perspective alone, in contrast to those made based on the empirical evidence. This chapter is being developed as a manuscript for publication, with the co-author Sean D. Connell.

4.2 Statement of authorship

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Principal Author

Name of Principal Author (Candidate)	Heidi K. Alleway		
Contribution to the Paper	Conceptualised and designed the research and experiment, organised and conducted field and laboratory work, collated and analysed the data, interpreted the results and developed the manuscript.		
Overall percentage (%)	80%		
Signature		Date	24/07/2015

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

vii. the candidate's stated contribution to the publication is accurate (as detailed above);

viii. permission is granted for the candidate in include the publication in the thesis; and

ix. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Sean D. Connell		
Contribution to the Paper	Conceptualised and designed the experiment, assisted with the interpretation of results and development of the manuscript.		
Signature		Date	21/07/2015

Historical ecology changes the options for management of invading species

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4.3 Abstract

Invasive species have for centuries affected communities and ecosystems and generate impacts that are unwanted by business and society. Despite the development of invasion ecology as a discipline and rigorous management frameworks, such as biosecurity, many species cannot reliably be described as native or alien and determining their degree of ‘invasiveness’ can be challenging. The introduction of non-native species can also return functions previously undertaken by native species that have been lost, but recognition for this possibility can be obscured by society’s amnesia of past environments, or collective acceptance of shifted baselines regarding lost functions. This chapter evaluates the ecological merit of the concern of a regional community toward a cryptogenic oyster *Pinctada albina sugillata*, which occurs in a locality of oyster loss. This species can occur as an epibiont, attached to the native bivalve *Pinna bicolor* in large numbers, which is an unwanted interaction and the community has thus branded it ‘highly invasive’. This model of invasion was tested using historical and experimental approaches. Historical records indicated a comparable past association between the native oyster *Ostrea angasi* and *Pi. bicolor* such that the association is not ‘unnatural’. Transplant experiments then tested the impact of *Pc. albina sugillata* as an epibiont on the condition of *Pi. bicolor* but did not detect a negative effect on individual health. Instead, a positive effect of *Pc. albina sugillata* on epifaunal species richness and abundance was observed as a result of the complex habitat this species creates in association with *Pi. bicolor*. The contradiction

between the societal perspective and the empirical data for management options was considered through a decision-making model. Decisions based on the perception that *P. albina sugillata* was highly invasive led to the investigation of eradication and biological control, but the inclusion of historical ecology led to a change in focus to resource use, with education and communication to seek containment. This outcome suggests that historical ecology could be used to inform the ecological context of invading species and options for their management.

4.4 Introduction

Invasive species are a challenge to ecosystems, societies and management (Simberloff et al., 2013), and global change infers they will play an increasingly prominent and dynamic role in the environment and in human communities (Walther et al., 2009). The increasing rate at which non-native species are introduced to new landscapes, which has at no time in the past been higher, represents both opportunity through benefits to biodiversity or ecosystem services, as well as risks due to negative impacts such as resource or biodiversity loss (Walther et al., 2009). A further risk is the mistaken classification of a species as 'alien' when it is in fact native (Willis and Birks, 2006), which might lead to xenophobia (Larson, 2005). Hence, the native-versus-alien dichotomy that is commonly used can be counterproductive to ecology and management (Davis et al., 2011). Despite the introduction of formal surveillance networks through biosecurity (Meyerson and Reaser, 2002) our ability to accurately describe a species as native or alien will continue to be limited (Preston, 2009, Walther et al., 2009, Webber and Scott, 2012), which is problematic under a future of systematic change in community assemblages and the "shuffling of species" with changing climate (Hobday, 2011, Dornelas et al., 2014).

Species-specific ecologies of invaders bring both ecological and social challenges. Consequently, debate around the management actions needed can arise from differing values for invasive species (Estévez et al., 2014). For example, species intentionally introduced during the course of European colonisation, for instance trout, can be despised or revered. Such species can be the subject of a shifted baseline that then acts to facilitate their conservation, because society is placing a high value on their presence (Clavero, 2014). The strict regime established through biosecurity has raised the profile of non-native species and communities are now aware of their occurrence (Meyerson and Reaser, 2002), but it has also contributed to the use of militaristic metaphors, including the terms 'invasion', 'invader', 'target' and 'strategy', that can create the belief we are at war with species not considered to be a natural part of the environment (Larson, 2005). Invasive species can contribute positive changes to ecosystems, including the provision of habitat, shelter and food (Schlaepfer et al., 2011). But these positive changes could be overlooked when there are little data available to determine their effect, or societal perspectives toward the species politically motivate decision-making (Gozlan et al., 2013).

Baselines against which natural and human mediated change can be measured can be impeded by the temporal span of available data and the action of the shifting baseline syndrome (Pauly, 1995, Jackson, 2001, Willis and Birks, 2006). Without accurate baselines we risk misinterpreting the absence or productivity of a species or ecosystem (Alleway and Connell, 2015), but we might also misinterpret positive change, including the benefits that introduced species bring to landscapes that are negatively impacted by human activity (Schlaepfer et al., 2011). It may well be worth contemplating the ecological services of non-natives and whether their coexistence with a historically and ecologically informed society is possible. Consequently, the temporal scale of measurement in invasion ecology is important and species-specific invasion ecologies can be improved by considering the occurrence of species over longer periods of time and applying a holistic understanding of ecosystem change (Willis and Birks, 2006, Carlton, 2009). Many studies in invasion ecology do not, however, adopt a long-term perspective toward the changes that a species might have contributed (Strayer et al., 2006), or the changes that have occurred within an ecosystem that might have facilitated its establishment (Sol et al., 2008). Historical ecological research, which works to build a representative measure of change over time using palaeoecological, archaeological or historical processes could, therefore, assist invasion ecology.

Non-native bivalves, including oysters, can be ecosystem engineers (Sousa et al., 2009) and, as a result, they represent some of the most widely distributed invasive species in the world contributing to positive feedback loops and 'invasional meltdown', such as the introduction of new diseases and pathogens (Ruesink et al., 2005, Heiman and Micheli, 2010, Mineur et al., 2014). Here, the ecological merits of community concern toward a cryptogenic oyster species and its management were evaluated. The species, a pearl oyster *Pinctada albina sugillata*, occurs in an area of past loss of oysters and oyster reefs, but the community considers its behaviour to be highly invasive and its presence of imperative concern. An experimental approach was combined with information from historical records to assess negative and positive aspects of the population. The hypothesis that the occurrence of *Pc. albina sugillata* as an epibiont, attached to the shell of native *Pinna bicolor* (razorfish or razor clam), would negatively affect *Pi. bicolor* condition was tested using transplant experiments. A second hypothesis was also evaluated; this being that interaction between these two species would positively affect epifaunal species richness and abundance due to the complex biogenic habitat created by the association. The influence of the historical baseline of oyster loss on societal perspective, and thus the management actions assigned to the species, was considered through the use of a decision-making model.

4.5 Materials and methods

4.5.1 Site description and population

Spencer Gulf in South Australia is an inverse estuary influenced by seasonally warm water on the continental shelf from the major southward flowing currents from northern Australia and is, consequently, characterised by a changing temperature regime; the shallow waters of the upper Gulf vary by approximately 12°C, between summer and winter, and summer temperatures reach greater than 24°C (Nunes Vaz, 2014). This oceanography creates a distinct subtropical environment that supports the presence of tropical and sub-tropical species, including a number of tropical 'relicts' (Shepherd, 1983, Edyvane, 1999b).

Pc. albina sugillata is one of two sub-species of pearl oyster distributed across areas of the Indo-Pacific and along Australia's northern coastline, from the Houtman-Abroholos Islands in the west to central NSW in the east (Hynd, 1960). In South Australia, the species occurs in the upper reaches of Spencer Gulf (Figure 1a). Voucher specimens were first lodged with the South Australian Museum in 2003, though anecdotally this species was reported sometime in the 1980s (Wiltshire et al., 2010). Surveys of benthic communities in the late 1970s at the southern end of the species current range did not highlight its presence

(Shepherd, 1983). The population is now patchily distributed at various densities across approximately 20 kms of the upper Spencer Gulf (Rutherford and Miller, 2011). Because the date of first occurrence and the vector of transfer are unknown the species is classified as cryptogenic.

4.5.2 Community perception

Responding to community concern the Government of South Australia provided a parliamentary inquiry into invasive species, at which the ecological effects of the *Pc. albina sugillata* population were considered. During their presentation of evidence to the inquiry, representatives from the community highlighted their concern for the way in which *Pc. albina sugillata* interacted with the native bivalve *P. bicolor*. It was stated; "*well, we can see it's fairly clear the razorfish are decimated; they have actually flattened whole areas of them and that is continuing*"; also, "*they literally form a blanket over the Razorfish smothering them from the intertidal zone*" (Figure 1b) (Invasive Species Inquiry, NRC, 2010). *Pc. albina sugillata* attaches to the outer shell of *Pi. bicolor* often in numbers of 10s of individuals across a range of sizes (Figure 1c). *Pi. bicolor* is a popular recreational fishery species throughout South Australia, particularly within the Spencer Gulf where it is an iconic species used for food and bait for fishing. Spatial closures and catch limits have been in place since 2006 to limit harvesting of *Pi. Bicolor*, due to concerns of high fishing pressure and localised depletion. Beginning in 2011, the local community of the upper Spencer Gulf was engaged in further dialogue, through direct discussion with individuals and presentation to the Local City Council of Port Augusta and members of their Marine Advisory Group (June 2011), encompassing representatives from local and state government, local community groups and businesses, and members of the public. Discussion was ongoing after this point, via direct conversation through phone, email and meetings during site visits.

4.5.3 Historical ecological records

To build an understanding of the local environment prior to the establishment of *Pc. albina sugillata* and the interaction of this species with *Pi. bicolor*, fisheries records held at the State Records of South Australia and voucher specimens within the South Australian Museum were searched for reference to the past observation of *Pc. albina sugillata* and information on the past occurrence and population characteristics of native oyster species, in particular *Ostrea angasi*. Sources searched were mollusc collections, which were manually checked for records of *Pinctada* species, and historical records, e.g. parliamentary papers, annual reports, diaries and correspondence, and marine charts, produced by the state government departments for Fisheries, and Marine and Harbour's.

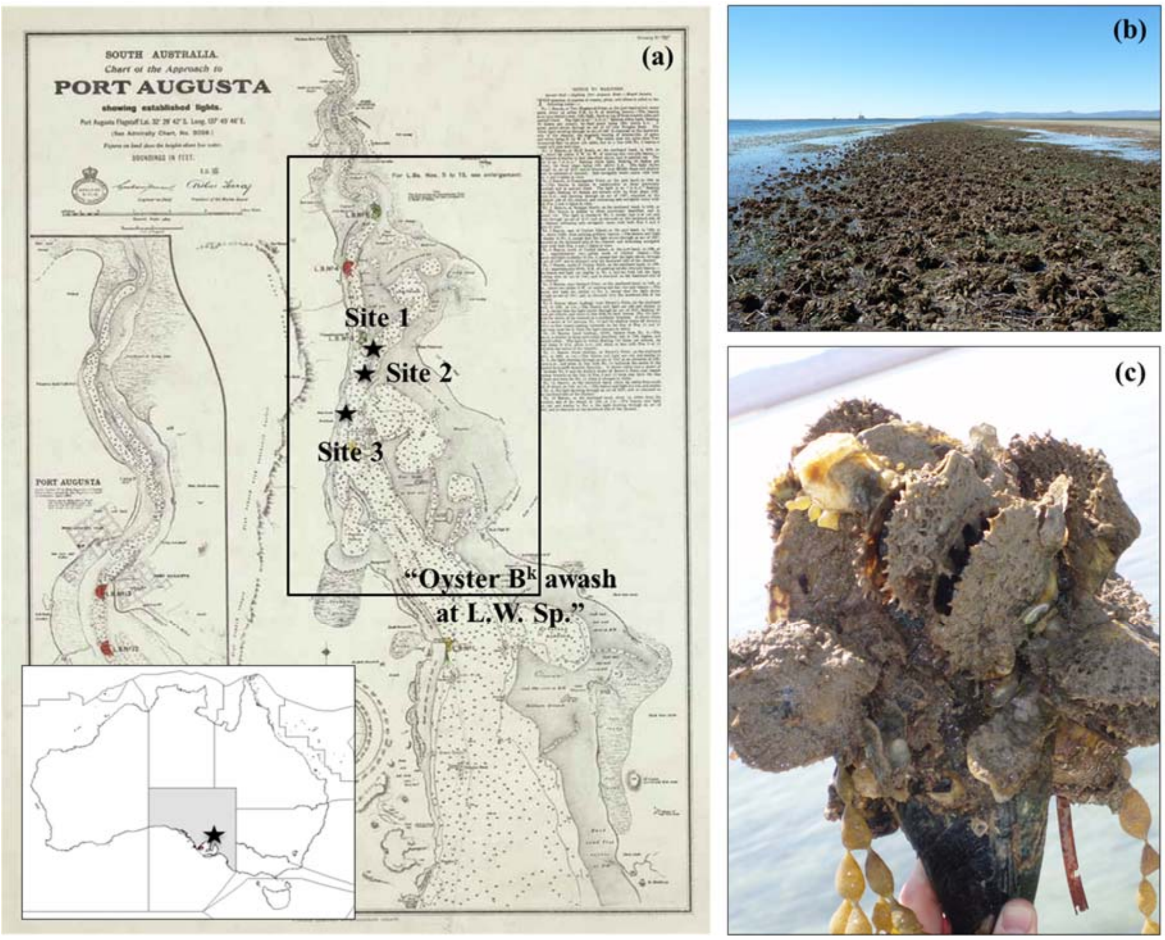

Figure 1. Historical map of upper Spencer Gulf, South Australia, (a) indicating the location of a population of cryptogenic pearl oyster, *Pc. albina sugillata* (indicated by inset square and ★), (b) the dense accumulations of individuals that can occur, and (c) the association formed between *Pc. albina sugillata* and the native bivalve *Pi. bicolor* (c).

4.5.4 Experimental test

An experimental approach was used to evaluate the effects of *Pc. albina sugillata* on the condition of individual *Pi. bicolor*. The model of concern, that *Pi. bicolor* is ‘decimated’ and ‘smothered’ by *Pc. albina sugillata* was assessed by testing the hypothesis that the condition of *Pi. bicolor* would be negatively correlated with the weight of *Pc. albina sugillata* attached to each shell, i.e. the larger the number of oysters attached to the shell the poorer the condition of *Pi. bicolor*.

In December 2012, 135 discrete associations of *Pi. bicolor* with *Pc. albina sugillata* attached (Figure 1c) were harvested from three sites, encompassing areas of higher density *Pc. albina sugillata* (denser aggregations, individuals attached to hard substrate in tens of individuals) and lower density (individuals loosely aggregated or occurring individually, not attached to hard substrate in more than single numbers), based on data in Rutherford and Miller (2011). Approximately 500 m separated Sites 1 and 2 and Site 3 was 2 km distant to Site 2 (Figure 1a). Spatial separation between sites was not equal because *Pc. albina sugillata* is patchily distributed, occurring across intertidal and shallow subtidal areas and on sand shoals interspersed with deep channels where the species does not occur. The separation was, however, considered sufficient to separate the effects of *Pc. albina sugillata* on individual *Pi. bicolor* between sites.

Three treatments were applied to the samples: Treatment (T) 1 = control (picked up and put down again with minimum translocation), T2 = *Pi. bicolor* cleaned of all *Pc. albina sugillata*, and T3 = *Pi. bicolor* uncleaned of *Pc. albina sugillata*. Samples were treated and translocated according to the sample statistics in Table 1 with 25 individuals in each category, other than Site 3 where two additional replicates were laid (n = 35) because of the locations proximity to boating and fishing activity and the higher risk of the experiment being tampered with. An uneven number of samples were laid due to the significant amount of time associated with laboratory processing of individuals, without compromising the experimental design.

Individual associations were laid in replicates of one metre wide rows, five *Pi. bicolor* within each demarcated by two metal pickets, and treatments were separated by two metres. This density was consistent with that observed at each study site; *Pi. bicolor* are also known to occur in densities greater than 20 individuals per m^2 (Butler and Keough, 1981). Hence, this density was also considered adequate to exclude the potential negative effects of the proximity of other *Pi. Bicolor*, such that their presence would not overwhelm the potential effect of *Pc. albina sugillata*. Treatments were left in-situ for 21 months, to allow sufficient time for an effect on *P. bicolor* condition to occur, after which the complete association – *Pi. bicolor*, *Pc. albina sugillata* and all associated epifauna – were harvested. Associations were individually bagged and placed in ice slurry prior to processing.

During the experiment replicates at Site 3 were tampered with and the metal pickets removed. Transplanted *Pi. bicolor* were systematically searched for but were not found and a haphazard collection of 25 *Pi. bicolor* were harvested in lieu of transplanted samples, reflecting as near as possible the original treatment of 'assemblages transplanted with *Pc. albina sugillata* attached from an area of a higher density of oyster', i.e. larger *Pi. bicolor* with higher numbers of *Pc. albina sugillata* attached to their shell were harvested.

4.5.5 Condition of *Pi. bicolor*

Epifauna were removed from the surface of each *Pi. bicolor* and retained. *Pc. albina sugillata* were separated from the rest of the sample, cleaned of excess material, e.g. mud and algae, patted dry with paper towel and the total total wet weight of oysters in grams recorded.

A condition index of *Pi. bicolor* was generated, sensu Wu and Shin (1998):

Condition index = (dry tissue weight (g) / maximum shell width (cm)) x 100

For this measurement, soft parts of each *Pi. bicolor*, e.g. stomach, gonads, were excluded and only the adductor muscle was included as tissue. It was thought the muscle tissue of *Pi. bicolor* would better reflect long-term condition because muscle mass, based on the hypothesis, would be effected by the persistent presence of *Pc. albina sugillata* as an epibiont, i.e. *Pi. bicolor* with a larger number *Pc. albina sugillata* on their shell would be persistently stressed and muscle tissue, as a result, would be atrophied. Furthermore, it was also assumed that variation in tissue mass due to seasonal and local variation of food or spawning could be reflected in the soft parts of *Pi. bicolor*, e.g. stomach and gonads, and might therefore confound measurement of condition due to collection of *Pi. bicolor* across a single point in time. *Pi. bicolor* is commercially and recreationally exploited for consumption and bait, and knowing whether muscle (meat) is reduced by the presence of *Pc. albina sugillata* was alsovconsidered important to community understanding. The adductor muscle of each *Pi. bicolor* was removed and oven dried at 90°C for 24 hrs to a constant weight (Wu and Shin, 1998).

Significant differences in the condition index, between sites and treatments, were visualised using box plots and evaluated using analysis of variance (ANOVA). Probability-plots and a Shapiro-Wilk test were used to check for normality in the data. Data for all treatments followed a normal distribution, hence data were not transformed and a linear model of correlation was then used to evaluate the effect of total wet weight of *Pc. albina sugillata* on *Pi. bicolor* condition.

Table 1. Sample statistics for an experimental test of the effect of *Pc. albina sugillata* on the condition of *Pi. bicolor*, using treatments of low and high quantities of *Pc. albina sugillata* as an epibiont, applied to samples harvested from three sites of low and high densities of *Pc. albina sugillata*.

Sample harvested from	**Density of *Pc. albina sugillata* at harvest site**	**Sample size (N *Pi. Bicolor*)**	**Treatment applied**	**Translocation Site (translocated to)**
Site 1	High	25	Control (T1)	Site 1
Site 1	High	25	Cleaned of oysters (T2)	Site 1
Site 2	High	25	Cleaned of oysters (T2)	Site 2
Site 3	Low	25	Not cleaned of oysters (T3)	Site 1
Site 3	Low	25	NA (original treatment tampered with; harvested *Pc. albina sugillata* attached (not treated)	Site 3
Site 1 (original experimental sample)	High	7 / 35	Not cleaned of oysters (T3)	Site 3

4.5.6 Epifaunal richness and abundance

In July 2012, *Pc. albina sugillata* and *Pi. bicolor* associations were harvested from three sites across areas of low and high *Pc. albina sugillata* density. One metre square quadrats were haphazardly placed over the benthos at Sites 1 and 2, with all *Pi. bicolor* within the quadrat harvested as well as associated epifauna. At Site 3 a haphazard collection of 37 *Pi. bicolor* was taken due to weather conditions, which limited the capacity to work with the quadrats. *Pc. albina sugillata* were removed from the sample, cleaned of any residual epifauna and patted dry with towel. Total wet weight of *Pc. albina sugillata* within each sample was then recorded and remaining epifauna was sieved through 0.5 mm mesh and retained. Epifauna were identified to the taxonomic level of family, or higher if this could not reasonably be determined. Total epifauna and the total number of taxonomic groups across all samples were categorically distributed according to classes of *Pc. albina sugillata* wet weight, and the mean and standard deviation were calculated.

4.5.7 Decision-making model

Although patchy in its distribution and abundance, *Pc. albina sugillata* occurs in large numbers and aggregations can form what could be considered oyster beds (dense accumulations of living oysters) (Figure 1b). Archival material indicated the native oyster *O. angasi* historically formed beds in the upper Spencer Gulf and grew on *Pi. bicolor* in large numbers. Based on this knowledge and the concern of the local community regarding the impact of *Pc. albina sugillata* on *Pi. bicolor*, a decision-making model was built that included and discounted the historical ecological baseline of *O. angasi* occurrence and growth on *Pi. bicolor* (Figure 2). The decision-making model was used to consider the influence of societal perspectives and the management actions that would consequently be assigned to the population.

4.6 Results

4.6.1 Community consultation and decision-making for management

The consequence of government response to community concern via consultation led to the management options of biological control, eradication and removal being investigated (Figure 2). This outcome was based on community information regarding the ‘invasiveness’ of *Pc. albina sugillata* and both the assumption, and political motivation as a result of the Invasive Species Inquiry, that the species was significantly, negatively affecting the *Pi. bicolor* population.

4.6.2 Historical ecological records

No records for *Pc. albina sugillata* other than those previously reported (Wiltshire et al., 2010) were identified. Historical records were, however, identified for the past occurrence of oyster reefs formed by the native *O. angasi* and for overexploitation of areas due to commercial fishing in the area overlapping the current range of *Pc. albina sugillata*. These references were found within the diaries and letter books of the Inspector of Fisheries (Fisheries, 1886), as well as cartographic material from 1863 of the area indicating at least one oyster bank (Figure 1a). Oyster reefs have been made functionally extinct by overexploitation, but knowledge of their previously widespread distribution and aspects of their ecology, including the manner in which they used to grow, has only recently become known (chapter three, Alleway and Connell (2015)). Records were also identified indicating *O. angasi* historically grew on *Pi. bicolor* in large numbers. *Pi. bicolor* were noted to provide a preferred hard substrate for the settlement of oysters. For example, on the 13th September 1881 the then Inspector of Fisheries commented in correspondence; “*some of the best formation as yet known in the History of Oyster culture for the oyster spat to cling, as many as fifty oysters, old and young, having been found on one razorfish*” (Fisheries, 1886). The importance of this interaction led the Inspector of Fisheries to repeatedly translocate live *Pi. bicolor* over hundreds of kilometres, in an effort to re-establish native oyster beds once they had started to deteriorate (Table 2) (Fisheries, 1886).

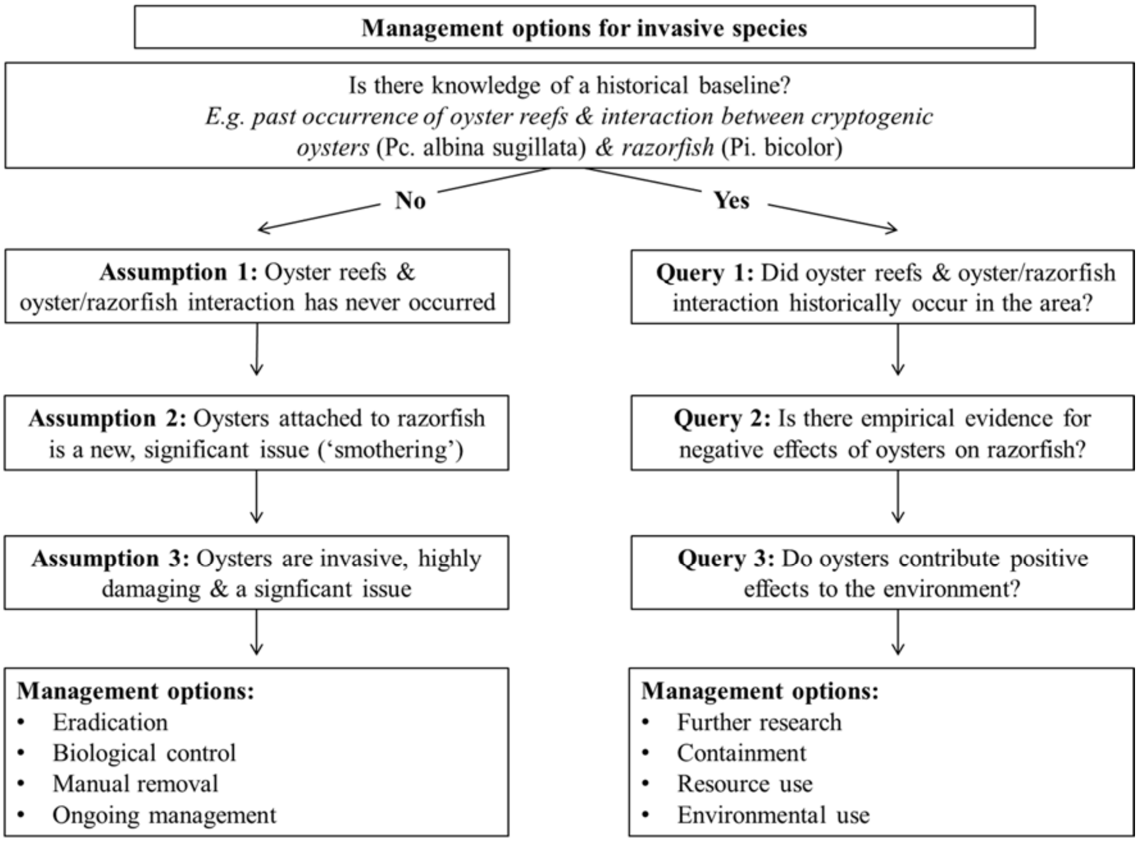

Figure 2. Decision-making model for management options of invasive species that includes and excludes knowledge of historical baselines, and the assumptions and management actions that can be applied to such situations, using the example of *Pc. albina sugillata* and *Pi. bicolor* in South Australia.

