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Review

Sydney Harbour: a review of anthropogenic impacts on the biodiversity and ecosystem function of one of the world's largest natural harbours

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Abstract. Sydney Harbour is a hotspot for diversity. However, as with estuaries worldwide, its diversity and functioning faces increasing threats from urbanisation. This is the first synthesis of threats and impacts in Sydney Harbour. In total 200 studies were reviewed: 109 focussed on contamination, 58 on habitat modification, 11 addressed non-indigenous species (NIS) and eight investigated fisheries. Metal concentrations in sediments and seaweeds are among the highest recorded worldwide and organic contamination can also be high. Contamination is associated with increased abundances of opportunistic species, and changes in benthic community structure. The Harbour is also heavily invaded, but invaders' ecological and economic impacts are poorly quantified. Communities within Sydney Harbour are significantly affected by extensive physical modification, with artificial structures supporting more NIS and lower diversity than their natural equivalents. We know little about the effects of fishing on the Harbour's ecology, and although ocean warming along Sydney is among the fastest in the world, we know little about how the ecosystem will respond to warming. The interactive and cumulative effects of stressors on ecosystem functioning and services in the Harbour are largely unknown. Sustainable management of this iconic natural system requires that knowledge gaps are addressed and translated into coherent environmental plans.

Additional keywords: contamination, habitat modification, NIS, Port Jackson, threats, urbanisation.

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Introduction

Sydney Harbour is a global hotspot for marine and estuarine diversity and has enormous economic, social and environmental importance for the city of Sydney, and Australia as a whole (Hutchings *et al.* 2013; Hedge *et al.* 2014*a*; Johnston *et al.* 2015*a*). However, the Harbour, like many urbanised and industrialised estuaries around the globe, has been radically altered by the activities of the large populace it hosts, and threats from historical and ongoing anthropogenic activities have had serious impacts on its biological diversity and ecosystem functioning (e.g. Bulleri *et al.* 2005; Dafforn *et al.* 2012*a*). A systematic review of our current understanding of past, present and future threats to the Harbour and their impacts is necessary if we are to devise clear, integrated, conservation, restoration and sustainability plans for the Harbour and for similarly urbanised estuaries worldwide.

Coastal systems are among the most productive and valuable in the world, providing an array of essential goods and services to society, such as the provision of food, fuel, trade and recreational opportunities (Costanza *et al.* 1997, 2014). They are also some of the most degraded systems, being subject to a range of threats from anthropogenic and natural sources (Kappel 2005; Crain *et al.* 2009). Many of the anthropogenic threats are intensified by the high concentration of coastal populations; more than 40% of the global population live within 100 km of the coast and >85% of Australians live within 50 km of the coast (ABS 2002). Estuaries are particularly vulnerable environments because they concentrate people and suffer cumulative impacts from shipping, industrial activities, agricultural run-off, overfishing, habitat loss and urbanisation. The majority of estuaries around the world are threatened in some way by these activities and more than 50% of Australia's estuaries (~1000) are considered to be modified (Arundel and Mount 2007). These impacts are likely to become more severe and widespread in the coming decades as populations and consumption rates increase and climate change accelerates (e.g. Kennish 2002; Lotze *et al.* 2006; Clark *et al.* 2015).

To preserve and manage marine and estuarine systems, it is necessary to establish efficient and practical ways and current management concepts, such as 'ecosystem-based management' (EBM) and Integrated Management (IM) adopt a holistic view of managing systems, promoting conservation and the sustainable use of resources (Grumbine 1994; Christensen *et al.* 1996; Curtin and Prellezo 2010). Attempts to implement IM plans are often criticised for lacking the required level of detail about the ecological criteria involved – scientific knowledge about the system to be managed is often insufficient (Kremen and Ostfeld 2005; Arkema *et al.* 2006). A sound ecological understanding of systems is necessary for the stipulation of clear, operational ecological goals aimed at sustainability and biodiversity conservation (e.g. Christensen *et al.* 1996). Therefore, gathering and reviewing the available data from a particular system is an important first step in the development of successful management strategies.