Table 2. Example historical records for the regional translocation and introduction of *Pi. Bicolor* (razorfish), across South Australia by the Inspector of Fisheries, from 1881 to 1910. These references were made in relation to efforts to re-establish the historical native oyster reefs and oyster fishing for *Ostrea angasi*, by reintroducing hard substrate, as reported in fisheries records held within the state archives of South Australia. Comments included in parenthesis are indicated by {}.

Reference	Date	Statement
Letter from Inspector of fisheries to Marine Board	13th Sep. 1881	"In Kellidie Bay where razor fish are non existent …"
Letter from Inspector of fisheries to Marine Board	13th Sep. 1881	"This can be done at very small expense for about £10 enough razor fish can be taken from Port Lincoln, where they exist in abundance, and transplanted to Coffins Bay {*greater Coffins bay includes Kellidie Bay*}, in which place they have made as yet no habitation."
Letter from Inspector of fisheries to Marine Board	8th Jan. 1887	"I must tell you that my time during the past month has been principally taken up by collecting the Razor Fish in Port Lincoln waters and transplanting them in Coffins Bay, where they are non existent at the present time ...'
Letter from Inspector of fisheries to Marine Board	25th Feb. 1887	"I have already transplanted about 400 {*razor fish*} of which about 10% have died."

Letter from Inspector of fisheries to Marine Board	9th Jun. 1887	"… in all 711 razor fish and planted there the natural beds in Kellidie Bay."
Letter from Inspector of fisheries to Marine Board	24th Nov. 1887	"The razor fish {*transplanted*} all along the mainland side of Boston Bay {*near Port Lincoln*} have formed a new foundation for the adhesion of oyster spat, three fourths of the oysters obtained are got from the razor fish beds, on much bottoms, where, but for the razor fish the oyster spat would have no hold."
Letter from Inspector of fisheries to Marine Board	2nd Apr. 1888	"I may add that the razorfish which I have transplanted from Port Lincoln waters to Coffins Bay about 15 month since, are thriving very favourably, the young fish are to be seen spreading through all parts of the Bays, I trust that this will be the means of reviving the decayed beds in Coffins Bay and form a new foundation for the Oyster spat to adhere to."
Letter from Inspector of fisheries to Marine Board	1st May 1888	"… "Oyster Shell" {*editorial letter*} appears to be ignorant that I have planted quantities of razorfish on ruined oyster beds and they are thriving admirably, I never lose an opportunity of doing this when it can be done without inquiry to other localities..."
Journal of travel, Inspector of Oyster Fisheries	28th Sep. 1888	"{*Coffins Bay*} Having examined the razor fish which I have planted then about two years ago, and the results of the same proved very satisfactory, the young razor fish is to be seen growing everyway."
Letter from Inspector of fisheries to Marine Board	4th Oct. 1889	"The razor fish I planted in these waters in different places are in splendid condition and are spreading rapidly, and I have some hope through them the decayed beds in Dutton Bay {*part of Coffins Bay*} may experience a revival."

Letter from Inspector of fisheries to Marine Board	5th Oct. 1888	“The razor fish I planted in different places about these Bays are in splendid condition and are spreading rapidly all about, and I have great hopes the increase of these fish will increase some of the decayed beds in Coffins Bay and elsewhere. Mount Dutton Bay I also examined the razor fish which I transplanted from Port Lincoln are thriving well.”
Journal of travel, Inspector of Oyster Fisheries	23rd Sep. 1889	“{*Mount Dutton Bay*} … I find that on some of the beds there were a fair quantity of the young Oyster brood settled since this Bay being closed. The razor fish which I placed there some time ago are progressing favourably, also the Sydney Rock Oysters which I put there they are thriving favourably.”
Annual Report of the Chief Inspector of Oyster Fisheries, 1911	May 1910	“In May, 1910, I visited Kellidie Bay, Mount Dutton, and Coffin Bays, where the beds had been closed for about 15 years. Personally conducted dredging gave encouraging results, and in reporting thereon I recommended that these old beds should be reopened. Owing to the absence of razor fish as natural "catchment" the injury done by over-dredging had not proved so destructive to other "catchments" as at Boston and Proper Bays …”

4.6.3 *Impact of* Pc. albina sugillata *on condition of* Pi. bicolor

One hundred *Pi. bicolor* were transplanted and recovered; of these samples 11 died during the course of the experiment, eight individuals from samples cleaned of *Pc. albina sugillata* (five harvested from Site 1 and three from Site 2) and three individuals from the control sample. The median value of the condition index of samples was consistent across all treatments (Figure 3) with no significant difference detected between sites or treatments (Table 3).

Wet weight of *Pc. albina sugillata* differed between experimental treatments, but not sites. A difference between the width of *Pi. bicolor* among treatments, but not sites, was also detected (Table 3) possibly reflecting a bias in the selection of individuals during harvesting, or shell morphology, which is known to vary with age and perhaps between populations (Butler et al., 1993). Although variable, median condition index of samples at each site was also not correlated with the wet weight of *Pc. albina sugillata* attached to the shell. A linear model of correlation indicated r^2 at Site 1, T1, T2 and T3, was 0.042, 0.026 and 0.003 respectively (Figure 4), and at Sites 2 and 3, r^2 = 0.028 and 0.034 respectively (Figures 5 and 6).

Table 3. Analysis of Variance of factors within the sample population and the experimental test, including the condition index for *Pi. bicolor* (* indicates significant values *p*<0.05 and ** highly significant values *p*< 0.001).

Factor	**Shell width *Pi. bicolor***		**Adductor muscle weight**		**Wet weight *Pc. albina sugillata***		**Condition index *Pi. bicolor***	
	F	*p*-value	*F*	*p*-value	*F*	*p*-value	*F*	*p*-value
Site	0.695	0.501	0.273	0.762	1.990	0.142	0.491	0.641
Treatment	3.575	0.016*	0.242	0.867	23.373	<0.0001**	1.082	0.360

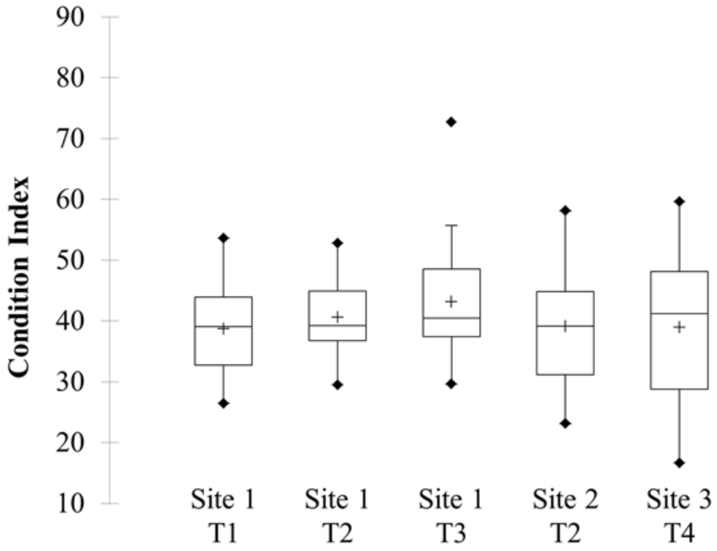

Figure 3. Box and whisker plot of median condition index of *Pi. bicolor* (+), the 1st and 3rd quartile and interquartile range, and the minimum and maximum values (◆), across all sites and all treatments.

4.6.4 Epifaunal richness and abundance

Mean values of total epifauna and total epifaunal taxonomic groups increased across categories of wet weight of *Pc. albina sugillata* (Figure 7). Samples sizes were not evenly distributed across the categories; the greatest three weight categories, from 450g onwards, were based on one record only.

A total of twenty one taxonomic groups were identified, including fauna from the phyla chordata, tunicata, echinodermata, arthropoda, mollusca, annelida, sipuncula, platyhelminthes, bryozoa, cnidaria and porifera. Several species of fish and crabs were identified and annelids, gastropods, amphipods and tanaids in particular, were the taxonomic groupings found to be most abundant within the samples (Figure 8).

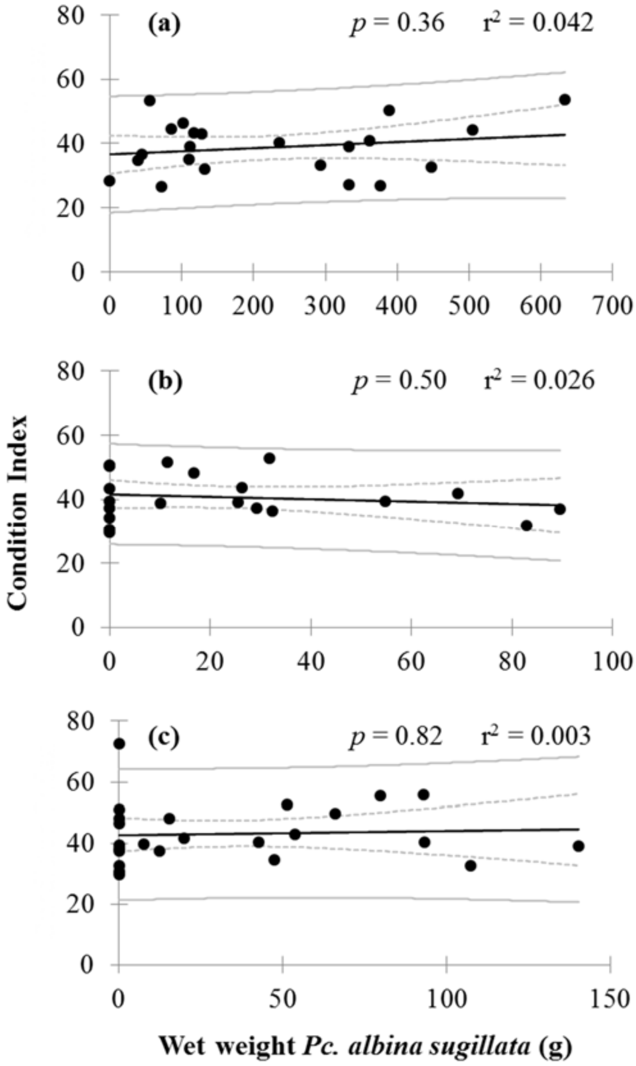

Figure 4. Correlation analysis using a linear regression model at Site 1, T1 (n = 22) (a), T2 (n = 20) (b) and T3 (n = 24) (c), and 95% confidence interval of the observations (solid line) and 95% confidence interval of the mean (dashed line).

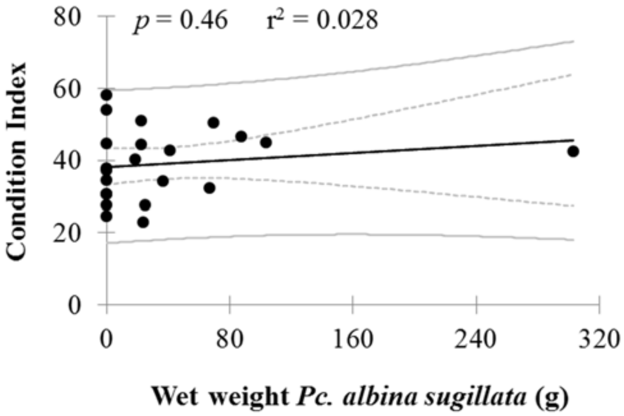

Figure 5. Correlation analysis using a linear regression model at Site 2 (n = 22) and 95% confidence interval of the observations (solid line) and 95% confidence interval of the mean (dashed line).

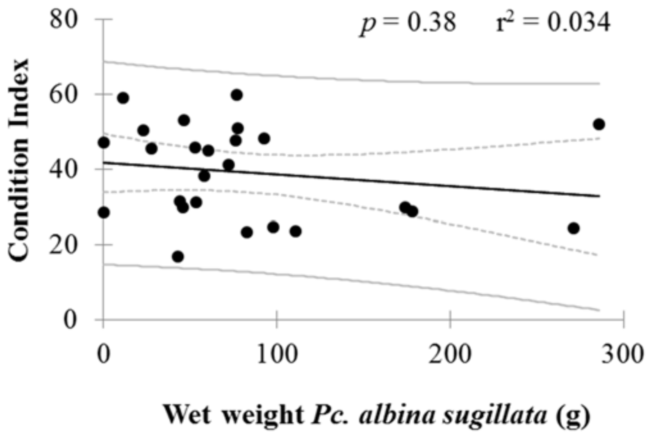

Figure 6. Correlation analysis using a linear regression model at Site 3 (n = 24) and 95% confidence interval of the observations (solid line) and 95% confidence interval of the mean (dashed line).

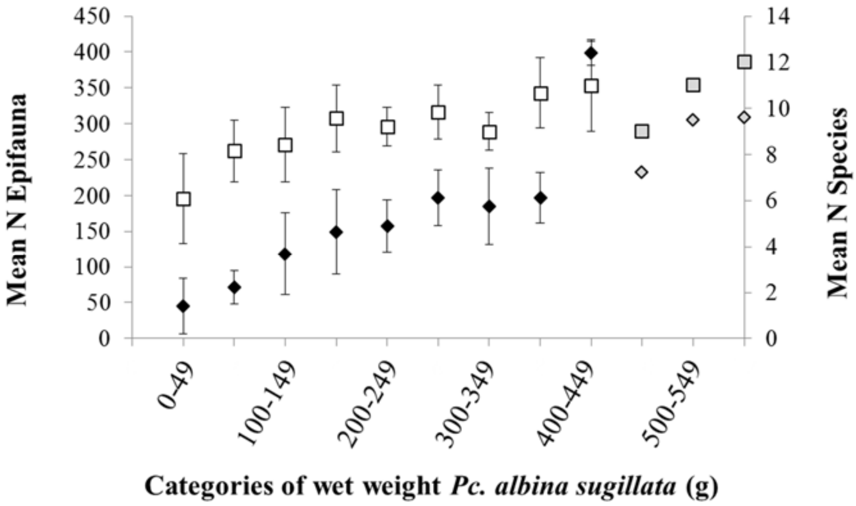

Figure 7. Mean values and standard deviation of the mean, of the total number of epifauna (□) and total number of species (♦) associated with *Pc. albina sugillata* attached to the shell of *Pi. bicolor* across increasing categories of wet weight (g). Points shaded in grey indicate values based on one sample only.

4.6.5 Revisiting community consultation and management outcomes

The results of the experimental test and the lack of a detectable effect of *Pc. albina sugillata* on the condition of *Pi. bicolor* were presented to the local community at an open forum in January 2015. Opinions of the community regarding this result differed dramatically; some participants accepted the suggestion that *Pc. albina sugillata* may not be 'wiping out' *Pi. bicolor* whilst others refused to acknowledge this position and continued to perceive a catastrophic effect of *Pc. albina sugillata* to the local and, in some cases, the broader marine ecosystem across the state of South Australia.

Management actions based on decision-making that incorporated the historical baseline were discussed with the community, these were: further research; the development of an experimental industry to identify a resource use; and education and communication to ensure containment of the population within its current range. After agreement, the Government of South Australia is now supporting the local community to pursue the development of an exploratory and developmental resource industry, and to communicate to the wider public voluntary biosecurity measures to ensure containment.

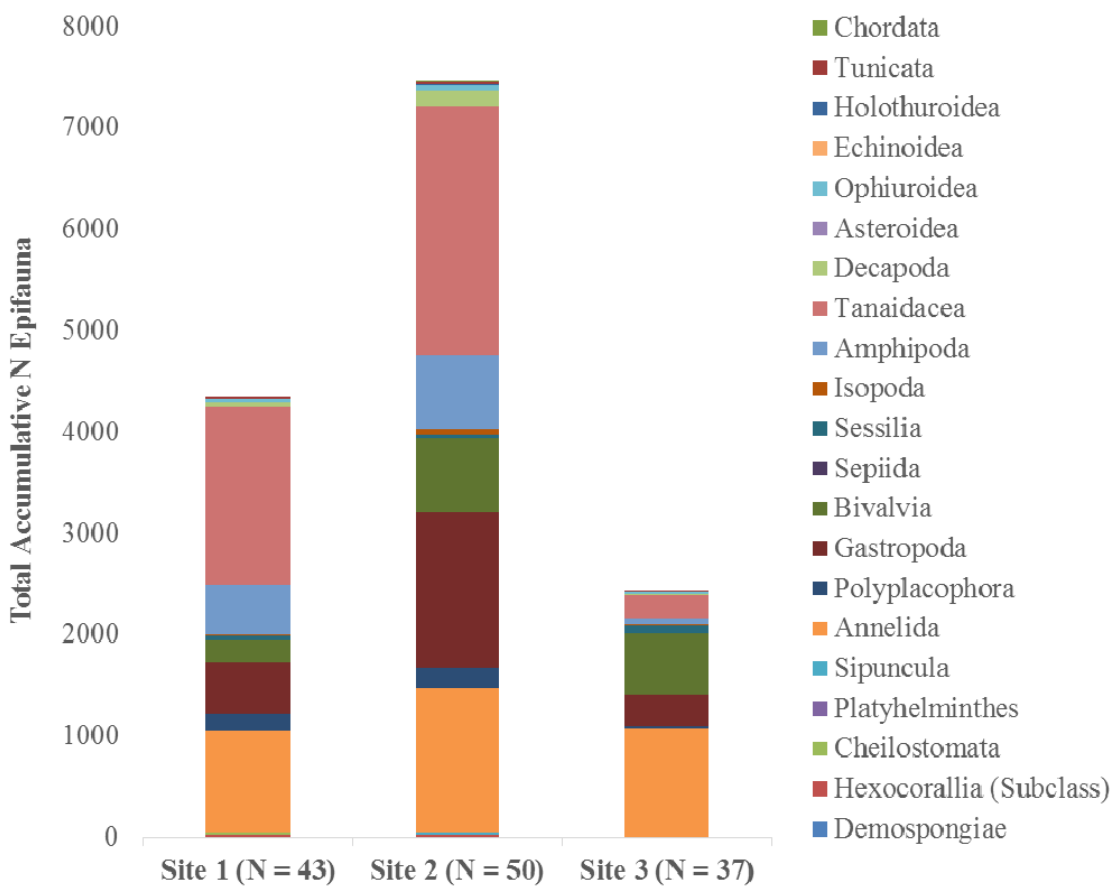

Figure 8. Total accumulative number of epifauna across all taxonomic groups identified, associated with samples of *Pc. albina sugillata* attached to the shell of *Pi. bicolor*, harvested from three sites in the upper Spencer Gulf.

4.7 Discussion

Although it was hypothesised that *Pc. albina sugillata* would have a negative effect on the condition of *Pi. bicolor*, this hypothesis was rejected. The results of this work suggest the relationship between *Pc. albina sugillata* and *Pi. bicolor* is not one of direct causality, at least not to the degree that reflects the societal concern for ‘smothering’ and ‘decimation’. Contemporary studies have shown that diverse and abundant epifauna can grow on *Pi. bicolor* (Kay and Keough, 1981, Keough, 1984). Bivalve aggregations comprising *Malleus malleus* (hammer oysters) and *Pi. bicolor* have been recorded within the upper Spencer Gulf in areas between the intertidal and 16 m depth (Shepherd, 1983, Edyvane, 1999b).

Historical studies indicate that large numbers of *O. angasi* used to attach to the shell of *Pi. bicolor* prior to their overexploitation and that the Inspector of Fisheries transplanted large quantities of live specimens from one location to another for use as hard substrate to try and re-establish failing native oyster reefs (Fisheries, 1886). Butler et al. (1993) also suggest that *Pinna* might be a relatively stress-tolerant species.

Identifying species-specific traits that reflect 'invasive' behaviors can be challenging (Sol et al., 2008). Literature and the Global Invasive Species Database do not indicate invasive populations of *Pi. albina* elsewhere, but even extreme impacts from invasive species are not always readily detectable (Simberloff et al., 2013). Consequently, the full range of ecological, economic and social impacts regarding the presence of *Pc. albina sugillata* should be considered (Simberloff et al., 2013) and the population monitored for lag effects (Essl et al., 2015), or cumulative negative impacts that could lead to a trophic cascade (Simberloff and Von Holle, 1999). Further research should also take into account potential effects on the spawning or recruitment of *Pi. bicolor*, including those that might incrementally impact the population over longer periods of time. *Pinna* have external fertilization, are sessile from settlement and are slow growing, hence, there is a reliance on proximity to other individuals and population dynamics depend on the 'storage effect', i.e. highly variable recruitment compensated for by a long adult life (Butler et al., 1993). The removal of adults from the population due to environmental effects, or fishing, could have considerable impact on the population in the upper Spencer Gulf.

Non-native species can contribute positive effects where they provide important ecosystem services to society, such as population control of other invasive species, or habitat or food for native species (Schlaepfer et al., 2011, Madin et al., 2012). *Pc. albina sugillata* in the upper Spencer Gulf forms dense aggregations and complex biogenic habitat. As indicated here, larger quantities of *Pc. albina sugillata* attached to the shell of *Pi. bicolor* can support larger amounts of epifauna, both total numbers and species diversity. These fauna, such as annelids, bivalves and tanaids, could be providing a food source to species of fish and crustacea associated with the area, including species of commercial and recreational value. The large biomass of oysters would also be providing enhanced water filtration capacity, thereby improving water quality (Kellogg et al., 2014). Both of these functions would likely have been provided historically by the presence of oyster reefs formed by *O. angasi*. These reefs are now functionally extinct and a collective inter-generational amnesia exists around their past occurrence, distribution and productivity (Beck et al., 2011, Alleway and Connell, 2015). *Pc. albina sugillata* may be providing environmental services that have been lost through the extirpation of oyster reefs in the past and, consequently, may be of ecological or conservation value (Schlaepfer et al., 2011, Davis et al., 2011).

Collective perception can shape public opinion of invasive species and public awareness of issues does not always correlate with actual ecological risk (Gozlan et al., 2013, Simberloff et al., 2013). The classification of *Pc. albina sugillata* as 'highly invasive' is being driven by societal sensitivity. The engineering behaviour of oysters in high densities would be confronting to a community that had no knowledge of or experience with this type of habitat, particularly for people who are interacting with the population regularly (there is strong opinion among recreational fishers that the species is highly invasive). This perspective may be affected by intergenerational amnesia, of the past occurrence of oyster reefs, such that the community now has a considerably lower expectation for this habitat and the productivity of the ecosystem (Alleway and Connell, 2015). Where communities have lower expectations it is possible they will have difficulty reconciling whether a species is invasive or a function of broadscale ecological change (Sol et al., 2008) or show resistance to the positive benefits that introduced species might bring (Walther et al., 2009, Davis et al., 2011).

The influence of the shifting baseline syndrome in invasion ecology is not widely studied, but offers a more comprehensive understanding of changing balances between species loss and addition. Historical ecological research, which has emerged as a field that explicitly seeks to understand past ecological states and the interaction of humans with the environment assists our interpretation of species-specific invasion ecologies (Jackson, 2001, Willis and Birks, 2006). Invasive species have contributed to ecological change over a very long period of time (Willis and Birks, 2006, Carlton, 2009) and the continued preoccupation with contemporary change as the time-frame for managing invasive species is inconsistent with the drivers of their occurrence, establishment and impact. Historical records could, therefore, be used to redress our understanding of cryptogenic and invasive species, particularly where there is little information about the initial stages of the species' establishment. Because invasive species could contribute to ecological functions that have been lost to history, as well as new opportunities (Walther et al., 2009, Schlaepfer et al., 2011, Madin et al., 2012), historical ecology would assist scientists, managers and society to perceive and coexist with non-native species.

Structured, transparent and participatory decision-making could also support clearer definition of the behaviours and impacts that establish whether a species is invasive (Estévez et al., 2014). The decision-making model developed here illustrates divergent management outcomes with and without consideration of a historical baseline. Based on the societal concern, and the political action achieved, initial discussions regarding management actions considered eradication using a biological control agent; an extreme measure for marine environments. Once the historical baseline was recovered consideration of management changed to focus on resource use, with education and communication to seek containment. This outcome suggests that shifting baselines could be used more extensively to inform the ecological context of invading species and options for their management. Certainly, management decisions based on perception alone are insufficient to address issues associated with invasive species (Pauly, 1995, Gozlan et al., 2013, Clavero, 2014). As changing climate will increasingly result in new instances of range expansion or introductions, it may well be worth contemplating the ecological services of range changing or dispersing non-natives and whether their coexistence with a more historically and ecologically informed society is possible.

Chapter 5: Loss of an ecological baseline through the eradication of oyster reefs from coastal ecosystems and human memory

5.1 Preface

Oyster reefs have been extirpated from many regions of the world. This loss has contributed to associated declines in productivity, of oysters and reef associated fish species, complex hard substrate and biological capacity for water filtration. Despite their widespread deterioration and associated loss of valuable ecosystem services, oyster reefs in many locations are given little consideration. This chapter uses archival fisheries records to reconstruct a shifted ecological and cognitive baseline for oyster reefs formed by *Ostrea angasi*. The reconstructed baseline illustrates that intergenerational amnesia can occur and that the shifting baselines syndrome might reduce our expectations for contemporary ecosystems. This chapter has been published in *Conservation Biology* and is reprinted here with permission from John Wiley & Sons (Appendix B). The original manuscript can be sourced from the publishers website:
http://onlinelibrary.wiley.com/doi/10.1111/cobi.12452/abstract.