Within Sydney Harbour the confluence of intense human activity with great natural diversity presents managers and scientists with a multitude of challenges. For example, threats vary over fairly small spatial scales – although the innermost reaches and protected inlets of Sydney Harbour are heavily contaminated (Birch 1996; Birch *et al.* 1999), a much larger area of the Harbour is reasonably well flushed. The ecology of the middle and outer zones of Sydney Harbour is instead threatened by foreshore development (Chapman and Bulleri 2003; Glasby *et al.* 2007), vessel activity (Widmer and Underwood 2004), resource extraction (Ghosn *et al.* 2010) and invasive species (Glasby and Lobb 2008). The sustainable management of Sydney Harbour requires, therefore, a sophisticated understanding of the structure, dynamics and threats to this complex natural ecosystem. Numerous individuals and institutions have studied the Harbour and its diversity, but the information has never been collated and reviewed. A synthesis of previous research will help scientists to communicate to managers what is known, what is not known and what should be known (Carpenter 1980; Christensen *et al.* 1996). The main goals of this study are to: (1) review and synthesise existing knowledge of the threats to Sydney Harbour, including their interactions; (2) identify important gaps in our knowledge; and (3) set down the challenges and prospects for future research. A companion study (Johnston *et al.* 2015*a*) has collated and reviewed information on the biophysical parameters of the Harbour, identified its key natural habitats and explored their biodiversity and, as with this paper, identified important knowledge gaps to be addressed by scientists and managers.

Systematic literature review

Our review used four search methods to uncover information: (1) a systematic literature search of databases, using the keywords: 'Sydney Harbour' or 'Sydney Harbor', and 'Port Jackson' or 'Parramatta River'; (2) a questionnaire, distributed to 111 scientists from around the world who had used the facilities at the Sydney Institute of Marine Science (SIMS) for work within Sydney Harbour; (3) direct approaches to Sydney-based research groups; and (4) A 2-day workshop and discussion with all the authors of this document to further interrogate the current state of knowledge of Sydney Harbour (see detailed methodology in Johnston *et al.* 2015*a*).

The titles and abstracts of each identified study were examined and all articles and reports on the threats occurring in the Harbour (e.g. contamination, overfishing, etc.) were included in the review if they presented data entirely or partially collected from Sydney Harbour. Sydney Harbour was defined to include all of Middle Harbour and the Parramatta and Lane Cove rivers upstream to their tidal limits (Fig. 1). This included papers and reports with data collected from locations up to 1 km along the coastline north and south of the Sydney Harbour entrance.

Each article was then assigned, where possible, to a Field of Study (e.g. Ecology, Oceanography), a Habitat Type (e.g. rocky intertidal, open water) and a 'Threat/Issue term' (e.g. contamination, fisheries). We have classified the types of threats into six main categories: (1) chemical contamination; (2) nutrient enrichment, (3) non-indigenous (NIS) and novel species, (4) habitat modification; (5) fishing; and (6) climate change.

Results of the systematic literature review

Two hundred studies, out of a total of 310 journal articles and reports identified in our comprehensive literature review, addressed a type of threat or impact occurring in the Harbour and

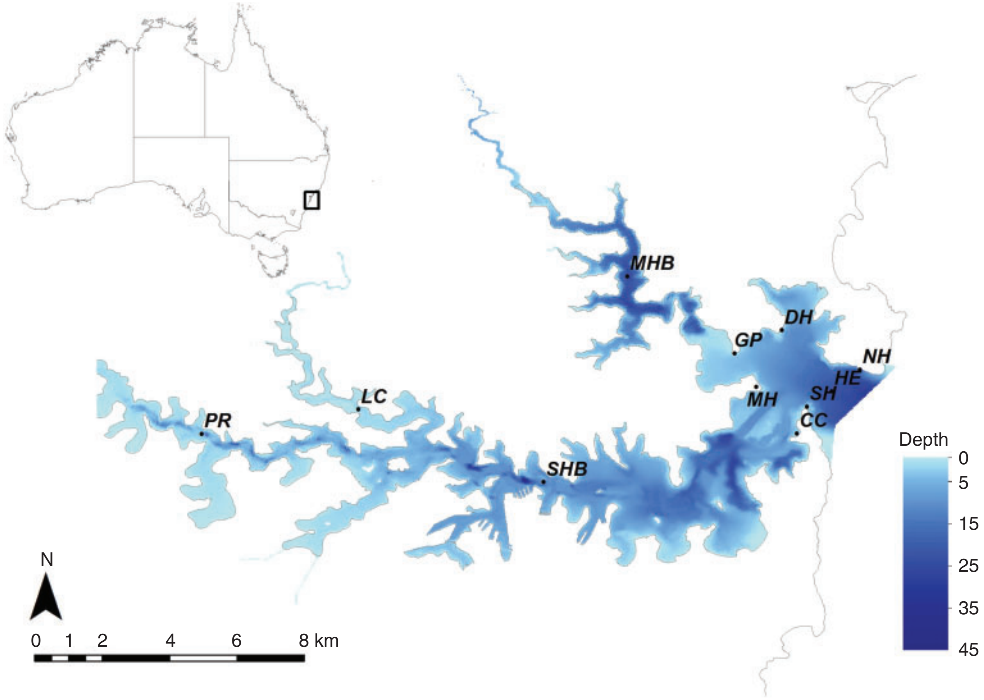

Fig. 1. Map of the Sydney Harbour, detailing its bathymetry and some geographical points (mentioned in the text). CC, Camp Cove; DH, Dobroyd Head; GP, Grotto Point; HE, Harbour Entrance; LC, Lane Cove; MH, Middle Harbour; NH, North Head; PR, Parramatta River; SH, South Head; SHB, Sydney Harbour Bridge.

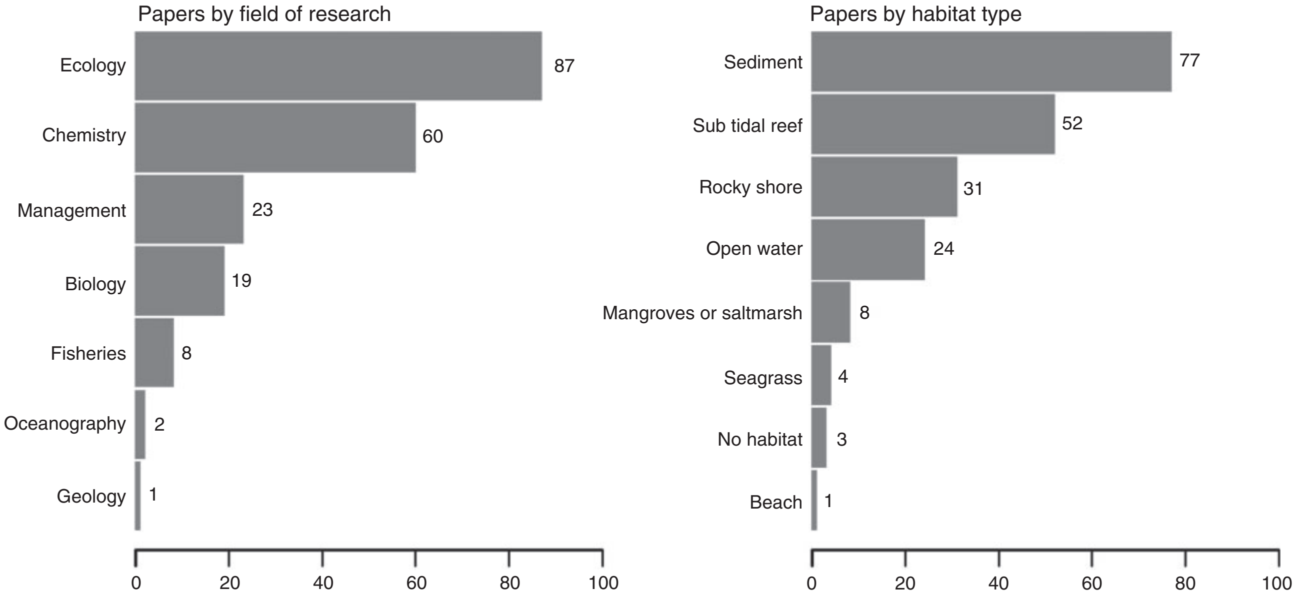

Fig. 2. Number of studies that have assessed the threats or impacts facing Sydney Harbour, separated by field of research and types of habitats.

were included in this review. The remaining studies, i.e. those with a predominant focus on natural history, are the subject of the companion review on the biophysical aspects of Sydney Harbour (Johnston *et al.* 2015*a*).

Of the 200 threat or impact studies included here, 109 focussed on contamination, 58 on habitat modification and 11 assessed the ecology of NIS, their effects in the Harbour or both. Despite the long history of commercial fishing since European settlement and the continued use of the Harbour by a large number of recreational fishers, we found only eight publications relating to a scientific study of its fisheries (Fig. 2).