5.2 Statement of authorship

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Principal Author

Name of Principal Author (Candidate)	Heidi K. Alleway		
Contribution to the Paper	Conceptualised and designed the research, collated and analysed the data, interpreted the results and wrote and edited the manuscript.		
Overall percentage (%)	80%		
Signature		Date	24/07/2015

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

x. the candidate's stated contribution to the publication is accurate (as detailed above);

xi. permission is granted for the candidate in include the publication in the thesis; and

xii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Sean D. Connell		
Contribution to the Paper	Assisted with the design of the research and analyses, the interpretation of results and writing and editing the manuscript.		
Signature		Date	15/07/2015

Conservation Biology

Contributed Paper

Loss of an ecological baseline through the eradication of oyster reefs from coastal ecosystems and human memory

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Abstract: *Oyster reefs form over extensive areas and the diversity and productivity of sheltered coasts depend on them. Due to the relatively recent population growth of coastal settlements in Australia, we were able to evaluate the collapse and extirpation of native oyster reefs* (Ostrea angasi) *over the course of a commercial fishery. We used historical records to quantify commercial catch of* O. angasi *in southern Australia from early colonization, around 1836, to some of the last recorded catches in 1944 and used our estimates of catch and effort to map their past distribution and assess oyster abundance over 180 years. Significant declines in catch and effort occurred from 1886 to 1946 and no native oyster reefs occur today, but historically oyster reefs extended across more than 1,500 km of coastline. That oyster reefs were characteristic of much of the coastline of South Australia from 1836 to 1910 appears not to be known because there is no contemporary consideration of their ecological and economic value. Based on the concept of a shifted baseline, we consider this contemporary state to reflect a collective, intergenerational amnesia. Our model of generational amnesia accounts for differences in intergenerational expectations of food, economic value, and ecosystem services of nearshore areas. An ecological system that once surrounded much of the coast and possibly the past presence of oyster reefs altogether may be forgotten and could not only undermine progress towards their recovery, but also reduce our expectations of these coastal ecosystems.*

Keywords: ecosystem collapse, historical ecology, historical fishing, *Ostrea angasi*, shifted baseline

La Pérdida de una Línea de Base Ecológica por Medio de la Erradicación de Arrecifes de Ostión de los Ecosistemas Costeros y la Memoria Humana

Resumen: *Los arrecifes de ostión se forman a lo largo de áreas extensas y tanto la diversidad y como la productividad de las costas resguardadas dependen de ellos. Debido al incremento relativamente reciente del crecimiento poblacional en Australia, pudimos evaluar el colapso y la extirpación de arrecifes del ostión nativo* Ostrea angasi *durante el desarrollo de una pesquería comercial. Usamos registros históricos para cuantificar la captura comercial de* O. angasi *en el sur de Australia desde la colonización temprana, aproximadamente 1836, hasta algunas de las últimas capturas registradas en 1944. Usamos nuestras estimaciones de captura y esfuerzo para mapear su distribución anterior y evaluar la abundancia de los ostiones a lo largo de 180 años. De 1886 hasta 1946 ocurrieron declinaciones significativas en la captura y el esfuerzo y en la actualidad no existen arrecifes de ostión nativo, pero estos se extendían históricamente a lo largo de más de 1, 500 km de línea costera. Parece no ser conocido que estos arrecifes fueron característicos de la mayor parte de la línea costera del sur de Australia de 1836 hasta 1910 porque no hay una consideración contemporánea de su valor ecológico y económico. Con base en el concepto de una línea de base modificada, consideramos que este estado contemporáneo refleja una amnesia inter-generacional y colectiva. Nuestro modelo de una amnesia generacional representa diferencias en las expectativas inter-generacionales de alimento, valor económico y servicios ambientales de áreas cercanas a la costa. Que un sistema ecológico que alguna vez rodeó una gran parte de la costa y posiblemente la presencia anterior de arrecifes de ostión probablemente estén olvidados,*

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en conjunto puede no solamente debilitar el progreso hacia la recuperación, sino también reducir nuestras expectativas de estos sistemas costeros.

Palabras Clave: colapso ambiental, ecología histórica, línea base modificada, pesca histórica, *Ostrea angasi*

Introduction

Oyster reefs have been extirpated from estuarine, coastal, and nearshore environments, primarily due to over extraction for food and disease and water pollution, to the extent that 85% of reefs have been lost worldwide (Lotze et al. 2006; Ogburn et al. 2007; Beck et al. 2011). The extraordinary scale of this loss was assisted by the use of dredging, an efficient fishing method that increased accessibility to and the value of oysters and stimulated increased extraction (Kirby 2004; Lotze et al. 2006). Degradation of oyster reefs has contributed to fundamental changes in ecosystem function, including the loss of filtering capacity of water, which predated impacts of eutrophication (Jackson et al. 2001; Zu Ermgassen et al. 2013), and the loss of complex hard substratum, which is a limited resource along many coasts dominated by soft sediment (Lenihan 1999; Beck et al. 2011). Ensuing declines in diversity and abundances of reef associated species, including recreationally and commercially important fish species, have been substantial (Cranfield et al. 2001; Airoldi et al. 2008), as has the rapid rise in coastal water quality problems (Lotze et al. 2006).

Globally, recognized losses include those of the eastern oyster (*Crassostrea virginica*) that occurs along the eastern coast of North America, in particular Chesapeake Bay and the Hudson River (Rothschild et al. 1994; Zu Ermgassen et al. 2012). The European flat oyster (*Ostrea edulis*) was once widely distributed along the Atlantic coasts, but it declined significantly during the 19th and 20th centuries (Airoldi & Beck 2007; Thurstan et al. 2013). Considerable investment is now being made in the restoration of these depleted species. Research and debate about the efficacy and requirements for restoration (Laing et al. 2006; Mann & Powell 2007; Schulte et al. 2009) have resulted in a comprehensive understanding of the dynamics and function of oyster reef oyster reefs, the value of the habitat they provide in coastal and estuarine systems, and the processes required for restoration. Programs to reestablish these reefs are in place in North America (Baggett et al. 2014) and are being investigated in Europe (Laing et al. 2006). In contrast to these efforts, discussion regarding oyster reef restoration in the southern hemisphere is limited (Cranfield et al. 2001) or nonexistent, despite loss of *Ostrea chilensis* in New Zealand and Chile and localized collapses of *Ostrea angasi* in temperate marine Australia (Ogburn et al. 2007; Beck et al. 2009; Beck et al. 2011). Natural resource decisions based on the most recent memories of biologists and managers can result in misleading management targets and contribute to continued degradation through the existence of shifting baselines (Pauly 1995; Dayton et al. 1998). Accordingly, the need to accurately quantify historical baselines and past losses is recognized (Lotze et al. 2006; Airoldi & Beck 2007).

Ubiquitous to temperate regions of the world, oyster reefs have for millennia sustained substantial marine ecosystems and economies. Because they are widespread, diverse, and abundant, Ostreidae oysters form an important part of coastal ecosystems as living and dead material. In southern Australia, *Ostrea* spp. reefs are geological formations (Pufahl & James 2006; Miranda et al. 2008), and *O. angasi*, which occurs as individuals along the sheltered temperate coastline of Australia (Dayton et al. 1989; Gowlett-Holmes 2008), is a principal component of consolidated and calcrete shell beds offshore (Shepherd & Sprigg 1976; Cann et al. 1988; Edgar & Samson 2004). Adults are free living, but spat, spawned from midspring through summer, requires a hard surface for settlement and growth (Grove-Jones 1986). Aboriginals consumed *O. angasi*, and remains can be found in shell middens along the coastline (Radford & Campbell 1982; Godfrey 1989). Living reefs were recorded during early explorations of Australia (Peron 1816), and in the 19th and 20th centuries the species supported commercial fisheries in southern states (Grove-Jones 1986; Edgar & Samson 2004). Overfishing and disease resulted in their eventual decline (Grove-Jones 1986; Ogburn et al. 2007).

We hypothesized that whilst oyster reefs are virtually absent today in southern Australia, they once characterized sheltered nearshore areas. We derived this hypothesis from a model of amnesia, through which biologists and managers have partly or wholly forgotten the once widespread occurrence of oyster reefs. This model of generational amnesia (Pauly 1995; Dayton et al. 1998; Papworth et al. 2009) seeks to account for differences in intergenerational expectations of food, economic value, and ecosystem services of nearshore areas. We evaluated the past distribution and extent of oyster reefs in South Australia by quantifying historical commercial fishery catches and reconstructing a profile of the past distribution and abundance of *O. angasi*. Although the species' history could also be considered through paleobiology and archaeology (Rick & Lockwood 2012), we intentionally used historical ecological records that were relevant to human activities and economies of the 1800s and 1900s. This source has not been examined and reflects a period of intense ecological change which provides the opportunity to understand the post-1800 interaction of humans with this species (Szabó & Hédl 2011).

Methods

We searched and recovered historical references relating to *O. angasi* within the state of South Australia. Our primary historical references included reports from the chief inspector of fisheries (e.g., Randall 1911; McIntosh 1913) and diaries and correspondence of fisheries inspectors (Inspector of Oyster Fisheries 1886; Inspector of Oyster Fisheries 1892). Secondary references were also reviewed (e.g., Wallace-Carter 1987) (information on references in Supporting Information).

Individual records (anecdotes or statements) were transcribed from these references and coded by date, bioregion, location, and age. Records of catch (numerical and qualitative), and quantity were coded (absent, 0; rare, 1; uncommon, 2; common, 3; abundant, 4; extremely abundant) when they occurred as were records of fishing effort, catch rates, the number of persons or boats engaged in the fishery, and catch per unit effort. Quantities of catch and effort within the fishery (number of licensed boats and men) were assessed across time and tested for a model of simple linear regression and significance of the fit. All locations with records of fishing or payable beds (i.e., beds and fishing in named bays and near coastal townships, headlands, or geographical features) were mapped.

Proxies and phases of fisheries management provide a means to assess past changes or phenomenon that can no longer be quantified, as previously demonstrated through the historical loss of oyster reefs (Kirby 2004; White et al. 2009). We summarized changes in the South Australian fishery, taking into account the proxies described by Kirby (2004); that is, the date of implementation of regulations to manage the fishery, the beginning of importation of oysters to restock locations, and the earliest evidence for bottom dredging. Records describing environmental variables were collated, for example the influence of rainfall or seasonal growth of weed or interactions between *O. angasi* and other species.

Coding qualitative records to calculate perceived abundance has been used when quantitative surveys were not available (e.g., Fortibuoni et al. 2010; Al-Abdulrazzak et al. 2012). We coded all records that referred to the abundance of oysters on a scale of 0 (absent) to 5 (extremely abundant) (sensu Pandolfi et al. 2003) (examples of coding in Supporting Information) and calculated the mode of all values per annum. The modal value, being the most frequent record of abundance and most likely ecological state of the region at that time, was used to estimate oyster abundance in 2 marine bioregions and evaluate change over time.

Results

Past and Present of the Fishery

Beginning "in the early days of the colony" (c. 1836), *O. angasi* were commercially fished in South Australia for more than 100 years. As many as 30 sailing cutters (a secondary reference indicates there might have been 50 [Wallace-Carter 1987]) formed a fishing fleet that traveled large distances, often as a group (Fig. 1a). A dredge, consisting of an iron bar and mesh bag (Fig. 1b), was used throughout the term of the fishery. A cutter would drag multiple dredges back and forth across a bed and all material in the bag was brought on board, where live oysters were separated from bycatch. Beds were actively "worked down" (i.e., fished until the catch was low or nil), after which fishers would move on to other locations (Table 1).

Regulations governing oyster fishing formed South Australia's first fisheries legislation and came into effect in 1853, 4 years before the state attained its own government (Fig. 1c). Further legislation was enacted in 1873 to introduce minimum size limits, a closed season for young from September to November, closure of areas as deemed necessary, and penalties for depositing "injurious matter" on a bed, including matter dredged from that bed (Governor 1873). In 1885 a licensing system and exclusive rights to newly found beds was also introduced. These acts indicate the government was sufficiently concerned about the state of oyster beds and that declines in stock were likely noticeable (Table 1) (Inspector of Oyster Fisheries 1886; Kirby 2004).

Presently, recreational and commercial fishing of *O. angasi* is permitted, although there has not been a recent commercial catch (Knight & Tsolos 2012). Commercial oyster fishing is restricted through licensing, but spatial or seasonal closures are not prescribed. The species is also not the subject of legislation, policy, or management for conservation, protection, or recovery.

Catch and Effort

Total catch for the state of South Australia was recorded by the inspector for several non-contiguous periods from 1886 to 1944. Catch was 2342 bags in 1886 and reached a peak of 3549 bags in 1890 before declining to <1000 bags/annum from 1910 onwards (Fig. 2a; $R^2 = 0.673$, $p = 0.000$). The last catch reported was 139 bags in 1944. Gaps in the time series from 1891 to 1909 and 1915 to 1936 were the result of a lack of reporting, and fishing was recorded as occurring during this time. Fishery-wide effort declined from at least 27 boats and 48 men in 1887 to 8 boats and 14 men in 1914 (Fig. 2b; boats $R^2 = 0.594$, $p = 0.015$; men $R^2 = 0.832$, $p = 0.002$). After 1944 the oyster industry in South Australia turned to aquaculture of the introduced species *Crassostrea gigas* (Pacific oyster)

(c) Timeline of fishery development:

- **1836** Colonization of South Australia
- **1853** First introduction of legislation, to permit the "laying down" of oysters where beds did not occur
- **1873** Legislation to "prevent the wanton destruction of oysters" (fishery closures, minimum size, the deposit of "injurious matter" on a bed)
- **1881** Appointment of first inspector of oyster fisheries
- **1885** Legislation to "promote the breeding of oysters and regulate the fishery" (licensing)
- **1890** Highest recorded catch of 3,549 bags
- **1895** Inspector recommended "all further dredging on known deposits must be suspended to enable the beds to be restocked by spawn"
- **1911** Inspector reports on the failure of the industry, "attributable chiefly to uncontrolled overworking"
- **1912** Establishment of the first National Oyster Reserve and Nursery
- **1932** First wastewater treatment system built in Adelaide
- **1944** No men engaged full time in oyster fishing
- **1970** *Crassostrea gigas* aquaculture begun

Figure 1. Historical photographs and timeline of fishery development: (a) part of the South Australian oyster fishing fleet circa 1910 (State Library of South Australia, B32440), (b) dredge and tools used to catch O. angasi *circa 1909 (State Library of South Australia, B54098), and (c) key developments of the fishery over time.*

(Fig. 1c), but interest and investigation into aquaculture of the native species has recently increased (Heasman et al. 2004; Hurwood et al. 2005; O'Connor & Dove 2009).

Historical catch quantities may be underrepresented because returns were made voluntarily and represent what was reported to the inspector (Randall 1912). We found isolated records of catches from specific locations that indicated high catch quantities prior to 1886. These figures were not included in the assessment of total catch because they were location specific and total catch could not be reliably reconstructed. Examples include Coffin Bay on the Eyre Peninsula, where in 1870 the catch was 23 bags/day/boat by an unknown number of boats and from 1872 to 1874 >16,000 bags were caught, and Kellidie Bay, Eyre Peninsula, where from December 1886 to June 1887 in an embayment of <17 km^2 22 cutters dredged continuously catching 2308 bags (Supporting Information).

Past Distribution of Oyster Reefs

We recorded fishing, or the presence of payable beds, across more than 1500 km of coastline (Fig. 3a). Fishing occurred at 67 locations (Supporting Information), including in several of the "West Coast Bays," where oysters were "plentiful" and "thickly distributed" (Inspector of Oyster Fisheries 1892). The building of a small preserving works at Streaky Bay in the 1870s (Wallace-Carter 1987) implies oysters would have been sufficiently abundant to support the industry. The Eyre Peninsula was a primary area for the *O. angasi* fishery and after regular steamship communication was established in the mid- to late-1800s between this region and the state's capital, Adelaide, large catch quantities of oysters were recorded (Table 1). Fishing was also recorded north of Port Lincoln along the west and east coasts of Spencer Gulf and in the vicinity of the offshore islands of the Sir Joseph Banks Group. The importance of this area is reflected in *O. angasi* now being commonly referred to as the Port Lincoln oyster.

In the South Australian State Archives, we found a map of a proposed closure, indicating that oyster reefs were probably widely distributed within St. Vincent Gulf and that our profile of distribution may be underrepresented. The map, from 1889, requested a fishery closure of approximately one-third of the gulf for 2 years and the opening of an equal sized area for the same time (Fig. 3b).

Table 1. Examples of historical records of fishing, decline, and associated environmental changes on oyster reefs in South Australia.

Topic	*Record*	*Reference*
Working down of beds	"I proceeded and examined the Louth Bay Oyster Beds; here six cutters were working, but doing little business as the beds are worked down to about a bag and a half each per day . . . "	Inspector of Oyster Fisheries (1886)
Decline	" . . . our once prolific oyster beds are every year becoming less reproductive and it is my firm conviction that nothing but decisive measures can cope with the difficulty under which our oyster beds and cutters at present labour, the continual dredging and redredging by large number of boats . . . if we are to conserve existing oyster beds and extend the industry, all further dredging on known deposits must be suspended to enable the beds to be restocked by spawn from properly matured oysters."	Inspector of Oyster Fisheries (1892)
Sequential expansion	"In the early days of the colony the Oyster supply was obtained from the Eastern shores of Yorke Peninsula and the dredging there was continued for years, crossing and recrossing over the same beds constantly without hinderance, protection or regulation of any kind, so much so that the beds were never allowed to rest, and the result was that Oyster beds were completely depopulated of all power of reproduction to such an extent that for nearly 20 years there were hardly any oysters to be obtained, where previously there was abundance, when the supply ceased on Yorke Peninsula then the Bays in the neighbourhood of Port Lincoln were resorted to, where there was an ample supply of splendid Oysters obtained from fine natural beds covering a large area both in deep and shallow waters, chiefly Port Lincoln proper and Boston Bay."	Inspector of Oyster Fisheries (1886)
Abundance	"I was engaged Oyster dredging myself at the time referred to and it was no uncommon thing for two men in one boat to raise 23 bags Oyster in one day . . . no less than 16,000 bags oysters were dredged during the years 1872, 1873 and 1874."	Inspector of Oyster Fisheries (1886)
Overexploitation	"The causes leading to the vanishment of what was at one time a flourishing industry were believed to be attributable chiefly to uncontrolled over-working, by which the beds had not only become depleted, but the natural "catchment" on which the spat is collected, consisting chiefly of razorfish, had been destroyed."	Randall (1911)
Settlement and translocation of native bivalves	"I may add that the razorfish which I have transplanted from Port Lincoln waters to Coffins Bay about 15 month since, are thriving very favourably, the young fish are to be seen spreading through all parts of the Bays, I trust that this will be the means of reviving the decayed beds in Coffins Bay and form a new foundation for the Oyster spat to adhere to."	Inspector of Oyster Fisheries (1886)
Impact of dredging	"I would point out that dredging is always accompanied by a large amount of unavoidable destruction to young oysters and oyster brood, and taking more than the market requirements from the natural beds simply means ruin . . . "	Inspector of Oyster Fisheries (1892)

Records indicated that large quantities of oysters were caught within the St. Vincent Gulf, and in the early days of the colony (approximately 1836–1870) markets in Adelaide were supplied from extensive beds along the Yorke Peninsula and the north coast of Kangaroo Island (Randall 1911; McIntosh 1913). Records of early overfishing in the region were identified, and beds along the eastern shore of Yorke Peninsula were referred to as prolific until about 1855, after which a decrease in harvest and the number of oysters on the beds was reported (Table 1).

Estimated Abundance of Oysters

Estimated abundance of oysters for all age classes at locations on the Eyre Peninsula ($n = 174$) was 5 in 1836 and 2 in 1938 (Fig. 4). Estimated abundance within St. Vincent Gulf ($n = 113$) was 4 in 1836 and 2 in 1925 (Fig. 4). Abundance of spat and young was estimated as 4 and 5 from 1888 to 1895, which may have reflected recovery of previously fished beds within the St. Vincent Gulf after fishing moved to the Eyre Peninsula (Inspector of Oyster Fisheries 1892).

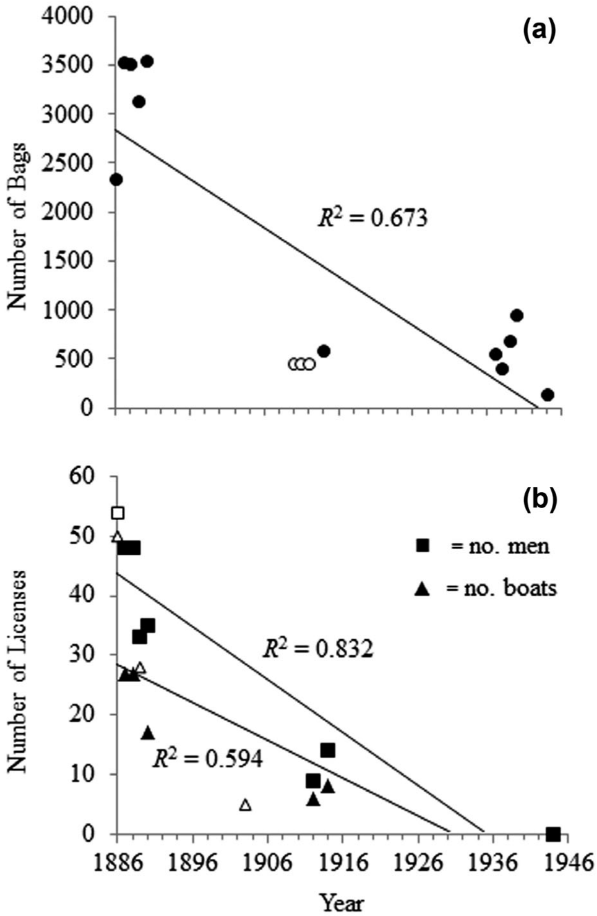

Figure 2. Historical statewide (a) total number of bags of oysters (approximately 350 oysters per bag) and (b) number of licenses (as a measure of effort) in the South Australian O. angasi *fishery from 1886 to 1946 (open symbols, values retrieved from secondary references only).*

Declines in estimated oyster abundance were supported by records of actual declines, which we identified through the diaries and correspondence of the inspector. For example, it was reported in 1895 that the "once prolific beds" were every year becoming less productive and the inspector stated that "nothing but decisive measures" were required, including the suspension of all further dredging until the oysters could sufficiently recover (Table 1; Supporting Information).

Environmental and Ecological Records

We found no quantitative historical data on oyster distribution, but we summarized the qualitative records to determine something of the ecology of oyster reefs, their associated species, and the influence of environmental factors and dredging on population numbers and reef formation (records in Supporting Information). There was no evidence of population decline resulting from pests or diseases, such as bonamiasis and *Polydora* spp. (Ogburn et al. 2007). Records referenced the lack of both pest issues in South Australia and a perceived resistance of *O. angasi* to *Polydora* spp.

Rainfall was recorded as promoting spawning and the recruitment and growth of spat. It was thought that runoff provided food, and "starvation" of oysters was reported during years of low rainfall. A lack of rainfall in 1914 was recorded as greatly affecting the work to recover beds in Port Lincoln. *Cladophora* spp. was recorded as "blanketing" beds in summer and dying back in winter.

Between 1885 and 1887, the inspector introduced a non-native oyster, *Saccostrea glomerata* (Sydney rock oyster), in an effort to establish an alternative oyster stock. During the early 1900s reestablishment of native populations was tried through the translocation of *Pinna bicolor* (razor fish) across parts of the coastline. This species could be found with upwards of 50 native oysters attached to its shell and the Inspector repeatedly transferred hundreds of individuals to locations where they did not naturally occur to provide hard substrate for the settlement of spat (Table 1). In 1912, the inspector established the National Oyster Reserve and Nursery in Proper Bay, Port Lincoln (Fig. 1c), and laid out artificial hard substrate, including tree boughs, iron pots, pans, and tins to seed oysters (Supporting Information). Juveniles were then translocated to other parts of the state.

The impact of dredging was known and recorded particularly in reference to its non-selectivity, its impact on young oysters, the breaking up and removal of hard substrate (Table 1), as well as the potential long term siltation and smothering of reefs (Supporting Information) (Shepherd 1986). Dredging also affected *P. bicolor*, decreasing its abundance, but this species was reported to have increased in numbers in some areas after the areas were closed to fishing (Inspector of Oyster Fisheries 1892).

Discussion

The decline in catch from 1890 to 1910 signals the collapse of the oyster fishery in South Australia. Historical accounts, the implementation of legislation in the mid and late 19th century, and patterns of perceived abundance suggest, however, that regional declines in oyster abundance were noticeable prior to the collection of these catch records. The southern Australian fishery traveled and dredged as a fleet, sometimes in groups of 10–20 boats, at different sites across the state, where beds were then worked down before the fleet moved on to another location (Inspector of Oyster Fisheries 1886; Inspector of Oyster Fisheries 1892). This is consistent with the sequential expansion and exploitation of fisheries elsewhere (Kirby 2004) and, at a reduced spatial scale, the practice of roving exploitation (Berkes

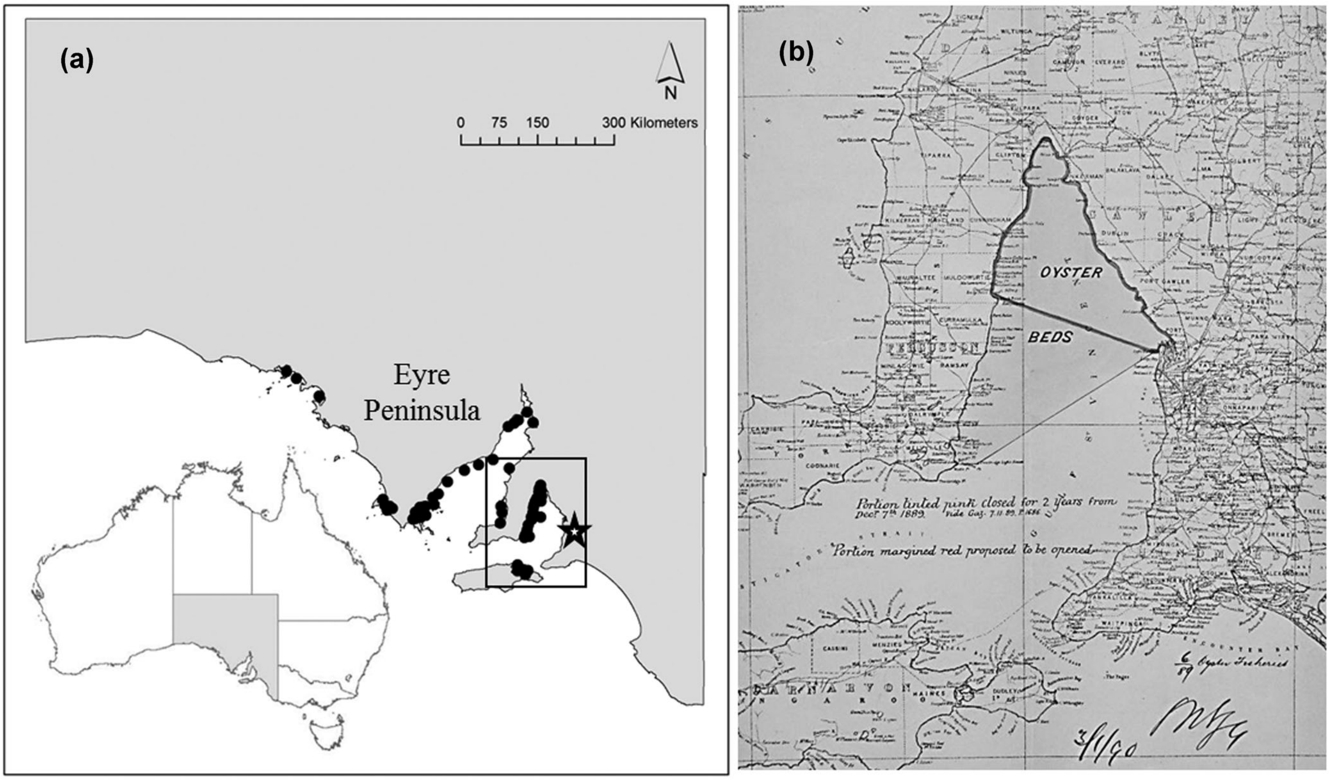

Figure 3. (a) Historical distribution of oyster reefs in South Australia that no longer exist (solid circles), interpreted from records with reference to historical fishing or the presence of "payable beds" (star, location of Adelaide; square, the area outlined in [b]) and (b) a map of St. Vincent Gulf in 1889 showing a proposed area of oyster fishing closure (solid bold outline) and an area to be opened to fishing (triangular-shaped area below the proposed closed area).

et al. 2006). Dredging removed hard substrate, which contributed to siltation and the failure of larvae to recruit such that overexploitation was the driver of the eradication of oyster reefs (Randall 1911). Changes due to land use, including water pollution, have contributed to the decline of oyster populations in other areas (Lotze et al. 2006; White et al. 2009). It is possible that these impacts occurred in South Australia, but the local spatial scale of catchment-based impacts cannot account for the larger scale of degradation and declines in oyster numbers that occurred prior to major catchment changes.

The eradication of reefs is similar to losses in other areas (Airoldi & Beck 2007; Zu Ermgassen et al. 2012; Thurstan et al. 2013). Oyster fishing in South Australia began in the early days of the colony, around 1836, and formed the state's first commercial fishery, illustrating that oysters are vulnerable to cases of historical overexploitation because they are accessible (Kirby 2004; Lotze et al. 2006). The timing of legislation indicates the importance of oysters to the colony. The first act to encourage development of the oyster fishery was gazetted in 1853, 4 years before South Australia attained a state parliament. Subsequent legislation in 1873 introduced a minimum legal size, closed seasons, and protected areas. For this legislation to have been necessary, declines in abundance were likely noticeable (Inspector of Oyster Fisheries 1892; Kirby 2004). This act also introduced penalties for dumping bycatch onto reefs, including "ballast, sand, mud, refuse, or injurious matter of any nature whatsoever," even when this material was removed from that same bed (Governor 1873). Hard substrate is necessary to the perpetuation of reefs through time (Mann & Powell 2007), and it is possible that the removal of excess material from the reef area contributed to their degradation.

Commercial oyster fisheries occurred concurrently across the southern coastline of Australia, and our profile represents only a portion of this activity (Grove-Jones 1986; Edgar & Samson 2004). The geological and archaeological presence of oysters has not been quantified in our study area (Szabó & Hédl 2011; Rick & Lockwood 2012), although *O. angasi* has been identified in Aboriginal shell middens at other locations (Radford & Campbell 1982; Godfrey 1989). Combined with the potential underrepresentation of catch statistics because of voluntary reporting (Randall 1912), although under reporting may not have occurred consistently and in some years comparatively more oysters may have been reported, our profile likely understates the overall scale of loss of reefs across space and time.

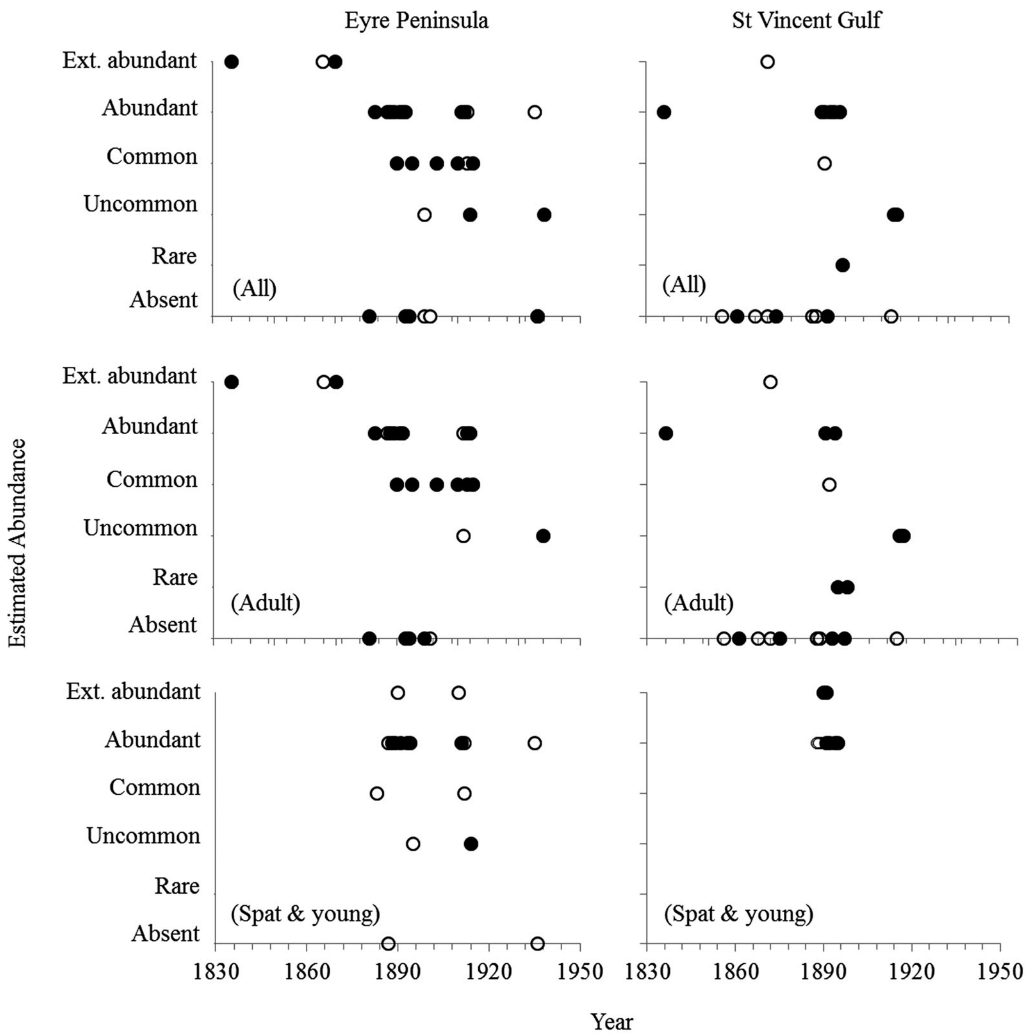

Figure 4. Estimated abundance of all O. angasi*, of adults, and of spat and young on the Eyre Peninsula (n = 174) and within St. Vincent Gulf (n = 113), South Australia, based on calculations of annual perceived abundance from 1830 to 1950 (closed circles, modal value of all records per year; open circles, values based on a single record of abundance for that year).*

Although oyster reefs formed by *O. angasi* were previously widely distributed in southern Australia, to date there has been a focus on reporting historical oyster fishing and the loss of oyster reefs from only a small number of locations (i.e., greater Coffin Bay, the area surrounding Port Lincoln, and Stansbury on the Yorke Peninsula) (e.g., Grove-Jones 1986; Hone 1993; Olsen 1994). Fishing was not limited to these locations, and we found that oyster reefs were present in the past across more than 1500 km of coastline. Recent quantitative surveys of the distribution and abundance of fauna encompassing these locations detected only individuals, not aggregations (e.g., Shepherd 1983; Tanner 2005). These locations are now predominantly areas of sand and mud. In some areas, algae and seagrass predominate (Grove-Jones 1986), and in other areas the benthos lacks large macrofauna and flora (Tanner 2005).

Early attempts, over 100 years ago, to prevent the collapse of native oyster reefs through protected areas were not realized, and no reefs are known to exist today. We believe the loss of reefs in southern Australia represents one of the more substantial losses of an ecologically important and widespread ecosystem because these reefs would have supported the productivity of associated fishes, stabilized soft sediment, and helped maintain water quality (Lenihan 1999; Jackson et al. 2001; Lotze et al. 2006). Decreases in the diversity of species associated with oyster reefs have been attributed to loss of habitat (Airoldi et al. 2008), as have declines in the density and productivity of commercially important fish species (Cranfield et al. 2001; Peterson et al. 2003).

As filter feeders, oysters play a disproportionately large role in maintaining coastal water quality (Officer et al. 1982; Ulanowicz & Tuttle 1992). The degradation of coastal water quality has contributed to substantial ecological (Connell et al. 2008) and economic costs in localities like South Australia (Fernandes et al. 2009), and it is possible that the loss of oyster reefs has compounded these costs. Seagrasses and kelp forests in South Australia have declined by 60–70% from their original state at a cost of AUD$67.1 million (Connell et al. 2008; Hatton MacDonald et al. 2014). To readdress this loss, the government spends more than AU$100 million/annum to improve the quality of water discharged from its wastewater treatment plants (South Australian Water Corporation 2013). For many locations, including Australia, the feasibility of improving coastal water quality through restoring oyster populations is unknown. The cost of programs in the United States for such purposes are substantial (Zu Ermgassen et al. 2013; Baggett et al. 2014) and the success uncertain (Mann & Powell 2007).

Amnesia represents a state in which there has partly or wholly been a loss of human memory. We suggest that the 180 years that have lapsed since fishing for *O. angasi* began and a lack of data (Papworth et al. 2009) has contributed to a collective amnesia regarding this species' past distribution, abundance and reefs. The current lack of consideration of this species represents a striking contrast to the attention it was paid historically. Despite repeated introduction of legislation during the mid- to late-1800s, for protected areas, minimum size limits, and restoration, current legislation relates only to the licensing of commercial fishing. By recalling the former extensiveness of oyster reefs, a shifting baseline can also be recovered (Pauly 1995; Dayton et al. 1998). Recovering a past baseline will improve the perception and expectations for oyster reefs and create a more accurate model for setting conservation targets (Papworth et al. 2009). Our model of generational amnesia accounts for differences in intergenerational expectations of ecosystems and the food, economic value, and ecosystem services they provide. Such amnesia may undermine progress toward restoration of ecosystems because researchers, managers, and the public may have reduced expectations of an ecosystem's potential. Our results highlight that the baseline for oyster reefs in southern Australia needs to be corrected. If it is not, it may be forgotten that oyster reefs once characterized the coastline or that they were present at all.

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Supporting Information

A historical reference list (Appendix S1), codes for abundance (Appendix S2), fishery timeline (Appendix S3), catch estimates (Appendix S4), list of locations (Appendix S5), example records (Appendix S6), and map of the National Oyster Reserve 1889 (Appendix S7) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than the absence of material) should be directed to the corresponding author.

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Supporting Information

Loss of an ecological baseline through the eradication of oyster reefs from coastal ecosystems and human memory

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Appendix S1. List of the historical references used to evaluate the past distribution, abundance and fishery for the mud oyster *Ostrea angasi* (references listed are only those found to contain records relating to this species).

Reference	Details	Location of Reference
Correspondence and notes (assembled by H. M. Hale) on oyster beds and commercial fisheries, 1926-36	Letters discussing aspects of oysters and oyster fishing, including regarding the *First Progress Report of the Royal Commission on the Fishing Industry, January 2 1934* (GRG19/402)	State Records of South Australia: South Australian Museum
Correspondence Files of the Senior Inspector of Oyster Fisheries (no date)	Letters, correspondence and informal reports, including reports on surveys for new locations of oyster beds	State Records of South Australia: Department of Fisheries
Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Diary containing draft and printed correspondence, and notes regarding travels, inspections and investigations (GRG51/289)	State Records of South Australia: Department of Marine and Harbors and predecessors
Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 2), 1892-95	Diary containing draft and printed correspondence, and notes regarding travels, inspections and investigations (GRG51/289)	State Records of South Australia: Department of Marine and Harbors and predecessors
Stray Documents	Box of stray documents (letters, maps and correspondence) (GRG51/169)	State Records of South Australia: Department of Marine and Harbors and predecessors
Randall, W. G. 1911. Report of the Chief Inspector of Oyster Fisheries on Oyster-Fishing Industry. House of Assembly, South Australia	Report summarizing research on past aspects of the oyster industry, its failure and options of restoration of oyster beds and the fishery (includes photographs of work)	State Records of South Australia: Parliamentary Papers
Randall, W. G. 1912. Report of the Chief Inspector of Oyster	Report summarizing work undertaken for restoration of oyster beds and the fishery	State Records of South Australia:

Fisheries on Oyster-Fishing Industry. House of Assembly, South Australia	(includes photographs of work)	Parliamentary Papers
McIntosh, S. 1913. Fisheries—Report of Chief Inspector for 1912-13. House of Assembly, South Australia	Annual fisheries report, including summary of oyster fishery	State Records of South Australia: Parliamentary Papers
McIntosh, S. 1914. Fisheries—Report of Chief Inspector for 1913-14. House of Assembly, South Australia	Annual fisheries report, including summary of oyster fishery	State Records of South Australia: Parliamentary Papers
Moorhouse, F. W. 1938. Report on the Operations of the Fisheries and Game Department, 1936-38. Government Printer, Adelaide	Annual fisheries report, including summary of oyster fishery	State Records of South Australia: Legislative Council Papers
Moorhouse, F. W. 1939. Report on the Operations of the Fisheries and Game Department, 1938-39. Government Printer, Adelaide	Annual fisheries report, including summary of oyster fishery	State Records of South Australia: Legislative Council Papers
Moorhouse, F. W. 1940. Report on the Operations of the Fisheries and Game Department, 1939-40. Government Printer, Adelaide	Annual fisheries report, including summary of oyster fishery	South Australia: Legislative Council Papers
Moorhouse, F. W. 1943. Report on the Operations of the Fisheries and Game Department, 1942-43. Government Printer, Adelaide	Annual fisheries report, including short summary of oyster fishery	South Australia: Legislative Council Papers
Moorhouse, F. W. 1945. Report on the Operations of the Fisheries and Game Department, 1943-45. Government Printer, Adelaide	Annual fisheries report, including short summary of oyster fishery	South Australia: Legislative Council Papers
Marine Invertebrates Collection Records	Identification cards for dry *O. angasi* samples	South Australian Museum
Chart of the Approach to Port Augusta: Showing Established Lights	Cartographic Material of the Adelaide Marine Board	State Library of South Australia
Corbett, D. (Ed). 1973. Yorke Peninsula: A Natural History. University of Adelaide, Adelaide	Natural history text with chapters relating to different aspects of the environment (terrestrial and marine) of the Yorke Peninsula	State Library of South Australia
Olsen, A. M. 1994. The history of the development of the Pacific oyster *Crassostrea gigas* (Thunberg) industry in South Australia. Transactions of the Royal Society of South Australia 118:253-259	Research article describing the development of Pacific oyster aquaculture in South Australia	University of Adelaide Library
Perry, D. 1985. Early Glenelg and Holdfast Bay. Research	Research paper discussing aspects of the early settlement and development of	State Library of South Australia

Paper, Adelaide	Holdfast Bay, Adelaide region	
Tyler, M. J. & C. R. Twidale (Eds). 1979. Natural History of Kangaroo Island. Royal Society of South Australia, Adelaide	Natural history text with chapters relating to different aspects of the environment (terrestrial and marine) of the Kangaroo Island	State Library of South Australia
Wallace-Carter, E. 1987. For They Were Fishers. Amphitrite Publishing House, Adelaide	Humanities text discussing the fisheries of South Australia and their development	State Library of South Australia

Appendix S2. Categories, examples of historical records regarding *O. angasi* ascribed to each category, and the code allocated to calculate estimated abundance of oysters and oyster reefs in South Australia.

Perceived abundance	**Example anecdotes**	**Code**
Extremely abundant	Prolific, very large supply, very plentiful, immensely large quantity	5
Abundant	A large/fairly large/considerable quantity/s, plentiful/plenty, an ample supply, good supplies, entirely satisfactory, doing a fine business, good returns for the labour	4
Common	A quantity, a good/moderate/fair quantity/s, fair quantity, satisfactory returns/results, obtainable, doing fairly well, progressing favourably	3
Uncommon	Very limited quantity/s, not entirely satisfactory	2
Rare	Not satisfactory, very few, without marked success	1
Absent[a]	Absent, not found	0

[a] 'Absent' was assigned for references to known current or past presence of oysters. Where no records or no data were available for a site the anecdote was not coded.

Appendix S3. Timeline of the development of oyster fishing and key events in the South Australian *O. angasi* fishery.

Year	Reference
c. 1836	*'During the first twenty years of the colony's existence oyster lovers rejoiced in the abundance of the tasty mollusc which were 'a valuable element in the pleasure of a visit to the Bay* (Holdfast Bay) … (Perry, D. 1985. *Early Glenelg and Holdfast Bay*. Research Paper (State Library of SA). Adelaide, South Australia).
1853	'*An Act to encourage the formation of Oyster Beds, and to protect the same*.' [First Act implemented for: the 'laying down' of beds where no natural beds occur and prohibiting the unlawful taking of oysters from these areas.]
1873	'*An Act to provide for the formation and protection of Oyster Beds, and to prevent the wanton destruction of Oysters.*' [New Act implemented for the 'laying down' of beds where no natural beds occur and prohibiting the unlawful taking of oysters from these areas, as well as: 1. the introduction of penalties for the taking and sale of any oysters or oyster brood during the months of September, October and November, 2. the introduction of penalties for the depositing of injurious material on any natural or artificial bed, 3. the right of the Commissioner to close any natural oyster bed for a set term (not exceeding 3 years) and the introduction of penalties for fishing within these areas, 4. the introduction of penalties for raising, taking or catching oysters less than six inches in circumference and not returning this spat, cultch or small oysters to the bed within 6 hours, unless replenishing an artificial bed, and 5. the provision of an exclusive access license to any new natural oyster bed found by any person.]
1881	Appointment of first Inspector of Oyster Fisheries.
1885	'*An Act to promote the Breeding of Oysters and to regulate the Oyster Fishery*.' [New Act implemented for: 1. the issuing of licenses for every vessel and every person engaged in oyster fishing and introduction of penalties for fishing without a license, 2. continued provision of exclusive rights to a natural oyster bed found by any person as well as the revocation of this license if believed that the bed is likely to be exhausted or greatly reduced in value, 3. the provision of licenses to form artificial beds, 3. the right of the Treasurer to close any natural oyster bed for a set term (not exceeding 4 years) and the introduction of penalties for fishing within these areas, 4. continued penalties for the depositing of injurious material on any natural or artificial bed, and 5. the appointment of an Inspector by the Governor for administration of the Act.]
Prior to 1885, through 1889	Introduction of *Saccostrea commercialis* (Sydney rock oysters). *S. commercialis* were deposited in various regions including, Victor Harbor, Port Adelaide, Port Lincoln and Coffin Bay and while reported to have thrived did not establish a spawning population.
1887 onwards	*Pinna bicolor* collected by the Inspector of Oyster Fisheries from Port Lincoln waters and transplanted to Coffin Bay (where they were not present at the time) to try and promote the recruitment and growth of oyster spat.
1895	Correspondence by the Inspector of Oyster Fisheries indicated the depleted state of stocks and the need for the suspension of dredging on all beds: "*Before concluding however I would beg respectfully to bring under your notice a fact that I have alluded to in my former reports namely that our once prolific oyster beds are every year becoming less reproductive and it is my firm conviction that nothing but decisive measures can cope with the difficulty under which our oyster beds and cutters at present labour, the continual dredging and re-dredging by large number of boats, over our known beds for the last 35 years to my knowledge, has had the effect of reducing the size of marketable oysters, and their quantity to a minimum, and if the same treatment prevails over the same grounds the evil will be yet greater and quite irremediable, if we are to conserve existing oyster beds and extend the industry, all further dredging on known deposits must be suspended to enable the beds to be restocked by spawn from properly matured oysters*."

1911	Annual Report of the Chief Inspector of Oyster Fisheries included a review of the Oyster-Fishing Industry: "*THE FAILURE OF THE INDUSTRY – After some months of research the following conclusion was arrived at:- That the oyster supply was practically exhausted. The few remaining licensed oystermen were not making a living; many of them had put wells into their boats and engaged in other fishing. As a matter of fact, the State was dependent upon New South Wales, Queensland, and New Zealand for her oyster supply. Such was the position at this time.*" "*CAUSES OF THE FAILURE - The cause leading to the vanishment of what was at one time a flourishing industry were believed to be attributable chiefly to uncontrolled over-working, by which the beds had not only become depleted, but the natural "catchment" on which the spat is collected, consisting chiefly of razorfish, had been destroyed.*" "*SUGGESTED REMEDY - OYSTER CULTURE - The next consideration was the best method of repopulating the at present almost barren waters. Artificial cultivation was believed to be the only practical solution. Simply closing the beds had been tried with apparently small benefit; just as well take off your crop and sit on the nearest fence in the vain expectation of seeing a fresh one spring up.*"
1911	Material used as cultch (kerosene and other tins, galvanized iron, pots, pans, kettles, old iron, and tanks, as well as 50 tons of green mallee boughs) deposited in Proper Bay (Port Lincoln) in early October to try and promote greater settlement and establishment of spat.
1912	Establishment of the first National Oyster Reserve and Nursery in Proper Bay; reported to be Australia's first State oyster reserve.
1912	Continued introduction of *Saccostrea commercialis*
1913	Oysters naturally growing within the Proper Bay nursery transferred to Eastern Cove and Western Cove on Kangaroo Island to try and establish a second oyster reserve in this region.
1914	Continued transplanting to try and restock depleted beds.
1938	In the 1936-38 Report on the Operations of the Fisheries and Game Department it was highlighted that few oysters passed through the Adelaide Fish Market anymore and the small number caught went directly to private buyers. This report also indicated the effective end of the industry: "*The oyster industry in South Australia is languishing. Only one centre of any consequence now produces oysters commercially. This centre is the bays and waters in the Coffin's Bay area, Mount Dutton Bay, and Kellidie Bay being the two waters in particular from which the oysters are taken. Oyster dredging is a very arduous task, so with the price of oysters averaging 25s. a bag of 35 to 40 doz., few oystermen are operating to-day, the majority having turned their attention to fishing.*"
1943-45	No men were engaged full time in the industry with 139 bags marketed for the year 1943-44 (through the Adelaide Fish Market, other regional centres may have traded) and the department held no records for any oysters being marketed in 1994-45.
1970	*Crassostrea gigas* (Pacific oyster) spat imported from Japan and set out in Coffin Bay, Eyre Peninsula for the development of aquaculture.

Appendix S4. Examples of historical records of total catch quantities and Catch Per Unit Effort (CPUE) for *O. angasi*. Total estimated number of oysters (individuals) calculated based on 350 individuals per bag (Wallace-Carter, E. 1987. *For They Were Fishers: The History of the Fishing Industry in South Australia*. Amphitrite Publishing House, Adelaide). Footnotes indicate source of record.

Bioregion	Location	Date	Catch or CPUE	Length of time fishing	Number of boats	Estimated individuals
Murat[1]	Denial & Smoky Bay	Jan 1894	8 to 10 bags^{-1}.day^{-1}	12 months	Unknown	3 150 day^{-1}.boat^{-1}
Eyre[1]	Coffin Bay	1870	23 bags^{-1}.day^{-1}	Unknown	Per boat	8 050 day^{-1}.boat^{-1}
Eyre[1]	Coffin Bay	1874	16000 bags	3 years	Unknown	5 600 000
Eyre[1]	Kellidie Bay	Dec 1886 – Jun 1887	2 308 bags	7 months	22 boats	807 800
Eyre[1]	Boston Bay & Mount Dutton Bay	Jan – Jun 1887	1 886 bags	6 months	Unknown	660 100
Eyre[1]	Port Lincoln	Nov 1887	90 bags	8 hours	Unknown	31 500
Eyre[1]	Point Longnose	Jul – Dec 1887	1 635 bags	6 months	Unknown	572 250
Eyre[1]	Dutton Bay	Apr 1888	200 bags	2 days	Unknown	70 000
Eyre[1]	Proper Bay, Port Lincoln	Jan – Jun 1889	1 586 bags	6 months	Unknown	555 100
Eyre[1]	Boston Bay	Jul – Dec 1889	1 711 bags	6 months	Unknown	598 850
Eyre[1]	Mount Dutton Bay	Jul – Dec 1888	1 630 bags	6 months	Unknown	570 500
Eyre[1]	Port Lincoln	May 1888	4 to 6 bags^{-1}.day^{-1}	Unknown	Per boat	1 750 day^{-1}.boat^{-1}
Eyre[1]	Spalding Cove	Oct 1889	3 to 5 bags^{-1}.day^{-1}	Unknown	Per boat	1 400 day^{-1}.boat^{-1}
Eyre[1]	Point Fanny	Oct 1889	5 bags^{-1}.day^{-1}	Unknown	Per boat, 13 boats	22 750 day^{-1}
Eyre[1]	Boston Island	Nov 1890	4 to 5 bags^{-1}.day^{-1}	2 weeks	Per boat	1 575 day^{-1}.boat^{-1}
Eyre[1]	Louth Bay	Apr 1891	4 to 5 bags^{-1}.day^{-1}	Catch will continue for many months	3 boats	4 725 day^{-1}
St Vincent Gulf[2]	NW of Perara	c. 1836	9 000 oysters day^{-1}	Unknown	Unknown	9 000
St Vincent Gulf[3]	Orontes Bank	1870s	100 000 per week	Unknown	Unknown	100 000
St Vincent Gulf[1]	Yorke Peninsula	Jan 1890	660 bags	1 month	12 boats	231 000
St Vincent Gulf[1]	Port Alfred	Apr 1890	1 300 bags	3 months	Unknown	455 000
St Vincent Gulf[1]	Point Morrison	Jun 1895	70 bags	2 days	Unknown	24 500

[1] Diary and Letter Book of the Inspector of Oyster Fisheries (Volumes 1 & 2), 1886-92 and 1892-95

[2] Wallace-Carter, E. 1987. For They Were Fishers: The History of the Fishing Industry in South Australia. Amphitrite Publishing House, Adelaide.

[3] Perry, D. 1985. Early Glenelg and Holdfast Bay. Research Paper, Adelaide

Appendix S5. List of locations where *Ostrea angasi* oyster reefs used to occur within South Australian marine bioregions, as indicated by records to historical commercial fishing or the presence of known 'payable beds'.

Marine Bioregion	**Location**
1. Eucla (EUC)	*No records*
2. Murat (MUR)	Denial Bay Smoky Bay
3. Eyre (EYR)	Bickers Island Bird Rock Boston Bay Boston Island Cape Donington Coffin Bay Coffin Bay (all bays) Garden Island (near Mount Dutton Bay) Grantham Island Kellidie Bay Louth Bay Louth Island Mount Dutton Bay Point Bolingbroke (north tip of Louth Bay) Point Boston Point Longnose Point Fanny Port Douglas / Point Douglas Port Lincoln Porter Bay Proper Bay Rabbit Island Salt Creek (just north of Tumby Bay) Sir Joseph Banks Group Spalding Cove Stamford Hill Streaky Bay Tumby Bay Yangie Bay
4. Spencer Gulf (SG)	Dutton Bay (north of Tumby Bay, not Mount Dutton) Franklin Harbour/Cowell Hardwicke Bay NW coast of gulf NW coast as far as Cowell NW coast north of Franklin Harbour Point Riley Port Victoria, South
5. Northern Spencer Gulf (NSG)	False Bay (Point Lowly) Head of the Spencer Gulf Mount Young (near Whyalla) Port Pirie
6. St Vincent Gulf (SVG)	American River Ballast Head (Point Morrison) Black Point (Port Alfred) Eastern Cove Eastern shore of Yorke Peninsula (all along the coast from Black Point

	to Troubridge Lighthouse) Eastern shore of Yorke Peninsula (the whole of the coast from Port Wakefield to Port Vincent) Eastern shore of Yorke Peninsula (from Price to Stansbury) Edithburgh Head of the Gulf Kingscote Mangrove Point Marion Reef North coast of Kangaroo Island Orontes bank Oyster Bay Perara Pine Point Port Clinton Port Julia Port Price (Wells Creek) Port Vincent Port Wakefield Red Cliff Rogue's Point Sandy Spit Sheoak Flat Stansbury Surveyor's Point Western Cove (Cygnet River) Wool Bay
7. Coorong (COR)	*No records*
8. Otway (OTW)	*Records but no reference to historical occurrence*
Unknown or unsubstantiated locations (eg. references to presence of large number of shells only, or low confidence report)	Backy Bay (just north of Fitzgerald Bay) (NSG) Blanche Harbour (NSG) Holdfast Bay Port Broughton (NSG) Roper Bay (Unknown Bioregion) Victor Harbor (COR)

Appendix S6. Examples of records regarding *O. angasi* contained within the historical references.

A. South Australia (general records related to fishery)

Date	Source	Topic	Record
1870	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Decline	I am enabled to afford some information as far back as the year 1866. The supply of oysters for the Adelaide market was limited to the beds situated on the eastern shores of Yorke Peninsula the dredging there being carried on indiscriminately without protection or regulation of any kind it was well known that natural oyster beds of a very prolific kind existed in Port Lincoln waters, but in the days referred to it was impossible to convey them to Pt Adelaide in a condition for sale, the distance being too great, however the Steamship Marion took the place of the former slow sailing craft and at once the difficulty was removed, and since then there has been a more or less constant supply of good marketable oysters for Adelaide, dredging went on in Boston Bay, that is Port Lincoln Bay, and Port Lincoln Proper Bay in the same indiscriminate manner as at Yorke Peninsula previously referred to, the beds in the neighbourhood of the Port Lincoln Bays covered a large area and it was unfortunate that the restrictions subsequently imposed were not in force earlier thereby saving much destruction the disastrous effects of which was felt for many years after the beds were completely depopulated almost beyond the power of reproduction consequently when this source of supply faded it was felt to be a great hardship as the population of Adelaide had meanwhile greatly increased and the demand for oysters with it.
1895	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 2), 1892-95	Decline	I am sorry to say that year by year the yield of our once prolific oyster beds in the neighbourhood of Port Lincoln, Coffins bay, and Yorkes Peninsula is growing less in the supply, the reason for this is mostly owing to the continual dredging and redredging over the same beds, by so large a number of boats every year employed, this continual dredging I may say for upwards of 36 years to my knowledge has of course brought the beds to the minimum quantity.
1911	Randall, W. G. 1911. Report of the Chief Inspector of Oyster Fisheries on Oyster-Fishing Industry. House of Assembly, South Australia	Recovery	Reviewing the experience of the past 18 months, I believe that there are fair prospects of the oyster industry again becoming in time a valuable asset. Patience is necessary, as oysters do not grow like mushrooms. Past mistakes have to be atoned for, but if absolute protection is assured to the cultivated areas the progress is more likely to be reliable; much, indeed, depends upon this
1911	Randall, W. G. 1911. Report of the Chief Inspector of Oyster Fisheries on Oyster-Fishing Industry.	Oyster propagation	SUGGESTED REMEDY - OYSTER CULTURE - The next consideration was the best method of repopulating the at present almost barren waters. Artificial cultivation was believed to be the only practical solution. Simply closing the beds had been tried with

	House of Assembly, South Australia		apparently small benefit; just as well take off your crop and sit on the nearest fence in the vain expectation of seeing a fresh one spring up. … The work (report) was put in hand in September of last year. Rubbish, consisting mainly of kerosine and other tins, galvanized iron, pots, pans, kettles, old iron, tanks, etc., was carted to Proper Bay, lightered out to a ketch, and discharged over carefully selected bottom: in addition about 50 tons of green mallee was cut and laid down. Early October everything was ready for the spat season, now close at hand. The locality selected for the undertaking was the extreme south-western potion of Proper Bay ...
1893	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 2), 1892-95	New bed	… since the closing of the Spalding Cove oyster beds, the Boats under licence for the current year are dredging in Louth Bay on a bed of Oysters which has been recently discovered extending over a large area of sea ground (although not very thickly distributed) from which I anticipate a fairly large supply of Oysters to the Colony for some months to come.
1890	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	New bed	(Stansbury) Having resumed the usual inspection of the grounds, and when off Oyster Bay Point, and about 1/2 a mile off land, here I hit upon a patch of fine large oysters.
1888	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Settlement of spat	… resumed the inspection of the Oyster beds in Kellidie Bay I find that large quantities of young Oyster brood having settled on the beds, since the Bays being closed.
1889	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Settlement of spat	(Kellidie Bay) … the young Oysters and Oyster brood on several beds are accumulating in large quantity in fact all over the bay that could reasonably be hoped for, the razor fish (?) very favourably also.
1888	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Market	… the supply is greatly in excess of the market demand - there is at the present time 300 bags of oysters laying on the storage beds in Port Lincoln, more and above of the market demand.
1889	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Market	… there has been no difficulty in keeping the market supplied, in fact double the quantity could have been forwarded if required, the demand however is now on the increase and will continue to increase as the summer season advances. 365 bags of Oysters, has been forwarded for the Steamer Ferret to Port Adelaide, and out Ports during the past month of November.
1887	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Market	… since the opening of Kellidie Bay and Port Douglas for oyster fishing this season there has been twenty cutters constantly employed in oyster dredging and the catch has greatly exceeded the market demand… the oysters are certainly far superior both in size and quality to any in the Colony, still the demand during the summer has been exceedingly small compared with that of other years - owing I expect to the great depression that exists in the colony at the present time.

1888	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Market	For the current year the number of boats is 16 and 27 men working the Boats, this decrease in the Oyster industry is no doubt due in a large degree to the general depression of the trade and consequent scarcity of money which has of late prevailed throughout the Colony.

B. Murat marine bioregion

Date	Source	Topic	Record
1894	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 2), 1892-95	Abundance	For the last 12 months been dredging oysters in Denial and Smoky bay, (and) informed me, that oysters are plentiful and that 8 to 10 bags of oysters (2 800 to 3 500 individuals) can be easily obtained in one days dredging, and the oysters are of excellent quality and condition.
1840	Wallace-Carter, E. 1987. For They Were Fishers. Amphitrite Publishing House, Adelaide	Abundance	"One of the earliest records of oysters was from the explorer Edward Eyre who writing in his Journal in 1840 commented on regular fishing by the men at the southerly bight of Streaky Bay."

C. Eyre marine bioregion

Date	Source	Topic	Record
1870	Wallace-Carter, E. 1987. For They Were Fishers. Amphitrite Publishing House, Adelaide	Catch quantities	"By 1870 some thirty sailing cutters, varying in length from twenty-five to forty feet, were dredging in the Coffin Bay area. Eighty or so men were employed on the boats and the production average 60 000 bushels a year (some 18 000 wheatbags (6 300 000 individuals) full)."
	Wallace-Carter, E. 1987. For They Were Fishers. Amphitrite Publishing House, Adelaide (Commissioner of Police during his visit to the Eyre Peninsula on 12th September 1849)	Catch quantities	"My attention was called to this inlet (Coffin Bay) during my stay in the Port Lincoln district because of the quantity of oysters which were brought to Port Lincoln in drays, deposited among the rocks in beds, and, as opportunity offered, shipped to Adelaide in small 'crafts' to supply the market, and there retailed at one shilling and sixpence per down. Since this discovery, no less than 100,000 oysters have been brought to Adelaide and within the last few days two cutters arrived with 100,000 more; these last were brought direct from here. They appear to be inexhaustible and so easily collected as may be imagined from the fact that the natives on one occasion collected in a few hours 15,000 ..."

1888	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Decline	During last month 25 cutters arrived here from Port Lincoln and began their dredging operation which very soon tested the beds far better than I had the opportunity of doing with one boat, the result being that on several of the beds especially those situated in deep channels, and from which the greatest supply of Oysters were expected to be obtained, very few indeed are to be found and others are completely depopulated, but this is by no means the case with every bed, for upon one bed just off the Dutton Bay Jetty in shallow water and where bottom consist of a hard rocky formation and free from the (?) accumulation 200 bags were caught in about two days, but you can easily form an idea how soon any ordinary Oyster beds would disappear under such large numbers of boats employed, and leave very little behind to mark the spot, except some empty shells.
1893	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 2), 1892-95	Decline and accumulation of seaweed	I examined the beds in Kellidie Bay which were closed on the 23 July 1889 and there have been no boats dredging since the above date, consequently the results of the increase of Oysters there, I am sorry to say has proved very unsatisfactory. I find that the oyster beds are not so prolific as I anticipated considering the length of time have been closed. The reason for this I find, is the great accumulation of seaweeds and other marine sediment of every description settled over the principal breeding grounds, and has completely covered the old Oyster shells, and all other such hard materials to which the oyster spat could not obtain any solid holding ground, thus causing the failure of the beds in Kellidie Bay.
1881	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Oyster propagation	Now there are few positions better than the last named place (Kellidie Bay) for the propagation of the oyster - plenty of land drainage from the ranges beyond, and mud banks where the young oysters can fatten and produce both fish and shell, but as there are no razor fish thereon the young spat can not cling, and the Bay became impoverished in a single season.
1887	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Transplant of *Pinna bicolor*	I must tell you that my time during the past month has been principally taken up by collecting the Razor Fish in Port Lincoln waters and transplanting them in Coffins Bay, where they are non existant at the present time…
1887	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Transplant of *Pinna bicolor*	The razor fish (transplanted) all along the mainland side of Boston Bay have formed a new foundation for the adhesion of oyster spat, three fourths of the oysters obtained are got from the razor fish beds, on much bottoms, where, but for the razor fish the oyster spat would have no hold.

1888	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	New bed	… resumed the usual inspection of Oyster beds in the course of the day, I discovered a fresh bed of Oysters about a mile South West of Grantham Island, on this bed I believe to be about 200 bags of good marketable Oysters.
1889	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Increased supply	I am pleased to inform you, that since the division of the beds have taken place, there has been a steady increased supply of Oysters on the Port Alfred Coast Yorke Peninsula, Port Lincoln Proper and Boston Bay owing to such large quantities of razor fish accumulating on the beds, and have formed new foundation and the oyster spat adhering in large quantities.

D. Spencer Gulf and Northern Spencer Gulf marine bioregion

Date	Source	Topic	Reference
1912	McIntosh, S. 1913. Fisheries—Report of Chief Inspector for 1912-13. House of Assembly, South Australia	Abundance	Oysters are known to be present on the east cost of Spencer's Gulf, particularly from Port Victoria southerly. ... Being satisfied that the razor fish supply was considerable he (a fisherman) took out a licence, and it is understood that he is securing fair returns. It is the first licence taken out for oyster fishing on that portion of the coast, and may lead to further discoveries.

E. St Vincent Gulf marine bioregion

Date	Source	Data Type	Reference
1836	Perry, D. 1985. Early Glenelg and Holdfast Bay. Research Paper, Adelaide	Early years of fishery	“Oysters - When a number of fishermen took up their trade in colonial South Australia they were individually induced to push the capture to extremes without regard to spawners and small fry and the consequence was that the sea coast was denuded of its denizens by the eagerness of the chase. To cite but one instance, in the early days of the colony the whole of the coastline from Port Wakefield to Surveyor's Point was the home of the oyster and there were thousands on thousands there on a natural bed and no sooner was the cupidity of the fishers aroused than cutters cruised in those waters.”
1877	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Decline	The same occurred about 26 years ago when the once prolific beds on the Eastern shore of Yorke Peninsula which supplied the demand of the colony, were destroyed by the excessive dredging (which was carried on a few years previously) thereby every available oyster caught... Consequently the beds never recovered again until 3 or 4 years ago when the razorfish made a new foundation

			which are now here in large quantities, all along the coast commencing from the northernmost end of the Gulf down as far as Stansbury Bay, and adhering to them is a great amount of young oysters and oyster brood, which promise a three year supply of oysters to the Colony when they become marketable size provided care and judicious management be exercised.
1894	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 2), 1892-95	Decline	… having inspected the natural deposit of Oysters known as Black Point or Port Alfred Beds. This beds have now been closed for about four years but the progress of young Oysters has not been satisfactory. In only one locality did I find oysters of a marketable size and quality, and in that place I should estimate that only a very limited quantity could be taken, the remainder of the beds appear to have in some places overgrown with weed and sediment or every sort, which has so thickly covered the ground, and has completely killed all the spat which was being deposited at the time the beds were closed...
1866	Perry, D. 1985. Early Glenelg and Holdfast Bay. Research Paper, Adelaide	Decline	“By 1866 Holdfast Bay was not 'the bivalvular Goshen as it once was' for the natural beds had been destroyed through the stupidity and carelessness of the dredgers. A few years previously an attempt had been made to lay down artificial beds 'on the French principle' but failed in consequence of the sites being ill-selected. Recourse was only available from a 'course, flabby article from Port Lincoln' or an expensive import from Sydney.”
	Perry, D. 1985. Early Glenelg and Holdfast Bay. Research Paper, Adelaide	Decline	“Irrespective of cause of effect, regardless of legislative enactment, the toilers of the sea dredged and dredged until the demand overcame the supply. They paid little regard to the fishery in which they were engaged; in no case was a selection made, but the whole of the fish, great or small, were drafted off to supply the city. The end came and finally not a mollusc was available - not a solitary native oyster remained and the dredgers were constrained to seek fresh fields and pastures new. Coffin Bay, Port Lincoln and other desirable spots then furnished the gourmand with this luxury.”
1845	Perry, D. 1985. Early Glenelg and Holdfast Bay. Research Paper, Adelaide	Decline and legislation	“By 1845 the excessive removal of oysters from local beds was cause for concern and a complainant pleaded for appropriate government action. Alas, this was not forthcoming.”
1853	Perry, D. 1985. Early Glenelg and Holdfast Bay. Research Paper, Adelaide	Decline and legislation	“When the falling away of supply was first discovered a Bill, sponsored by Mr C.S. Hare was passed through the Legislative Council in 1853 to encourage artificial beds and, while its provisions were no doubt sounds and sufficient from a legal point of view, it was rendered practically useless by the want of knowledge among those who took advantage of it as to the management of beds. ... but the ground was sandy and quite unsuited to oysters as it 'gave them nothing to hold by and as little to live on.' Further, the little chance the oysters had of coming to maturity in such circumstances was destroyed by the careless manner of dredging for them. The unripe

			ones were not carefully returned to the bed but thrown recklessly on to the living oysters, thousands of which were smothered.”
1890	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Decline and accumulation of seaweed	(Yorke Peninsula) … In addition I tried all the waters off Port Wakefield, Clinton, Port Price, and other places in the neighbourhood in order to find some payable new beds of oysters, particularly so, on the old bed off Clinton, where some 30 years ago Oysters existed in abundance, and now I find, the very large and exceptional accumulation of mud seaweeds and other marine rubbish having settled over the grounds, is a very serious obstacle to the satisfactory growth of Oyster brood, the spat being unable to obtain solid holding ground, consequently the beds had faded into nothing.
1889	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Increased supply	I am pleased to inform you, that since the division of the beds have taken place, there has been a steady increased supply of Oysters on the Port Alfred Coast Yorke Peninsula, Port Lincoln Proper and Boston Bay owing to such large quantities of razor fish accumulating on the beds, and have formed new foundation and the oyster spat adhering in large quantities.
1890	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Catch quantities	… the dredging operation during the past three months on the Port Alfred coast are being vigorously proceeded with I may say however that no less than 1 300 bags of Oysters (455 000 individuals) have been caught during that time …

F. Ecological and environmental records

Date	Source	Data Type	Reference
1935	Correspondence and notes (assembled by H. M. Hale) on oyster beds and commercial fisheries, 1926-36. Letter from T. C. Roughely to H. M. Hale re culture of NSW oysters in SA, June 21, 1935	Ecology and *Polydora* spp.	The habit of O. angasi of living in water where it is never bared by the tide exposes it to a far greater risk of attack by Polydora, and the fact that you can find no evidence of attacks by the worm seems rather propitious for the success of the growth of the NSW oyster in similar situations. … It (polydora) appears to have a less serious effect on O. angasi because of the greater readiness with which that species can deposit shelly material. … It is not that O. angasi is attacked less, but that it is more capable of dealing with the attacks. But from the fact that you can find no evidence of the worm attaching your oysters I should be inclined to assume that it is not virulent in South Australia and that the NSW oysters should stand a good chance of survival in submerged situations.
1913	Randall, W. G. 1912. Report of the Chief	Ecology	Most, if not all, of the oyster-bearing waters are practically local and in fairly shallow depths. The

	Inspector of Oyster Fisheries on Oyster-Fishing Industry. House of Assembly, South Australia		presence of shells of full-grown oysters that have been found on wide stretches of the coast incline to the belief that there may be important supplies in deeper waters, for which it may be considered proper that a search should be made.
1914	McIntosh, S. 1914. Fisheries—Report of Chief Inspector for 1913-14. House of Assembly, South Australia	Influence of rainfall	OYSTER FISHERIES - Early in the summer months, 1914, the oysters began to deteriorate in condition, and dead shells became numerous; as summer advanced the position became more acute. These was not the slightest sign of disease of any kind, the sole cause of the trouble is the absence of food in the waters, and the absence of ordinary rainfall is accountable for this position. Although the experience is regrettable, I pointed out in each annual report, that given a succession of dry years losses must follow, both in reproduction and in the welfare of existing oysters; this has been fully borne out, and is the experience of other countries. According to statistics courteously furnished by the Meteorological Bureau of South Australia, 1913 was the driest season for 48 years, which is the period during which records have been taken, the rainfall of Port Lincoln being 13.23in., compared with 25.14in. in 1909-10, and this latter year was most prolific in reproduction. The condition of the oysters on the natural beds in the nursery is exactly similar to that in the cultivated areas.
1911	Randall, W. G. 1911. Report of the Chief Inspector of Oyster Fisheries on Oyster-Fishing Industry. House of Assembly, South Australia	Influence of rainfall	Another important factor lies in the character of the coming seasons. As has already been indicated, a good rainfall materially assists growth and spat production. The process of restoration should quicken after the first two or three years, because the replenishing powers of the accumulating stock will be more rapidly augmented. Oysters may spat at 12 months old, but the best period of reproduction is from three to six years.
1910	Randall, W. G. 1911. Report of the Chief Inspector of Oyster Fisheries on Oyster-Fishing Industry. House of Assembly, South Australia	Influence of rainfall	SUGGESTED REMEDY - OYSTER CULTURE - I believe that the fall of spat in the 1910 season was unusually heavy; this is accounted for by an exceptionally large rainfall in the winter months. In that portion of Proper Bay where the "catchment" is laid there are strong springs of fresh water coming in which has a tendency to reduce the salinity of the sea water and is, undoubtedly, conducive to prolific spawning and assists growth. It has been proved everywhere that wet seasons are advantageous to oyster culture; accordingly, if dry seasons prevail we must be prepared to anticipate poor results.
1914	McIntosh, S. 1914. Fisheries—Report of Chief Inspector for 1913-14. House of Assembly, South Australia	*Cladophora* spp.	OYSTER FISHERIES - The closure to oyster-fishing of Spalding Cove and Proper Bay expired on February 15th, 1914. An examination of the oyster beds was twice attempted, but owing to the accumulation of marine fauna, it was not possible to ascertain their condition. During the winter months, under normal conditions, this material decays, and by

			the action of the tide much is removed. Early in November of the present year permission was given for two boats to prospect these waters, and dredging was carried out under our personal supervision, but the results were not satisfactory.
1913	McIntosh, S. 1913. Fisheries—Report of Chief Inspector for 1912-13. House of Assembly, South Australia	*Cladophora* spp.	*St. Vincent's Gulf* - A considerable portion of the old beds was covered with blanket weed (Cladophora), which would appear to be closely allied to the eelgrass found to be troublesome in the Canadian Oyster Fisheries. It is considered probable that this growth is swept over these shallower waters from the deeper portions of the Gulf during the prevalence of strong south-east and north-east winds in summer time.
1913	McIntosh, S. 1913. Fisheries—Report of Chief Inspector for 1912-13. House of Assembly, South Australia	*Cladophora* spp.	WEED (OYSTER RESERVE & NURSERY, PROPER BAY) – During the early months of the year the reserve suffered from an invasion of blanket weed, a growth regarded as troublesome in St. Vincent's Gulf, and which enveloped the catchment. It is hoped that the season's spat has not been seriously affected, because it should have become established prior to the advent of the weed. Fortunately this growth dies off in winter, and the prevailing winds from the north-west to south-west assist in dispersement.
1891	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	*Cladophora* spp.	Unfortunately however, owing to the fine weather and calms that prevailed during the past fortnight or three weeks the dredging boats have been unable to work sufficiently to keep the grounds clear, consequently a rapidly growing weed has covered the beds to such an extent that the dredges cannot remove it without much labour and loss of time. I may mention that this weed generally appears about this time of the year, especially on a shallow water beds, and its effects are disastrous to growing oysters, in fact many beds and patches that were known and worked some years ago are now nothing but masses of empty shells.
1888	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Influence of seaweed	I would also point out that the beds in Mount Dutton Bay, some of which are getting covered with sea weed, as referred to in my previous report, are quite ready for dredging operation which would remove the weeds and improve the beds, there is an ample supply for a few month of good Oyster available, in this Bay.
1888	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Dredging	I would also point out that dredging is always accompanied with a large amount of unavoidable destruction to young oyster brood, and this increases in proportion to the decrease of full grown Oysters dredged, it is therefore necessary to close beds, not when all the full grown Oysters are unobtainable but when the young brood came up in the dredges in to large a proportion to full grown ones, this was the case with the Boston Bay beds...
1892	Diary and Letter	Excess	… I have carefully inspected the present supply of

	Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	oysters on storage beds	Oysters now lying on the storage beds in Port Lincoln, and find that there are about 700 bags of Oysters awaiting a market. The weekly catch at the present time on the natural bed in Spalding Cove is in excess of the market demand, consequently still adding to the extraordinary large number of Oysters that are already caught and laid on a very shallow ground exposed to the inclemancy of the weather, of which a large portion are dead, and still dying daily on the beds to the great detriment of the Oystermen, and the general public, and should this continue the destruction will be still great.
1881	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Interaction with *Pinna bicolor*	… some of the best formation as yet known in the History of the Oyster culture for the oyster spat to cling, as many as fifty oysters, old and young, having been found on one razorfish.
1912	McIntosh, S. 1913. Fisheries—Report of Chief Inspector for 1912-13. House of Assembly, South Australia	Interaction with *Pinna bicolor*	PROPER BAY, PORT LINCOLN - The three years' closure of these beds expired on February 15th, 1912, and their condition, although certainly improved, did not warrant re-opening. The Honorable the Treasurer approved of the closure being extended for a further term of two years, at the expiration of which they should have materially benefited by the spat from the earliest cultivated oysters in the adjoining reserve which will have become reproducing. It is noticed that the natural "catchment" (razor fish) has considerably increased as the result of the absence of dredging.
1887	Diary and Letter Book of the Inspector of Oyster Fisheries (Volume 1), 1886-92	Interaction with *Pinna bicolor*	The razor fish (transplanted) all along the mainland side of Boston Bay have formed a new foundation for the adhesion of oyster spat, three fourths of the oysters obtained are got from the razor fish beds, on much bottoms, where, but for the razor fish the oyster spat would have no hold.
1913	McIntosh, S. 1913. Fisheries—Report of Chief Inspector for 1912-13. House of Assembly, South Australia	Interaction with *Pinna bicolor*	(Proper Bay and Spalding Cove) The five years closure of these waters will expire on February 15th, 1914, at which time it is hoped that the process of restoration may justify a recommendation for re-opening. Razorfish, which is here the natural catchment, have appreciably increased during the period of protection.
1912	McIntosh, S. 1913. Fisheries—Report of Chief Inspector for 1912-13. House of Assembly, South Australia	Use of catchment in Oyster Reserve	*Spat Season*, 1912 - Mallee bows only were used. These answer better than metals, for although the latter are good collectors, the oyster thereon display a tendency to spread themselves and cannot be removed where necessary without risk of injury. On the boughs the oysters do not attach themselves so closely and thus have more room to develop a good shape. It is intended to experiment during the coming season with limestone as catchment. Oysters in Kellidie and Coffins Bay do well on limestone, which there is a natural catchment; no razor fish are found in these bays.

Appendix S7.

Figure 1. Historical map identified within miscellaneous fisheries files in the State Records of South Australia indicating the National Oyster Reserve at Proper Bay, Port Lincoln, 1889.

Chapter 6: Incorporating historical data into aquaculture planning

6.1 Preface

Despite an increasing appreciation of the need to consider past ecosystem states and ecological baselines in natural resource management, there remain few examples in which the application of historical information to policy and management have been explicitly considered or profiled. Due to this paucity of 'case studies', it is possible that the use of historical data in management will continue to be limited, because scientists and managers may not see the need, nor value, to such an approach. This chapter uses historical data to inform several aspects of planning for aquaculture in South Australia. Quantitative and qualitative data from the historical fishery for the oyster *Ostrea angasi* and information relating to this activity, such as the introduction of a non-native species of oyster after native oyster reefs deteriorated, were incorporated into existing management processes and used to assist the setting of policy, thus demonstrating its value in this application. This chapter is in press with the *ICES Journal of Marine Science*, for a special issue on the 2015 'Oceans Past Symposium', and is reprinted here with the permission from Oxford University Press (Appendix C). The original manuscript can be sourced from the publishers website:

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Contribution to the Paper	Conceptualised and designed the research, collated the historical data and generated the statistics for planning, conducted consultation with government stakeholders, conducted the risk assessment, and wrote and edited the manuscript.		
Overall percentage (%)	80%		
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By signing the Statement of Authorship, each author certifies that:

xiii. the candidate's stated contribution to the publication is accurate (as detailed above);

xiv. permission is granted for the candidate in include the publication in the thesis; and

xv. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Incorporating historical data into aquaculture planning

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Marine historical research has made progress in bridging the gap between science and policy, but examples in which it has been effectively applied remain few. In particular, its application to aquaculture remains unexplored. Using actual examples of natural resource management in the state of South Australia, we illustrate how historical data of varying resolution can be incorporated into aquaculture planning. Historical fisheries records were reviewed to identify data on the now extinct native oyster *Ostrea angasi* fishery throughout the 1800 and early-1900s. Records of catch, number of boats fishing, and catch per unit effort (cpue) were used to test fishing rates and estimate the total quantity of oysters taken from select locations across periods of time. Catch quantities enabled calculation of the minimum number of oysters per hectare for two locations. These data were presented to government scientists, managers, and industry. As a result, interest in growing *O. angasi* increased and new areas for oyster aquaculture were included in regulatory zoning (spatial planning). Records of introductions of the non-native oyster *Saccostrea glomerata*, Sydney rock oysters, from 1866 through 1959, were also identified and used to evaluate the biosecurity risk of aquaculture for this species through semi-quantitative risk assessment. Although applications to culture *S. glomerata* in South Australia had previously been declined, the inclusion of historical data in risk assessment led to the conclusion that applications to culture this species would be accepted. The examples presented here have been effectively incorporated into management processes and represent an important opportunity for the aquaculture industry in South Australia to diversify. This demonstrates that historical data can be used to inform planning and support industry, government, and societies in addressing challenges associated with aquaculture, as well as natural resource management more broadly.

Keywords: aquaculture, historical data, historical ecological research, natural resource management, *Ostrea angasi*, oysters, planning.

Introduction

Impacts from the human use of aquatic resources are well known, but the time-scales over which these impacts have occurred have only recently become of interest to natural resource managers. Increasingly, there is evidence of the early onset of, for instance, overexploitation and habitat modification (e.g. Airoldi and Beck, 2007; Erlandson and Rick, 2010), which has motivated an agenda for marine historical ecological research (Kittinger *et al.*, 2014; Schwerdtner Máňez *et al.*, 2014). Historical research provides insight into the magnitude and trajectories of past change and has been used as a powerful validation of the value of incorporating historical data into contemporary natural resource management (Connell *et al.*, 2008; Ban *et al.*, 2014; Thurstan *et al.*, 2014). However, examples in which such research has been applied to planning in aquatic resource use remain few and its effects on ocean governance, to understand and manage ecosystem changes, are not always well understood.

Patterns of change in aquatic resources, particularly fisheries resources, including species biomass, stock structure, or distribution, have been attributed to fishing (Berkes *et al.*, 2006; Pinnegar and Engelhard, 2008; Erlandson and Rick, 2010), but alternative resource uses such as aquaculture have also occurred over long periods of time, in some cases, for thousands of years (Costa-Pierce, 1987). Critically, the mere knowledge of past ecological states (e.g. historical baselines for species' abundances), can alter an individual's or a community's perception of the state of "naturalness'" of an environment, and therefore the degree to which it has changed and their expectations for its productivity (Jackson, 1997; Dayton *et al.*, 1998; Connell *et al.*, 2008). Although changes to community composition due to climate change, species introductions, or widespread anthropogenic impacts or invasions may limit the scope of comparison between times (Greenstein and Pandolfi, 2008; Carlton, 2009; Hobday, 2011), particularly where the cumulative impact of multiple stressors is yet to be realized (Essl *et al.*, 2015), pragmatic use of historical ecological models could provide information to reduce uncertainty around our perspective and management of aquatic resource use. Modelling approaches have been used to bridge the gap between current and past ecosystem states to allow for reconstruction of past ecosystems and their services, e.g. knowledge on population demographics and filtration capacity of oyster reefs (Mann *et al.*, 2009; zu Ermgassen *et al.*, 2013), and protein production via population modelling of former cod biomass (Rosenberg *et al.*, 2005). Using a similar approach, historical records and data that can inform aquaculture in present and future environments could be identified and reconstructed.

Over the last five decades, aquaculture has become the fastest growing global food production sector (Diana, 2009; FAO, 2014), which has in part been a response to the limited capacity of fisheries to meet continued demand for seafood, a key source of protein (Godfray *et al.*, 2010; Thurstan and Roberts, 2014). This growth has presented challenges to the ecological sustainability of aquaculture, due to negative environmental impacts such as the introduction of pollutants, the escape of non-native species, and overexploitation of fish stocks for feed (Naylor *et al.*, 2000; Diana, 2009). However, the continued growth of global aquaculture provides a means to meet demand for seafood in the future (Duarte *et al.*, 2009) and, as a result, industries, sectors, and aquaculture practices must develop to maximize production in an ecologically sustainable manner (Naylor *et al.*, 2000; Duarte *et al.*, 2009; McClanahan *et al.*, 2015). "Demand" includes developing nations having access to food, protein for nourishment, and income (Allison, 2011), which implies that there is a need for quantity as well as continuity in supply. But demand can also be driven by global markets through expectations for seafood being diverse, of high quality and food secure. Hence, the challenges to the sustainable growth of aquaculture are complex and will be assisted by the identification and use of a range of comprehensive socio-ecological data.

In southern Australia, oyster reefs have been classified as functionally extinct due to the impacts of overexploitation and associated stressors, including disease and poor quality coastal water (Beck *et al.*, 2011). Oyster reefs formed by the native flat oyster *Ostrea angasi* used to occur across more than 1500 km of coastline in the state of South Australia and formed a significant commercial fishery from 1836 to 1910. However, the extent of both was not known until recently (Alleway and Connell, 2015). During colonial settlement in southern Australia (ca. 1836), the oyster industry harvested *O. angasi* from more distant areas, after which they frequently "bedded down" the catch in places closer to port for later distribution to market (Inspector of Fisheries, 1886). This activity was, in many respects, a form of sea ranching. Oysters were occasionally reported to die in large quantities in these areas during hot spells or when demand for product was low, and in time the fishery collapsed due to overharvesting and the overexploitation of oyster reefs (Randall, 1911, 1912). While a commercial fishery for *O. angasi* no longer exists, the species is endorsed for growing on approximately half of the states' oyster aquaculture licences. Recovering the historical baseline thus provided the opportunity to explicitly consider the contemporary role of this species in aquaculture.

The South Australian aquaculture industry as a whole began in 1969 with the importation of 50 bags (~6000 individuals) of *Crassostrea gigas*, the Pacific oyster, from Tasmania (Olsen, 1994). Across all sectors, the industry contributes almost 55% of the states' total landed seafood value with a projected annual growth of around 8% (Econsearch, 2014), the second largest share of gross value of production in Australia (Stephan and Hobsdawn, 2014). Production centres on premium, high value products such as the southern bluefin tuna (*Thunnus maccoyii*), and abalone (*Haliotis* species). Nearly 50 years after a modest beginning, South Australia is focused on the sustainable development of aquaculture and maintains a high profile industry position (Stephan and Hobsdawn, 2014). Production is managed using a comprehensive process incorporating ecological data, e.g. habitat mapping of important habitats, such as a seagrasses, and water quality testing, into the determination of aquaculture production locations and models of regional carrying capacity, to establish production limits, as well as ongoing data collection and reporting to meet legislated requirements for environmental monitoring (Lauer *et al.*, 2015). Ecological and production-related data extending across more than one or two decades has, however, had limited use and historical data have not been included in planning.

Oyster aquaculture in South Australia principally occurs for the introduced species *C. gigas*, but government and industry have identified *O. angasi* as an alternative species for culture and growers have recognized the opportunity and value of diversifying their products. Government and industry-based investment is being made in diversification to meet local and global market demand and to reduce the consequences of reliance on one species and the risk of a disease event significantly affecting production (Roberts *et al.*, 2013). Furthermore, as current industry awareness and interest in growing a native oyster species has recently increased, this has created a degree of support for further research and development of culturing techniques for this species. This is principally in relation to development in a commercial sense, but will also aid efforts to achieve conservation, recovery, and restoration of this significantly degraded species (Beck *et al.*, 2011; Alleway and Connell, 2015).

Using three actual examples of natural resource management in the state of South Australia, we illustrate how historical data ("historical" being data collected more than three decades ago) can be used to inform aquaculture planning ("planning" being strategic development, regulation, policy, or management). The methods used to identify and incorporate this type of data into decision-making are described and the value of this approach is discussed. Our aim is to raise the profile of historical data in natural resource management, in particular aquaculture, and to highlight opportunities for continuing to develop methods for its application. The need for a secure global seafood supply implies that there will be increasing pressure placed on aquaculture to meet future demand.

Methods

Historical data collation

Historical records held within the State Records of South Australia, the State Library of South Australia, and the South Australian Museum were reviewed for information regarding the native oyster, oyster fishing, and aquaculture in South Australia. Records sourced included: annual government reports on the oyster fishery (e.g. Randall, 1911); the diaries and travel journals of state fisheries inspectors (Inspector of Fisheries, 1886); and correspondence between the inspectors and the overseeing government agency. These records spanned the 1880s through the mid-1900s. Records of catch, catch rates, quantities of oysters sold, fishing effort, and locations and depths of oyster beds were identified. During this review, records describing the translocation of a non-native oyster *Saccostrea glomerata* (Sydney rock oyster) from the eastern coast of Australia from at least 1885 to 1959 were identified, and locations to which *S. glomerata* were translocated were collated. The survival of *S. glomerata* was recorded (e.g. Randall, 1911), though the species did not establish a wild population because it does not currently occur within state waters (Wiltshire *et al.*, 2010).

Locations of historical oyster beds

References to locations of commercial oyster fishing were used to identify the historical distribution of beds. These locations were referred to by fisheries inspectors as having "payable beds" or being "payable areas" (Inspector of Fisheries, 1886), meaning these locations had densities of oysters sufficient to warrant commercial fishing by dredging. "Beds" are what are now widely termed oyster reefs; oysters in this formation grow in aggregations often in high densities (Inspector of Fisheries, 1886; White *et al.*, 2009).

Calculating historical catch quantities

Within the historical literature, we identified two locations, Kellidie Bay on Eyre Peninsula and Black Point on Yorke Peninsula, for which periods of continuous catch reporting occurred across discrete periods of time. Fishing records also existed for a further two locations, Stansbury on Yorke Peninsula and Spalding Cove on Eyre Peninsula, but these records contained disparate and missing information, and could not be used in isolation to calculate total numbers of oysters removed.

For the two locations where continuous catch reporting occurred, monthly catch recorded in bags (each containing ~350 oysters) were used to calculate total catch of oysters over 6 in in circumference (Gazette, 1873), the minimum size limit, for the period that catch was recorded (see Supplementary material). Monthly catch and references to the number of boats fishing at these locations were then used to estimate average daily catch rates (bags of oysters $boat^{-1}\ d^{-1}$) over the same period. We assumed that all recorded boats fished throughout the months for which catch was recorded, but that due to weather restrictions and the need to convey oysters to market, boats would not fish every day. Hence, to present a more accurate estimate of catch per unit of fishing effort, we tested two degrees of fishing intensity; 1/3 of days per month spent fishing and 2/3 of days per month spent fishing (Table 1) and cross-referenced these estimates with qualitative data sourced from historical records (see Supplementary material). This estimate was then used to fill gaps in the disparate data sourced for Stansbury and Spalding Cove. Estimated fishing intensity was applied to the number of boats reported fishing by the fisheries inspector and the daily catch rate of oysters at these locations (see Supplementary material), to calculate a mean monthly cpue, and thus an estimate of the total number of oysters removed from these beds.

Calculating historical densities

Density refers to the number of oysters per hectare (ha) of seabed. Owing to a minimum landing size of 6 in diameter, implemented in 1873, oysters <6 in were not recorded and thus could not be included in our calculations. Area of available seabed (ha) was calculated for the two embayments on Eyre Peninsula, Kellidie Bay and Spalding Cove (Figure 1, Supplementary material). Polygons were created in Google Earth Pro, based on historical references to areas fished, the limits of which were dictated by the entrance to the bay, and from which, fishing grounds historically referred to by a different name were excluded. The area of the polygon (in hectares) reflects the maximum area the oyster fleet would have fished at that time and, therefore, the maximum area of which oysters and oyster reefs at that location would have been distributed. Total catch quantities calculated for those locations were divided by the area of the embayment to estimate the minimum per hectare historical density of *O. angasi* (individuals >6 in).

Incorporating historical data into natural resource planning

The records collated and calculations made were utilized in three formal processes of natural resource management for aquaculture planning.

Consulting with government and industry

South Australia's *Aquaculture Act 2001* permits aquaculture through licences and leases, which are prescribed for through regional zone policies. "Zone policies" inform spatial planning and describe where, what species, and in what quantities products can occur within the zone boundaries, and are developed in consultation with industry, stakeholders, and local community. In October 2014, knowledge of the past ecological baseline of oyster reefs in South Australia (Alleway and Connell, 2015) and underlying historical data were presented to the state's research community through an open forum and then targeted meetings with aquaculture scientists and natural resource managers. The knowledge that oyster reefs historically occurred on the far west coast of South Australia was used to inform the allocation of localized growing areas in that

Table 1. Average catch (bags d^{-1} $boat^{-1}$) estimated from two scenarios of fishing rates, based on known total catch per month and number of boats fishing in 1887, at Kellidie Bay, Eyre Peninsula.

Date	Bags $month^{-1}$	Number of boats fishing	Average catch $boat^{-1}\ month^{-1}$	Average catch $boat^{-1}\ d^{-1}\ \frac{1}{3}$ fishing rate	Average catch $boat^{-1}\ d^{-1}\ \frac{2}{3}$ fishing rate
31 December 1886	470	22	21.36	2.07	1.03
31 January 1887	520	22	23.64	2.29	1.14
28 February 1887	392	22	17.82	1.91	0.95
31 March 1887	276	22	12.55	1.21	0.61
30 April 1887	220	22	10	1	0.5
31 May 1887	240	22	10.91	1.06	0.53
30 June 1887	190	22	8.64	0.86	0.43
Total	2 308 bags (807 800 individuals)				

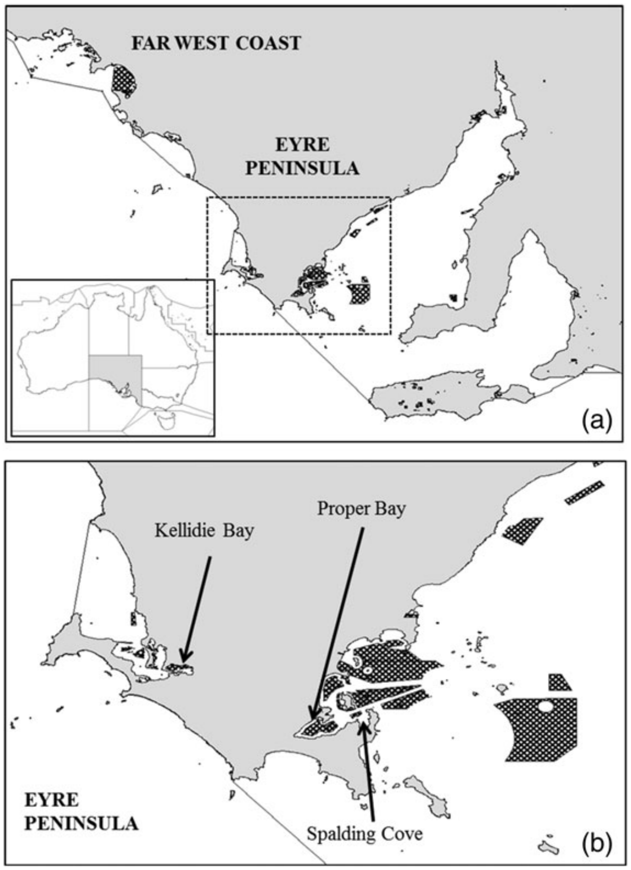

Figure 1. Map of South Australia, (a) indicating state waters in which aquaculture currently occurs, through leased and licensed water (shaded areas), and (b) the Eyre Peninsula and bays in which commercial fishing for the native oyster *O. angasi* historically occurred.

region and included in drafting of the Aquaculture (Zones—Denial Bay) Policy. In November 2014, state government managers of the aquaculture sector presented this knowledge and the draft policy to oyster growers and the community.

Consultation centred on the draft zone policy, which was made publicly available. Public and targeted meetings were held to answer questions and concerns, such as the proposal of growing in specific locations and whether the production quantities suggested might cause environmental harm. A period for the receipt of written submissions regarding the draft policy was also held. A response document to these submissions was then prepared, to highlight how variations to the draft policy were made as a result of consultation, as well as a final zone policy that incorporated these changes.

Assisting oyster production

In collaboration with the peak representative body for the sector, the South Australian Oyster Growers Association (SAOGA), government managers have developed national and state strategies to reduce and mitigate against the risks of the Osteroid herpes virus microvariant-1 (OHVμ-1) disease threat (Pacific oyster mortality syndrome, POMS). This disease, which affects *C. gigas*, has decimated the oyster-farming regions of Europe, New Zealand, and more recently New South Wales and presents a high risk to South Australia's industry because of its reliance on this single species of oyster (Roberts *et al.*, 2013). Increasing production of *O. angasi* to diversify the range of species produced through the oyster sector, to mitigate the economic effects of disease events, such as POMS, by enabling continued production of other species was recognized as a strategy to reduce uncertainty in production and was thus promoted to industry by both SAOGA and the government.

At the request of government scientists and managers, historical data of the past occurrence of *O. angasi* and oyster reefs, including depth records and quantitative estimates of oyster density, were collated for their use in planning. These data were discussed with government stakeholders, in particular scientists and managers, to promote a wider understanding of, for instance, the past presence of oysters in contemporary growing locations, abundances of oysters that historically occurred, and the ecological structure and function of these populations.

Conducting risk assessment

Ecological risk assessment is used in the management of aquatic resources and is considered an important tool to an ecosystem-based approach (Smith *et al.*, 2007). The process is used in fisheries management and continues to be refined because of the advantages it provides for explicit consideration of risks and in the incorporation of multiple objectives and differing stakeholder perspectives (Fletcher, 2005, 2014). The definition of risk assessment provided by the International Organisation of Standards includes the complete process of risk identification, analysis, consequence, likelihood, and evaluation (ISO, 2009). Analysing risk requires the identification of "risk events", which are then evaluated by quantifying the likelihood and consequence of their occurrence (ISO, 2009). A lack of information is often cited as a challenge to risk assessment, but not assessing risk events due to limited availability of data is effectively equivalent to the existing management action, or inaction, being rated by default as acceptable (Fletcher, 2014).

A species of interest for the diversification of aquaculture in South Australia is the non-native oyster *S. glomerata*. However, species exotic to South Australia are not permitted for release into state waters unless exempt by assessment and permit. Over the last two decades, applications made by industry to have this species assessed to permit growing have been rejected by government based on the species' perceived risk that it could become established in the wild through intentional translocation or spawning and recruitment from farmed oysters. Location-based historical records of "failed" translocations of this species were thus identified and incorporated into a risk-assessment framework.

On the basis that past and present environments may not be directly comparable, particularly due to climate change (Hobday, 2011), and unknown variation in the accuracy of the source of historical data, we applied a series of questions to pre-assess: (i) the validity and (ii) the contemporary application of the historical records. These questions specifically sought to qualify whether the historical records were likely to be accurate, rather than speculative, and contained information that could be applied to the contemporary environment (full method in Supplementary material). Risk events associated with the introduction of *S. glomerata* into South Australia were identified, e.g. the risk of "escape" through spawning and recruitment of farmed oysters, and the historical data and spatial records of earlier translocations were considered. Departmental monitoring data, from 2001 onward, were used to identify temperature and salinity profiles for six locations in which oyster growing currently occurs. These data were considered alongside knowledge of the optimal levels for the embryonic development, recruitment, and survival of spat from the native range of this species (Dove and O'Connor, 2007), and the historical records.

Results

Changing expectations of productivity; recovering a native oyster industry

Historical data of the past distribution of commercial oyster fishing and oyster reefs indicated areas on South Australia's far west coast (Figure 1) were important fishing grounds for *O. angasi* during the 19th century. These areas now support a regionally significant oyster-farming sector for the non-native oyster *C. gigas* and location data suggested these areas might also be suitable for commercial farming of the native species, as well as other native bivalves such as *Pinna bicolor*, razorfish. The presentation of historical data on the spatial distribution and prevalence of native oysters, and evidence of extensive commercial fishing in the past, generated government and industry interest in understanding location-based information of their past occurrence and the formation of oyster reefs. Practitioners felt that this knowledge was important to their understanding of contemporary production processes and directions for both management and industry development. The subsequent development of the zone policy for these areas, pursuant to the *Aquaculture Act 2001* (Lauer *et al.*, 2015), now proposes future expansion of oyster aquaculture, in particular for *O. angasi*, in areas that previously supported oyster reefs. The inclusion of these waters into this policy was a direct response to government and industry interest in *O. angasi* and new knowledge that oyster reefs were historically more widespread than originally thought (Alleway and Connell, 2015).

Reducing production uncertainty

Surveillance efforts have not yet detected POMS in South Australia, but this disease has affected oyster culture in other states. However, the disease does not affect the native oyster. Owing to the South Australian oyster culture industry's reliance on the production of *C. gigas*, *O. angasi* culture was accepted as a strategy to mitigate the economic consequences of a disease event devastating the industry.

Records of fishing depth or the depth of oyster reefs were collated for various locations in South Australia (Table 2). Depth records guided the development of the Draft Aquaculture (Zones—Denial Bay) Policy, by informing specific locations in which it could be appropriate to allocate growing areas on the far west coast, including subtidal and offshore areas.

Catch quantities, effort, and cpue were identified for a number of locations during the 1880s and 1890s (Table 3), e.g. 555 100 oysters were dredged from Proper Bay, Port Lincoln during 6 months of fishing in 1889 (Inspector of Fisheries, 1886). Estimates of fishing

Table 2. Examples of historical references of habitat characteristics relating to the past occurrence of oyster reefs formed by *O. angasi* in South Australia, and the depth of oyster fishing.

Location	Year	Historical record (qualitative statement)	Depth (m)
Boston Bay, Eyre Peninsula	1888	I beg to inform you that a bed of oysters was accidently hit upon in the middle of Boston Bay Port Lincoln in 9 fathom of water . . .	16.46
Boston Bay, Eyre Peninsula	1889	During the past month, my time has been chiefly occupied in my usual duties of inspection and observing the progress of the Oyster beds chiefly by personal dredging in both deep and shallow waters to ascertain the quantity of Oysters, as well as their condition. I have discovered several small beds of Oysters in 8 and 9 fathoms water, on a spit off the east side of Boston Island, the Oysters are large but there condition is not good being watery	14.63 – 16.46
Louth Bay, Eyre Peninsula	1890	. . . the Louth Bay oysters are principally found at a depth from 6 to 10 fathoms, and are exposed to the east and Southeast winds; therefore, they cannot be very well worked in the summer season	10.97 – 18.29
Smoky Bay, far west coast	1892	It is now my pleasing duty to be able to inform you that the aspect of the Oyster deposits in Smoky Bay is very satisfactory, the Oysters are principally found adhering to the razor fish, and extending over a large area of sea ground all along the shallow margin of the coast from a low water mark to 2.5 fathoms deep . . .	Low water—4.57
American River, Kangaroo Island	1914	The position is in ∼3 fathoms of water on firm sand, weed, and occasional rock; the bottom is distinctly a favourable one for the experiment (McIntosh, 1914)	5.49

Table 3. Selected recorded and reconstructed catch quantities and effort for historical *O. angasi* fishing in South Australia.

Location	Year	Original historical records of catch or cpue and length of time fishing	Estimated total *n* oysters removed during the period
Denial and Smoky Bay, West Coast	1894	8 – 10 bags d^{-1} for 12 months	3 150 d^{-1} $boat^{-1}$
Coffin Bay, Eyre Peninsula	1874	16 000 bags in 3 years	5 600 000
Dutton Bay, Eyre Peninsula	1888	200 bags in 2 d	70 000
Proper Bay, Port Lincoln	1889	1 586 bags in 6 months	555 100
Mount Dutton Bay, Eyre Peninsula	1888	1 630 bags in 6 months	570 500
Spalding Cove, Eyre Peninsula	1889	3 – 5 bags d^{-1} to each boat	1400 d^{-1} $boat^{-1}$
Reconstructed catch estimates based on historical records			
Kellidie Bay, Eyre Peninsula	1887	2 308 bags in 7 months, 22 boats	807 800
Black Point, Yorke Peninsula	1890	1 838 bags in 6 months, 12 boats and then 9 boats	643 300
Stansbury, Yorke Peninsula	1892	1 236 bags in 7 months, 8 boats and then unknown	432 600
Spalding Cove, Eyre Peninsula	1893	4 898 bags in 9 months, between 11 and 15 boats	1 714 300

Table 4. Minimum density of *O. angasi* oysters >6 in in circumference based on the maximum area available to fishing and oyster reef distribution and reconstructed catch estimates.

Location	Year	Maximum area available (ha)	Number of oysters caught >6 in	Minimum density of oysters >6 in
Kellidie Bay	1887	928.5	807 800	870 oysters ha^{-1}
Spalding Cove	1893	1 370.8	1 714 300	1250 oysters ha^{-1}

intensity extrapolated from these records suggested that one-third of time species fishing was likely to have reflected rates of historical fishing effort. Using the estimated and tested rate of one-third of time spent fishing (Table 1), additional location-specific catch records were calculated, e.g. an estimated 1 714 300 oysters were dredged from Spalding Cove, Eyre Peninsula during 9 months of fishing in 1893 (Table 3).

In Kellidie Bay in 1873, the minimum density of oysters >6 in was estimated at 870 oysters ha^{-1}, and in Spalding Cove in 1893, 1250 oysters ha^{-1} (Table 4). We considered these estimates conservative for the following reasons: the same locations were fished a number of times over decades (Inspector of Fisheries, 1886; Randall, 1911), the figures accounted for only a single point in time, and estimates did not account for oysters smaller than 6 in. The area estimated would also not have held continuous stands of oyster reefs, which were historically patchy in their distribution and their density variable (Inspector of Fisheries, 1886; Randall, 1911), resulting in a smaller total area over which oysters used to occur. Accurate knowledge of the historical area over which reefs used to occur, taking into account a higher degree of patchiness, would have increased the density of oyster per hectare estimated.

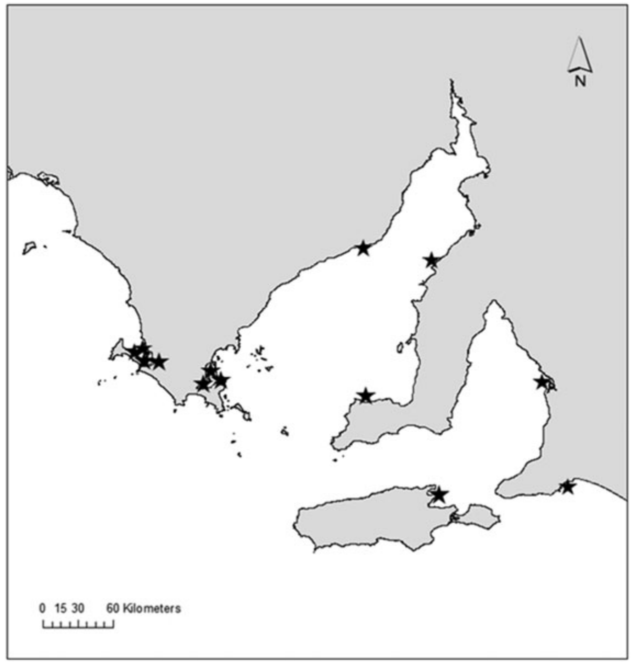

Figure 2. Locations of historical introductions of *Saccostrea glomerata* (Sydney rock oyster) along the coastline of South Australia from 1885 to 1959, as indicated by historical references within fisheries files of the State Records of South Australia and shell samples within the South Australian Museum.

Incorporating historical data in risk assessment

Fifteen locations were identified from the historical literature as having had releases of translocated *S. glomerata*, from 1885 to 1959 (Figure 2). Appraisal of the validity and applicability of the historical records from which these data were sourced indicated that the validity of the data was "high" and that it could, therefore, be used with "high confidence" (Table 5). This rating was reinforced by the data being reported solely by primary sources—fisheries inspectors and museum specimens—who are trained personnel with no known reason for reporting their observations with bias (see Supplementary material). Appraisal of the historical data in relation to its suitability for comparison to the current environment indicated the information was "reasonably applicable" (Table 6). The historical data were, consequently, considered appropriate for inclusion in risk assessment using a semi-quantitative Consequence × Likelihood (C × L) approach (Fletcher, 2014).

"Risk events" regarding the introduction of the exotic *S. glomerata* and its growing in South Australia were broadly categorized against the probability of its colonization and establishment, and the probability of its spread, and within these categories, the more specific risk events of spawning (release) from aquaculture leases, and recruitment, survival, and establishment of feral oysters as well as their spread through accidental and intentional translocation. Disease risk was also considered but was not informed by the historical records. Risk scores associated with these events were assessed as "low" to "moderate".

Table 5. Validity of information: 0–1 questions answered "yes" = low confidence of validity; 2–3 questions answered "yes" = moderate confidence; 4 questions answered "yes" = high confidence.

Validity of information—questions provide an indication of the confidence with which historical information can be used	Response for *S. glomerata*
Are multiple data points available?	Yes
Are multiple sources or types of data available?	Yes
Do primary information sources contribute >75% of the data?[a]	Yes
Was the information written by a person in a position of authority?[b]	Yes

[a]Information sources included published government reports, departmental diaries and correspondence, and Museum records.
[b]The authority of the person reporting information may increase objectivity in the response provided. This question places less value on historical records that are more difficult to authenticate or validate because of the author, e.g. personal statements in newspaper articles.

Through the risk assessment, researchers and managers concluded *S. glomerata* may spawn on aquaculture leases and recruit to the wild; however, the salinity of locations across South Australia would likely limit their growth and hence the impact they could have on the environment. Knowledge of multiple historical translocations of this species without its subsequent establishment provided confidence in the assessment that while *S. glomerata* might survive, it is not likely that the species will form a persistent wild population. It was also concluded that there remained a lack of information, often an outcome of risk assessment

Table 6. Applicability of information: 0–2 questions answered "yes" = not applicable, 3–5 questions answered "yes" = moderately applicable; 6 questions answered "yes" = very applicable.

Current applicability of information—questions indicate whether the information applies to the current setting	Response for *S. glomerata*
Does the information apply to the same species for assessment?	Yes
Does the information apply to the same geographical area for assessment?	Yes
Was the information reported <20 years?	No
Was the information reported <50 years ago?	Yes
Was the information reported <100 years ago?	Yes
Are the ecological conditions directly comparable to those in the period for which the information was recorded (with particular attention to climate)?	No

(Fletcher, 2014), but the historical data appreciably bridged this knowledge gap. The policy outcome of the assessment was that applications to culture *S. glomerata* in South Australia would be formally received by the government. This species represents a new commodity for the sector, which could support diversification and security in production.

Discussion

Reconstructed estimates of species' or habitat distributions or abundance provide a means to bridge the knowledge gap between past environments and their present use (Rosenberg *et al.*, 2005; Mann *et al.*, 2009). For example, contemporary aquaculture in open seas can be characterized by uncertainty, including high mortality due to environmental impacts (e.g. changes in water quality, and disease events; Nell, 2001; Roberts *et al.*, 2013), but knowledge of the occurrence of past species and their distribution can provide an informed position for industry and government's to support the diversification of aquaculture, through the range of species grown or spatial expansion and movement of aquaculture facilities. Diversification could reduce the economic risks associated with disease or environmental events, because identifying potential areas for the expansion or movement of aquaculture can provide some security to production (Oglend and Tveteras, 2009). The value and efficacy of underpinning planning decisions for aquaculture, such as spatial planning, with historical data is exemplified here.

A new focus on "native oyster aquaculture" in South Australia illustrates the value of identifying past ecological baselines and using historical data in natural resource management. Recovering the "lost" ecological baseline for *O. angasi* and oysters reefs in South Australia (Alleway and Connell, 2015) increased interest in the growing of this species and generated the incorporation of further historical data into multiple processes for aquaculture planning. Locations of oyster reefs formed by *O. angasi* and calculations of historical catch provided an evidence-based position for the development of aquaculture and planning activities in South Australia. Limitations of the catch records and density calculations applied to planning include the application of several assumptions, e.g. assumed fishing intensities and an unknown measure of confidence. Additional data that could reduce the use of assumptions, or assist in determining a confidence rating, would be of value. The use of multiple data sources, including alternative sources, e.g. newspaper articles, or interviews with fishers to elicit intergenerational data, is one method that can increase the certainty of historical estimates (Pinnegar and Engelhard, 2008; Thurstan *et al.*, 2014) and it might be possible to identify and collate additional historical records. However, the use of preliminary estimates, such as the minimum oyster densities generated from the historical catch data here, provide an earlier baseline for planning and an informed position for engaging and consulting with stakeholders.

Refined density calculations could be made using spatial layers that indicate habitat types or bathymetry data for shoals, sandbanks or mean low tide, and probable areas in which oysters would or would not historically have occurred. Records of the depth at which oysters occurred or were fished could also refine estimates, provided these records were complete for an embayment and could be incorporated into contemporary spatial data or mapping. Biological data on filtration rates and food consumption were also not available, but could, in time, be used to make comparisons between the minimum historical oyster density and contemporary stocking densities, of the native oyster or other bivalve species. It might be possible to incorporate such calculations into models for carrying capacity and marine spatial planning (Filguiera *et al.*, 2014), or use these to compare past and present water filtration rates and the residence time of water within embayments (e.g. zu Ermgassen *et al.*, 2013). Where the historical turnover of water is greater than that achieved by naturally occurring bivalves, in combination with those cultured, such calculations could alleviate concerns about the carrying capacity of embayments and stocking densities that are perceived to be high.

Increasing demand for seafood will result in multiple pressures on aquatic resources (Diana, 2009; Duarte *et al.*, 2009; McClanahan *et al.*, 2015), one of which will be the need to grow new or exotic species. Diversifying production provides a means to support food security, because it can contribute to stable production quantities and continuity of supply. Market demand for a range of commodities and societal expectations for high quality food will also drive increased diversification in seafood. The culture of new species must, however, be evaluated against their potential impacts and the possible negative effects of a simplified and homogenous ecosystem (Howarth *et al.*, 2014), which could result from the persistent and widespread introduction of exotic species in new areas. Risk assessment provides a means to objectively identify and evaluate the potential impacts of activities, to reduce uncertainty through multiple lines of evidence (Fletcher, 2014). It also provides an informed, transparent, and accountable decision-making framework for the management of aquatic resource use (McClanahan *et al.*, 2015). Historical data could, where available, support the qualitative and quantitative evaluation of risk events and be explicitly incorporated into risk assessment across the continuum of methodology, e.g. from qualitative evaluation of the C × L of a risk event, through semi-quantitative application of risk ratings based on scores associated with C × L, and a fully quantitative approach that uses measured changes in ecosystems as a result of human impact (Figure 3). These uses require testing, particularly for the quantitative application, across a range of species, locations, and scenarios, preferably through species-specific suitability models with long-term data (Karatayev *et al.*, 2015). Historical information can be incorporated immediately though, into risk assessment through informing the identification and qualitative consideration of risk events, and perhaps pragmatic evaluation of C × L ratings.

The potential for aquaculture to result in social and ecological impacts decrees a shift to physical systems and governance frameworks that can provide greater accountability (Duarte *et al.*, 2009; Smith *et al.*, 2010; Bush *et al.*, 2013). Practices and management

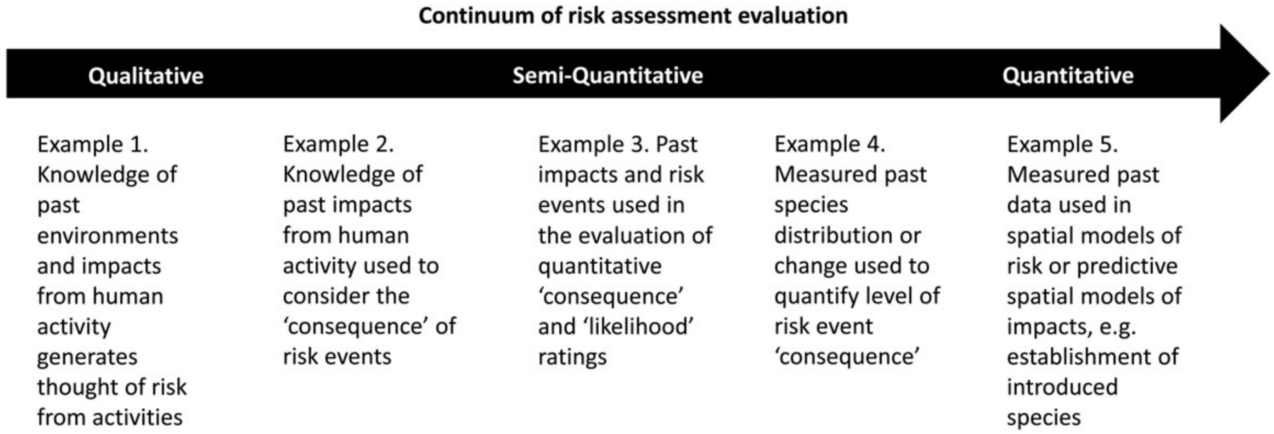

Figure 3. Schematic illustration of examples of how historical information and data can be incorporated into risk assessment across the continuum of evaluation, from qualitative to fully quantitative.

systems in aquaculture are improving (Diana, 2009; Duarte *et al.*, 2009), but the social licence to operate remains a challenge, for which community engagement plays a unique role (Dare *et al.*, 2014). Identifying situations in which historical baselines can be applied to aquaculture planning could improve the social perception of the industry and increase its social licence to operate. It could also assist in bridging the "people-policy" gap (Krause *et al.*, 2015), through the use of historical records that specifically relate to a community or industry and therefore create a degree of intrinsic interest, and will contribute to increased understanding of feedback between social systems and marine ecosystems through historical ecological research (Schwerdtner Máñez *et al.*, 2014).

Opportunities for progress

Active incorporation of historical data into natural resource management and planning is not common. However, the value of having knowledge of past baselines and older sources of information is being increasingly realized and there is a cumulative understanding of the methods and approaches that can be used to support its use in management (e.g. Kittinger *et al.*, 2014). Aquaculture is no exception and there is considerable scope to progress the incorporation of historical data in aquaculture planning and the reconciliation of marine historical ecology with the practice of aquaculture more broadly (science, research and development, production, and management). Based on our experience, through the examples presented here, we suggest several immediate opportunities to continue developing these methods and its application.

First, the link between past ecological states and contemporary use of marine environments needs explicit investigation in relation to aquaculture. Knowledge of past ecosystem states could underpin the value of aquaculture for "forgotten" species or resolve that production for particular sectors, or aquaculture in particular locations, might in fact not be appropriate. Highlighting the historical baseline for *O. angasi* in South Australia, to government and industry, led to interest from researchers and aquaculture growers and the community, in the underlying historical data and its potential application to other aspects of planning. Second, refining a method for the explicit unification of historical data and risk assessment would be useful to aquaculture planning for introduced species, aquaculture in new locations, the use of new farming methods, or the expansion of the area of water zoned to permit aquaculture and available to the industry. This application could also be applied to other food production sectors and in natural resource planning more broadly, particularly where risk assessment is an important tool in achieving ecologically sustainable development. Third, greater advocacy of the value of using historical data in planning is needed. This is true for many areas of policy and management; its use in relation to aquaculture could motivate and promote this value because of the high profile role the industry will maintain over coming decades through its contribution to global food security.

Seafood production through aquaculture has grown steadily over recent decades (Naylor *et al.*, 2000), to meet the demands of an growing global population, and it is likely that aquaculture will continue to increase (Diana, 2009; FAO, 2014). Ecologically sustainable development of aquaculture requires the setting of accurate management targets, which can be assisted by the inclusion of historical data (Connell *et al.*, 2008; Schwerdtner Máñez *et al.*, 2014; Thurstan *et al.*, 2014) to reduce risk to production and the environment. There is economic value in considering production in the face of past and future environmental change, whether global or locally caused, because the state of the environment, and concern for environmental degradation, not only affects yield but also societal perceptions towards aquaculture and the products and quantities that can be produced. Hence, the pre-emptive application of historical data has a central role in informing the setting of policy and future management.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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SUPPLEMENTARY MATERIAL

Incorporating historical data into aquaculture planning

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Appendix 1. Method for reconstructing historical records of catch quantities and catch rates, based on changes across time and assumptions of fishing intensity.

Four locations with subsets of continuous data or multiple data points were identified and used to make estimates about fishing rates and catch quantities. Monthly catch recorded in bags at two locations, Kellidie Bay (Eyre Peninsula) and Black Point (Yorke Peninsula) and references to the number of boats fishing at these locations were used to estimate average daily catch rates, over 7 and 6 months respectively. Catch rates were calculated for two different scenarios of fishing intensity; ⅓ and ⅔ of time (days) spent fishing per month. Scenarios of fishing intensity were estimates only, based on an assumed number of days, but estimates were cross-referenced with available anecdotal references of catch rates and catch per unit effort during the same time period to increase certainty. These sources were derived from diaries and letter books of the fisheries inspectors.

The estimates of fishing rates were then applied to a further two locations, Stansbury (Yorke Peninsula) and Spalding Cove (Eyre Peninsula), which had non-contiguous data but multiple data points of varied type, e.g. catch, daily or monthly CPUE or effort, over a known period of time. These data points were used to populate tables of monthly catch, effort, CPUE, daily catch rate and the total number of individuals caught. Monthly catch quantities, real and interpolated, were graphed and catch in bags, at the end of each month, was translated from a moving average trend line. Translated monthly catch estimates were summed to provide a total catch figure (bags and individuals) over the known period of time.

Estimate 1: Kellidie Bay, Eyre Peninsula

Data within the diary of the Inspector lists quantities caught per month in Kellidie Bay (Eyre Peninsula) from December 1886 to June 1887. The total number of bags caught during the 7 months was 2 308 bags (807 800 individuals) from multiple beds within the bay. A decline in the monthly catch was observed during this time from 470 bags in December to 190 bags in June and though it was likely that some level of fishing occurred after this date a letter from the Inspector to the Marine Board on the 9th June 1887 highlighted that; *"The quantity of a marketable size have been so reduced that each cutter cannot catch more than one bag per day …"*. Fishing rates from June onwards were likely greatly reduced after June 1887.

It was also recorded that 22 boats were dredging constantly during that time, at that location. From these records the average monthly catch per boat was calculated. Under a scenario of ⅓ time per month spent fishing the catch per day per boat was initially 2.07 bags. Catch increased to 2.29 bags before steadily declining to 0.86 bags. A scenario of ⅔ time per month spent fishing showed an initial catch rate of 1.03 bags to a decline of 0.95 bags after 3 months, in February 1887. Taking into account the above statement, and additional references that good fishing was at that time still occurring - *"The outer grounds in the outer Bays are not so prolific as those beds which are situated in Kellidie Bay …"* (letter to the Marine Board, 8th January 1887) - ⅔ of time spent fishing was considered to be too high and a fishing intensity of ⅓ time per month was considered to be the likely fishing scenario.

Estimate 2: Black Point, Yorke Peninsula

A second estimate was generated from comparable monthly catch data at Black Point (Yorke Peninsula) but in this example the number of boats dredging was initially recorded as 12 and in later months 9 (Table 1). An interim daily catch rate of 4 to 5 bags per day to each boat fishing was recorded on April 14th 1890.

Monthly catch increased initially and then decreased, from 410 bags to 179 bags in June 1890. Average daily catch rates per boat under a scenario of ⅓ time per month spent fishing declined from 3.31 to 1.99 bags per day and under the scenario of ⅔ time per month fishing showed an initial catch rate of 1.65 bags to a decline of 0.99. Because it was recorded that 4 to 5 bags per day were being caught per boat the ⅔ fishing scenario was not likely and ⅓ fishing intensity, or less, was more realistic.

The decline in catch was similarly recorded as being a result of overfishing; on 21st August 1890 the Inspector reported; "*In the morning off Port Alfred, or Black Point, these grounds have been worked out, and I find no Cutters dredging here*."

These calculations are only estimates and there are limitations to the data including the small sample set, the assumption that catch quantities were accurately reported by the Inspector and that all boats were fishing at all times. It is likely that there was fluctuation in the number of boats fishing and that monthly and daily catch was higher on some boats than others however, these estimates provide an indication of how much time was spent fishing by the oyster fleet as a whole.

Table 1. Average catch (bags per day per boat) estimated from two scenarios of fishing intensity, known total catch per month and number of boats fishing, at Black Point, Yorke Peninsula.

Date	**Bags month^{-1}**	**Number of Boats**	**Average catch boat^{-1} month^{-1}**	**Average catch boat^{-1} day^{-1} at ⅓ fishing rate**	**Average catch boat^{-1} day^{-1} at ⅔ fishing rate**
31/01/1890	410	12	34.17	3.31	1.65
28/02/1890	429	12	35.75	3.83	1.91
31/03/1890	313	12	26.08	2.52	1.26
30/04/1890	290	9	32.22	3.22	1.61
31/05/1889	217	9	24.11	2.33	1.17
30/06/1889	179	9	19.89	1.99	0.99
TOTAL	**1 838 bags (643 300 individuals)**				

Estimate 3: A single bed, Stansbury, Yorke Peninsula

A mix of total monthly catch quantities, the number of boats fishing and specific references to daily catch rates were identified for a bed just north of Stansbury (Yorke Peninsula) from 5th October 1891 to the 5th June 1892. Assuming a fishing intensity of ⅓ time per month recorded and interpolated monthly catch rates were calculated. End of month catch was translated from a moving average trend line with the total sum of bags caught estimated to be 1 236 in 7 months (432 600 individuals) (Table 3). Fishing occurred for at least 9 months but estimates of monthly catch were not able to be made for the first and last months.

Table 2. A single bed north of Stansbury: catch and effort records with interpolated quantities based on 1/3 fishing rate. **Bold** text = historical data reported through records. *Italicised* text = assumptions applied and normal text = extrapolated. End of month catch quantities translated from a moving average trend line between reported and interpolated catch quantities (bags).

Date	Monthly Catch (bags)	Effort	CPUE	Daily Catch Rate	Total Individuals Caught for Month
05/10/1891		**Boats dredging**			
31/10/1891	No estimate				
13/11/1891	320	**8 boats dredging**	40 bags month^{-1} boat^{-1}	3.87 bags day^{-1} boat^{-1}	112 000
30/11/1891	320				112 000
05/12/1891	**320**	*Assumed 8 boats dredging*	40 bags month^{-1} boat^{-1}	3.87 bags day^{-1} boat^{-1}	112 000
31/12/1891	267				93 450
09/01/1892	247.92	*Assumed 8 boats dredging*	30.99 bags month^{-1} boat^{-1}	**2 to 4 bags day^{-1} boat^{-1}** *(average 3 bags day^{-1} boat^{-1})*	86 772
31/01/1892	217				75 950
28/02/1892	176				61 600
31/03/1892	129				45 150
30/04/1892	85				29 750

01/05/1892	82.64	**'Continual dredging on this bed for the last 8 months. Average catch down.'** *(Assumed 8 boats dredging)*	10.33 bags $month^{-1}$ $boat^{-1}$	**1 bag day^{-1} $boat^{-1}$**	28 924
30/05/1892	42				14 700
05/06/1892		**'Continual dredging on this bed for the last 9 months. Average catch down.'**			
30/06/1892	No estimate				
TOTAL	**1 236 bags**	**7 months dredging**			**432 600**

Estimate 4: Location of Spalding Cove, Eyre Peninsula

Comparable isolated data points were identified for the location of Spalding Cove (Eyre Peninsula) between 31st August 1892 and 17th July 1893. Using the same approach as Estimate 3 a total catch of 4 898 bags (1 714 300) in 9 months fishing was calculated (Table 3). Fishing occurred for at least 12 months in this location, for 1 month prior to and 2 months after the last monthly catch value, however estimations could not be made for these months.

Although a total approximation of the number of oysters in particular locations or regions could not be found, or made, these estimates provide an understanding of the numbers of oysters on individual beds.

Table 3. The location of Spalding Cove: catch and effort records with interpolated quantities based on 1/3 fishing rate. **Bold** text = historical data reported through records. *Italicised* text = assumptions applied and normal text = extrapolated. End of month catch quantities translated from a moving average trend line between reported and interpolated catch quantities (bags).

Date	Monthly Catch (bags)	Effort	CPUE	Daily Catch Rate
31/07/1892	No estimate			
31/08/1892	1 011			
06/09/1892	975	**15 boats dredging**	65 bags month^{-1} boat^{-1}	**6.5 bags month^{-1} boat^{-1}**
30/09/1892	876			
31/10/1892	747			
19/11/1892	**1417 (in 4.5 months of fishing) 314.89**	**14 boats licensed and recorded catch**	22.49 bags month^{-1} boat^{-1}	2.18 bags day^{-1} boat^{-1}
30/11/1892	613			
31/12/1892	472			
12/01/1893		**11 boats dredging**		
25/01/1893	361.62	**All boats** *(Assumed 14 boats dredging)*	25.83 bags month^{-1} boat^{-1}	**2.5 bags month^{-1} boat^{-1}**
31/01/1893	371			
28/02/1893	430			
03/03/1893	433.86	*(Assumed 14 boats dredging)*	30.99 bags month^{-1} boat^{-1}	**3 bags.day^{-1} boat^{-1}**
31/03/1893	278			
11/04/1893	210	*(Assumed 14 boats dredging)*	15 bags month^{-1} boat^{-1}	**1.5 bags.day^{-1} boat^{-1}**
30/04/1893	100			
31/05/1893	No estimate			
17/07/1893		**Boats dredging**		
TOTAL	**4 898 bags (1 714 300 individuals)**	**9 months dredging**		

Appendix 2. Estimated area of embayments, generated from polygons in Google Pro and the consequent maximum area likely available for the historical distribution of *Ostrea angasi* reefs in these locations.

Figure 1. Area of Kellidie Bay, Eyre Peninsula, and the maximum area available to the historical distribution of oyster reefs formed by *O. angasi* and the fishing for this species, in this location.

Figure 2. Area of Spalding Cove, Eyre Peninsula, and the maximum area available to the historical distribution of oyster reefs formed by *O. angasi* and the fishing for this species, in this location.

Appendix 3. Information and method used to incorporate historical information into risk assessment for non-native oyster species (*Saccostrea glomerata*) aquaculture in South Australia.

Historical Data

Saccostrea glomerata has previously been introduced to South Australian waters, on a number of occasions between at least 1866 and 1977. Olsen (1994) described some of these introductions in relation to the development of oyster aquaculture in the state:

"Early attempts to grow rock oysters in southern Australia

An attempt in 1886-7 to acclimatise the Sydney rock oyster at Hobart, Tasmania was unsuccessful (Saville-Kent 1887). A trial shipment of the same species spread out on trays at Kelso, River Tamar, in northern Tasmania in 1948 by a Sydney rock oyster grower failed too (Olsen 1965).

In 1933-4 attempts were made to cultivate young Sydney Rock oysters on a commercial scale in South Australian waters. 228,000 oysters were laid out on trays off the west bank of the Port River below the Osborne Power Station where an earlier experimental consignment had reportedly grown very fast (Anon. 1934[1]; Wallace-Carter 1987). Other attempts to acclimatise the Sydney rock oysters were made in 1937 at Mt Dutton and Kellidie Bays without success.

A small consignment of juvenile Sydney rock oysters from a warm water environment at a solar saltfield at Port Alma, Queensland was transferred in May 1976 into seawater of approximately similar salinity and temperature of the primary pond of the solar saltfield at Dry Creek. Within 3 months 95% of the experimental consignment died. Later the same year a second experimental consignment was transferred from the same source and these oysters suffered 70% mortality within a month. As a result of these experiments further translocation experiments into quarantine areas at Dry Creek ceased (Melvin per comm.).

So far as the author is aware the last attempt to acclimatise Sydney rock oysters in South Australia was in 1977 when oysters put into the commercial prawn farm ponds at Port Broughton failed.

Thomson (1952) remarked that conditions of the waters of the southern states are outside the natural range of the Sydney rock oyster."

[1] *ANON. (1934) Large scale farming of Sydney rock oysters in Port River. "The Saturday Mail" 14 July, 1934.*

Other sources reported earlier introductions, including Randall (1911):
"REPRODUCTION OF OYSTER TRANSPLANTED FROM FOREIGN WATERS. Bearing on the possibility of reproduction of oysters that have been transplanted from foreign waters, a particularly interesting case has come under observation. In March last, in company with Mr. E. Nelson (the oyster merchant of Port Adelaide), and inspection was being made of the laying beds under Jervis Bridge. Here are laid down oysters for commerce from Queensland, New South Wales, New Zealand, and our own. Clusters of young oysters were noticed growing on one of the bridge cylinders. A number of there were forwarded to the Fisheries Department of New South Wales, with a request that they might be identified and classified. The naturalist to that department (Mr. David G. Stead) reported therein and stated that they appeared to be Ostrea cucullata, *or the common rock oyster of New South Wales. Before finally deciding on the species Mr. Stead asked to be furnished with some of the adult South Australian oysters in shell, and also the animal only preserved in formalin. These were sent, and Mr. Stead reported them to belong to the species* Ostrea edulis var. *In connection with his report he made the following interesting comment :--"It is worthy of mention here that I consider it probably that* Ostrea edulis *has only found its way to the east coast of Australia in recent geological times, viz., since the great subsidence of the land between Tasmania and Australia which made Bass's Strait, thus rendering the migration of southern forms to the east coast more easy." Pursuing our investigations, it was found that the supposed parent oysters were taken up in New South Wales when the rivers were in flood and the waters therefore brackish. They were laid down at Port Adelaide under similar conditions, the Torrens and Sturt Rivers being flooded at the time. The conclusion arrived at is that under these special circumstances reproduction had naturally taken place. This reproduction question is presenting difficulties to oyster experts both in Europe and America. For instance, there does not appear to be any authenticated instance of French or Belgian oysters reproducing in Great Britain, or* vice versa, *and the same applies to the east and west Pacific slopes of America. It will be readily realised that the case of ascertained reproduction here mentioned will be an occasion of much interest to student of ostreaculture, and worthy or recording here."*

Also Randall (1912):

"By courtesy of the Fisheries Department of New South Wales we received a sack of selected brood oysters (oystrea cuculllata) in September, 1911. These arrived in good order, and were laid down in secluded positions at the extreme western end of the oyster reserve. A severe easterly gale in February last brought in quantities of seaweed, and this interfered with those exposed to the weed, which at the time were thriving. The oysters in other parts are flourishing and well grown, but there are no signs of reproduction."

"Even if these foreign oysters prospered in our waters, the practical results may be considered to be of doubtful value, because the sufficiently sheltered localities suitable for the growth of rock oysters are comparatively small in area ; and it is just possible that some pest might be introduced with them that we are free from."

This same introduction was commented on two years later by McIntosh (1914):

"In September, 1911, a quantity of New South Wales' oysters (Ostrea cucullata) were procured from the Fisheries Department of that State, and laid down in the nursery. At first they were thriving, increased in size, and were in good condition ; later on they showed signs of depreciation, and during the past year have practically disappeared. There can, I think, be no doubt that the result if to be attributed chiefly to the effects of past dry season, the increased salinity of our waters being entirely different to the character of those from which they were taken. No signs of reproduction have been noticed. The apparent failure of these oysters need not, I think, be viewed as a drawback, the South Australian oyster (Ostrea edulis) is one of the best, and it is possible that the introduction of the New South Wales oyster into our waters might lead to the presence of some pest that at present we are free from."

An additional introduction in 1910 was commented on by McIntosh (1913), however this may have been incorrectly reported and been a reference to the 1911 event:

"Experimental Transportation of Foreign Oysters—The rock oysters (Ostrea cucullata) obtained from the New South Wales Fisheries Department in September, 1910, and laid down in secluded portions of the oyster reserve have made good growth, and are in excellent condition, no signs of reproduction having been noticed ; this was anticipated. In a previous report it was stated that even if this oysters should prosper in our waters, the practical results may be considered to be of doubtful value,

because the sufficiently necessary sheltered waters are limited, and it is just possible that some pest might be introduced with them that we are free from."

Numerous introductions were described by the Fisheries Inspector through correspondence with the Marine Board and in his journal of travel and inspection. These records were:

Source	Record	Date	Location
Letter from Inspector (Dabovich) to Marine Board, Port Lincoln, February 1st 1889	… in accordance with arrangements previously made I received from Mr. Charles Atkins of Port Adelaide on January 23rd two bags at a cost of 24 shilling of Sydney Rock Oysters which I had instructed him to collect for me in the locality of Jervois Bridge, Port Adelaide River.	1889	Port River
Letter from Inspector(Dabovich) to Marine Board, Port Lincoln, February 1st 1889	I have been busily engaged planting the contents of one bag in small quantities in Port Lincoln Proper Bay and neighbouring bays in suitable places, well protected from destruction either by stingray, sea wash or marine accumulation. On the 28th of January I proceeded overland to Coffins Bay taking with me the 2nd bag of Sydney Rock Oysters in a once horse conveyance, and immediately on arrival there proceeded to deposit them in various places which I deemed most suitable.	Jan.1889	Proper Bay (Port Lincoln) and Coffin Bay
Port Adelaide	The Sydney Rock Oysters I planted	Feb.	Port

November 2nd 1891, Letter from Inspector (Dabovich) to Under Treasurer	in Port Lincoln waters in February last, are thriving favourably but as yet I could not observe any young spat but this is all in good time yet.	1890	Lincoln
Journal of travel and inspection, Sep. 23rd 1889 (Mount Dutton Bay)	… I find that on some of the beds there were a fair quantity of the young Oyster brood settled since this Bay being closed. The razor fish which I placed there some time ago are progressing favourably, also the Sydney Rock Oysters which I put there they thriving favourably.	1889	Mount Dutton Bay
Journal of travel and inspection, Mar. 26th 1891	… to inspect the Oyster beds in Spalding Cove and also to lay down the contense of one bag of the Sydney Rock Oysters, which I have collected in the Port Adelaide River… I found the oysters there to be plentiful and in a remarkably good and healthy condition, but not for market being to small.	Mar. 1891	Spalding Cove
Journal of travel and inspection, Oct. 28th 1891	… rowed to Salt Creek and other places for the purposes to examine the Sydney Rock Oysters which I planted some months ago, found them in very healthy condition but could not see any young Brood.	1891	Salt Creek (Coffin Bay, West Coast)

The collections of South Australian Museum contain dry samples of *S. glomerata*, although they do not contain additional information regarding in what form or why they were collected (e.g. from a aquaculture, fouling on substrate or infrastructure, or naturally occurring). These samples were collected from:

- Port River
- Point Riley
- Franklin Harbour (Cowell) in 1910
- Kingscote (Kangaroo Island) in 1959
- Corny Point
- Coffin Bay
- Hindmarsh River
- Outer Harbour

Although a secondary reference, Wallace-Carter (1987) described introductions in additional locations including Victor Harbor:

"The importance of the oyster industry was made clear by the then Treasurer, William B. Rounsevell, when introducing the amending Act of 1885. He said: 'The oyster fishery at the present time is an important industry and anything that can be done to increase its importance must result in benefit to the State.' He went on to talk of planting the Sydney rock oyster on suitable parts of the coast and an unsuccessful attempt that had already been made by a Member of the House to grow these oysters at Port Victor (Victor Harbor). The failure he ascribed to the oyster being placed at too great a depth."

Introductions were reported in the early 1900s in Kellide Bay:

"Three years later he said, 'In 1889 there were twenty-eight boats employed in the oyster fishing industry. Since then each year it has shown a decrease in the number until now (1903) there are only five boats engaged. He went on to say that these five were doing fairly well, dredging near Point Bolingbroke and in Louth Bay. He also reported that the oysters in Port Douglas were quite good, those in Kellidie Bay were more prolific and 'the Sydney rock oysters, planted there some years ago are thriving."

Also:

"A Sydney rock oyster project was started that year – 1934 – but not by the oystermen. An attempt was made to farm these oysters on a large scale in the Port River at

Osborne. The newly-formed company – The South Australian Oyster Company – was managed by J. M. Laman, whose family had been oyster farming in New South Wales for the previous fifty years, according to the South Australian weekly newspaper, the Mail*. Their plan was to produce a million dozen oysters a year by 1938 of thereabouts for South Australian and Western Australian consumption.*

For about four or five months we have been carrying out experiments with Mr. Laman, an oyster farmer from Port Stephens, New South Wales', Chief Inspector Walter Bruce said in 1934. 'Those experiments have proved conclusively that the Sydney rock oyster will do particularly well in South Australian waters, their growth has been phenomenal. They have fattened more quickly than in their own state. …

On this occasion Chief Inspector Walter Bruce was wrong, as, like all other attempts to farm Sydney rock oysters in South Australia, the venture was unsuccessful."

Historical introductions

Collating the records indicated *S. glomerata* had previously been introduced at 16 locations in South Australia, between 1886 and 1977. The 1977 recorded was excluded from consideration because it did not occur in the natural environment, i.e. translocation was to saltfields. At some locations introductions occurred multiple times over a number of decades. No records indicated these introductions led to the long-term establishment of *S. glomerata* in South Australia. However, the relevance and application of this information must be considered because it is historical. Questions to evaluated the validity of the information and its applicability to the current setting were developed and applied to the historical records and data.

Pest Risk Assessment

Use of historical information in risk assessment

Validity of Information: The results of these questions provide an indication of the confidence with which the information can be used.

1. Are multiple data points available?
2. Are multiple types or sources of data available?
3. Is more than 75 % of the information from a primary source?
4. Was the information written by a person in a position of authority?

0 to 1 questions answered 'yes'	= Low confidence
2 to 3 questions answered 'yes'	= Moderate confidence
4 questions answered 'yes'	= High confidence

Current Applicability: The results of these questions indicate whether the information applies to the current setting.

1. Does the information apply to the same species for assessment?
2. Does the information apply to the same geographical area for assessment?
3. Was the information reported less than 20 years?
4. Was the information reported less than 50 years ago?
5. Was the information reported less than 100 years ago?
6. Are the ecological conditions the same as the time period for in which the information was recorded (give particular attention to temperature)?

0 to 2 questions answered 'yes'	= Not applicable
3 to 5 questions answered 'yes'	= Reasonably applicable
6 questions answered 'yes'	= Very applicable

Assessment of historical information for* S. glomerata *in South Australia

Validity of Information:

1. Yes
2. Yes
3. Yes
4. Yes

→ Information can be used with 'high confidence'

Current Applicability:

1. Yes
2. Yes
3. No
4. No (NB: 1977 record excluded because location used was prawn farming ponds and salt ponds, i.e. not a natural environment.)
5. Yes
6. No

→ Information is ‘reasonably applicable’

Supplementary Material References

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Chapter 7: Discussion

7.1 Summary of thesis

Although the spatio-temporal scale of human impacts can vary, anthropogenic influences have pressured ecosystems over prolonged periods of time. These ecosystems now define the way that species and habitats function and, as a result, our perspectives, expectations and management. Accordingly, there is considerable value in understanding the changes that have occurred, to species and habitats, and their drivers. The aims of my research were to ascertain whether aquatic ecological baselines in temperate Australia have shifted and, where they have, to reconstruct more representative baselines for use in ecology and management.

In chapter two the model of mean trophic level (MTL) of fisheries catches was used to evaluate whether fishing of higher trophic level species was leading to the 'fishing down' of marine food webs in South Australia. Using disaggregated catch statistics a decline in the MTL of fisheries catches over time was identified, at a rate greater than the global per decade average. This outcome was, however, the result of the expansion of catches at lower trophic levels rather than fishing down. I included a historical data set in this analysis – quantities of fish sold through the Adelaide Fish Market from 1936 to 1946 – to test whether alternative data sources could, perhaps, be combined with contemporary fisheries statistics and incorporated into the model of MTL. The inclusion of historical data could be particularly useful for disaggregating or refining statistics in other regions and in extending the time span of evaluation prior to 1950 after which the collection of global fisheries statistics began. This is the starting point for current calculations, but may not always reflect the time span over which changes have occurred.

Chapter three builds on this understanding, of patterns of change in fisheries in South Australia, using 'neo-Europe' as the basis for impact, induced by European colonisation. Neo-Europe (Crosby, 1986), a conceptual model from the discipline of history, was used for this evaluation to take a cross-disciplinary approach to this research and to contribute to the reconciliation of the disciplines of ecology and history (Szabó and Hédl, 2011). This chapter challenged my own understanding and perspective of contemporary fisheries and ecology. Through the use of the conceptual model a past societal preference for inland fisheries species was identified reflecting similar patterns of change in Europe, this being the overexploitation of inland fisheries species in the neo-Europe's. Hence, this chapter proposed this transition was, in part, predicated on the societal expectations of settlers, which establishes a new baseline for fisheries and aquatic ecosystems. Marine fisheries are often the focus of fisheries science and management, however, earlier deterioration of inland ecosystems might have contributed to an undue bias toward marine ecosystems and an intergenerational amnesia regarding their past productivity and need for restoration.

But it is not only resource use that drives change in ecosystems. In chapter four I evaluated the merit of societal concern toward a cryptogenic species, and, as a result, the management actions expected by the community. Options driven by societal concern alone, based on assumptions of a high degree of invasiveness were extreme measures such as the introduction of a biological control agent. These options contrasted those that were pursued based on an understanding provided by the empirical data, which indicated there may be positive benefits to the presence of the species. Accordingly, there is a risk that the potential benefits such species bring could be overlooked, particularly where society perceives a species to be extremely invasive and drives a political agenda for their eradication. Historical ecology, and shifting baselines, could be used more extensively to inform the ecological context of invading species and options for their management. In doing so, it would assist scientists, managers and society to appreciate the benefits and costs of living with new species, especially where these species are confronting, which can lead to politically motivated action as opposed to an evidence-based approach.

References to commercial fishing of *Ostrea angasi* and to 'payable' beds identified through archival research for chapter four, identified areas for which the historical occurrence of oyster reefs was not at all anticipated, i.e. the upper Spencer Gulf. This led me to seek a greater understanding of the past distribution and abundance of native oyster reefs across South Australia. Through archival searches I identified previously unused data recounting a commercial fishery for the native species, which operated throughout the 1800s and early 1900s. A past ecological baseline for oyster reefs was reconstructed and revealed that oyster reefs were historically distributed across more than 1,500 km of coastline, but their characterisation of the nearshore environment had gradually been forgotten. This chapter illustrated the occurrence of the shifting baseline syndrome, ecological and cognitive, implying that contemporary ecological baselines could require reevaluation.

Chapter six then tested the application of historical data to the setting of management targets. Qualitative information from archival sources was used to guide decision-making and quantitative statistics of past commercial fishing for oysters were reconstructed to underpin the planning process and consultation with government and industry stakeholders. Conclusively, reconstructing the ecological baseline of the past prevalence of oyster reefs (chapter five) stimulated a new focus on the 'native oyster', increasing the profile of the species and suggesting value in rebuilding productivity previously lost due to overexploitation, through aquaculture. This represented an important shift in government thinking and policy.

7.2 Future research

Where there are sparser human populations or a more recent onset of destructive human activities it may be anticipated that changes to species, habitats or ecosystems could be nominal. Many such areas have, however, been transformed by anthropogenic influences and the perception that little has changed, particularly within marine environments in temperate areas of Australia, is incorrect. Management actions based on recent data, such as fisheries statistics and fisheries management reference points built from data beginning in the 1980s, could misrepresent the objectives of natural resource management, ecologically sustainable development or conservation, which underpin an expectation of species' productivity and preservation. Accordingly, there is value in further research to determine past ecosystem states and reconstruct more representative measures for comparison. I suggest several improvements to this research and opportunities for continued development.

This thesis focused on changes induced by anthropogenic influences, particularly those proceeding European colonisation, hence it has an emphasis on the historical temporal scale. Incorporating data from other disciplines across a longer termporal scale, or investigating natural variation alongside the time series generated here through paleoecological investigations, could improve the baselines reconstructed, as could the use of archaeological methods to evaluate change in 'pre-European' environments (Lotze and Worm, 2009, Rick and Lockwood, 2012). It might also be possible to build on and refine the historical approach used in chapters two and three. Calculations of mean trophic level in chapter two could be refined if alternative sources of data were identified that could increase the accuracy of catch estimates for tuna and key species of shark. Incorporating market data into this model could also be tested in additional regions. The conceptual model of Neo-Europe, which is largely qualitative, could be enhanced by underpinning its use with a quantitative model. For example, population modeling could, perhaps, be used to hindcast past stock estimates of key fisheries species (Rosenberg et al., 2005), in particular *Maccullochella peelii peelii* (Murray cod), or a suite of community- or ecosystem-level indicators, such as estimations of biomass or indices of community diversity, could be generated through time (Fulton et al., 2005).

Identifying and interpreting patterns of change due to resource use is a primary aim of historical ecological research, but the introduction of species to new landscapes over hundreds and thousands of years can be the result of and contribute to significant ecological legacies (Willis and Birks, 2006, Essl et al., 2015). For that reason, a further research direction could be a broadening of the current focus of much historical ecological research to encompass other aspects of ecology and natural resource management, in particular invasion ecology. With respect to the presence of *Pinctada albina sugillata* in the upper Spencer Gulf ecosystem, chapter four investigated several aspects of this issue over a limited spatio-temporal scale and further research is needed to continue disentangling the negative versus positive effects of its occurrence. Specifically, this research should consider whether a cumulative negative impact could occur, arising from multiple stressors (Simberloff and Von Holle, 1999), and whether the presence of *Pc. albina sugillata* at the scale of individual *Pinna bicolor*, or local or regional spatial scales, impacts factors other than condition such as recruitment success through stress, displacement or competition.

As nature varies so does the lens, the science, through which it is evaluated (Kuhn, 1962). But science itself might be subject to secondary shifts in our perception of the natural world through the action of the shifting baseline syndrome (Pauly, 1995). Fisheries management was first implemented in South Australia in 1853, for the native oyster fishery. This framework has evolved over the past 160 years and it now provides a comprehensive, thorough and highly regarded approach to natural resource management that is underpinned by science. It is possible, however, that the continual focus on new and more rigorous methods for research and regulation has made us unwilling to question the baselines that we use or unaware of the value of continually seeking to improve their accuracy through the inclusion of new data or the use of new methods, as these become available. A lack of objective consideration, and critique, of the principles, assumptions, or philosophical perspectives that shape our investigations can lead to the unexamined acceptance of paradigms (Moon and Blackman, 2014, Williams and Gordon, 2014). Conscious critique of the baselines that we use in ecology and management would be valuable and could be taught (Williams and Gordon, 2014), and would provide a way forward for addressing complex and prolonged management problems, such as overfishing (Sáenz-Arroyo and Roberts, 2008).

7.3 Conclusions

Interest in the question "what is natural?" has gained momentum over the last two decades, due to the identification and description of the shifting baseline syndrome (Pauly, 1995, Dayton et al., 1998) and a growing appreciation for the antiquity of the impact of human activity (Jackson, 2001, Erlandson et al., 2009, Erlandson and Rick, 2010). There is a need to differentiate between variation that is natural and that which is induced by human activity (Finney et al., 2002, Pandolfi et al., 2011), but our ability to reconcile this difference will be challenged by a future of global change. Despite comprehensive systems for, for example, biosecurity surveillance (Meyerson and Reaser, 2002), our ability to discern whether a species is native or alien is limited by ecological and social challenges and many species continue to be classified as cryptogenic (Carlton, 1996, Walther et al., 2009, Webber and Scott, 2012). In such instances, where we cannot correctly interpret natural versus human-mediated change, we risk missing the arrival of new native species (Carlton, 1996) or the chance to capitalize on ecosystem services provided by introduced species in landscapes that have been impacted and have a reduced potential for productivity (Schlaepfer et al., 2011), as well as the opportunity to appreciate and benefit from the recovery of past losses (Roman et al., 2015).

The continual focus on producing more rigorous models in ecology, and more robust methods of measurement, can predicate the need for new data and lead to the exclusion of past data, the "erasure of history" (Graham and Dayton, 2002). This thesis demonstrates that we may not always need new data; sometimes we merely need new ways of using old data. Historical ecological research advocates for a cross-disciplinary approach to the definition of ecosystems (Szabó and Hédl, 2011, Rick and Lockwood, 2012, Schwerdtner Máñez et al., 2014). The integration of disparate and alternative information sources of data from fisheries in South Australia, and the use of multiple lines of evidence across the disciplines of ecology (including fisheries science) and history, permitted the reconstruction of several ecological baselines. The baselines generated through this approach contrast with the current contemporary approach to fisheries management, which only considers information from the most recent decades despite the length of time over which fishing has occurred and the availability of archival fisheries records.

Recovering and reconstructing past ecological baselines could increase managerial and societal expectations so that environmental degradation can be slowed, if not reversed (Dayton et al., 1998, McClenachan et al., 2012). Higher expectations, which align with the past, forgotten productivity of many species and habitats, could improve our capacity to recover past losses because people may now see the need and value of conservation (Bohnsack, 2003) or restoration, which is increasingly called for in aquatic environments (Pitcher, 2005, Humphries and Winemiller, 2009, Fitzsimons et al., 2015). Accordingly, we must continue to seek better measurement of past ecological states and the changes that have occurred through human activity and work to apply more accurate targets to natural resource management. Historical baselines can be successfully reconstructed and used to redefine our expectations for environments, which could provide a directive for their recovery.

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