Sydney Harbour

Sydney Harbour, one of the largest estuaries in the world, is situated on the east coast of Australia and has an area of ~55 km^2. The Harbour is ~30 km long with a maximal width of 3 km. Sydney Harbour is a drowned valley estuary with a narrow, winding channel and irregular bathymetry. It has an irregular shoreline of 254 km and includes seven islands (Johnston *et al.* 2015*a*). Monthly average surface sea temperatures in Sydney Harbour vary from 24°C in summer to 15°C in winter (Bureau of Meteorology website, accessed 15 January 2015). Its average depth is 13 m, including channels for shipping that vary from ~28 to 45 m and shoals with depths of 3–5 m. The Harbour hosts a wide range of habitats, e.g. mangroves, intertidal and subtidal rocky reefs and seagrasses and a diversity of organisms rarely compared to other estuaries and harbours worldwide and is therefore considered a global hotspot of marine diversity. Most of the Harbour (~93%) is composed by soft sediment. The total mapped areas of shallow rocky reefs and mangroves in the Harbour are ~1.6 (~3%) and 1.8 km^2 (~3.5%) respectively, whereas seagrasses and saltmarshes occupy, each, less than 0.5 km^2 (or less than 1% of the Harbour). However, most of these habitats have been mapped only at selected sites, so their total areas are probably underestimated (see details in Johnston *et al.* 2015*a*).

Threats to biodiversity and ecosystem functioning of the Harbour

Chemical contamination

Chemical contamination is increasing worldwide, with contaminants being found in most, if not all, ecosystems and considered one of the biggest threats to a large portion of aquatic species (Wilcove and Master 2005; Rohr *et al.* 2006). Contamination is linked to impairments in development and reproduction of several species (Miskiewicz and Gibbs 1994; Hayes *et al.* 2002), emergence of diseases (Kiesecker 2002) and declines in diversity and ecosystem function (Johnston and Roberts 2009; Johnston *et al.* 2015*b*). Alquezar *et al.* (2006) showed that metal contamination of sediments affected toadfish growth and reproduction and this differed between the sexes. Identifying the chemicals that pose the largest threats to estuarine ecosystems is essential for prioritising remediation and ecosystem management strategies.

Sydney Harbour is considered one of the most contaminated environments in the world (Davis and Birch 2010*a*; Davis and Birch 2011). Studies done in the 1980s (Irvine and Birch 1998) showed that sediments in the estuary contained high concentrations of a suite of metals. More recent studies have shown that sediments in large areas of Sydney Harbour also contain a wide range of non-metallic contaminants, e.g. organochlorine pesticides (OCs; Birch and Taylor 2000), polycyclic aromatic hydrocarbons (PAHs; McCready *et al.* 2000; Dafforn *et al.* 2012*b*) and polychlorinated dibenzo-para-dioxins (dioxins) and dibenzofurans (furans; Birch *et al.* 2007). Commercial fishing was banned in the Harbour in 2006 and recreational fishing severely restricted on the basis of dioxin contamination in fish tissues (Birch *et al.* 2007). The Harbour (more specifically Gore Cove) also suffered an oil spill of ~296 000 L in 1999, which caused, at the time, a decrease in the abundances of intertidal organisms in the most affected sites (MacFarlane and Burchett 2003). These impacts were, however, on a very small scale and the water quality at the affected sites has since improved considerably (G. Birch, unpubl. data).

Although many harbours around the world are contaminated, their impacts are usually restricted to specific areas or types of contaminants (e.g. Chesapeake Bay, USA; Dauer *et al.* 2000; and Bahia, Brazil; Hatje and Barros 2012), with some exceptions (e.g. Victoria Harbour, Hong Kong; Wong *et al.* 1995; Minh *et al.* 2009; Nicholson *et al.* 2011). In Sydney Harbour, over 50% of the surface sediment exceeds Interim Sediment Quality Guidelines – High (ISQG-H; a value that indicates a high risk of adverse effects to benthic populations) for some metals such as lead (Fig. 3). Organochlorine pesticides also exceeded ISQG-H concentrations over extensive parts of Sydney Harbour sediments, including the lower estuary. Sediments in almost all upper and middle parts of Sydney Harbour, including Middle Harbour, had at least one metal, OC or PAH concentration in excess of ISQG-H values (Birch and Taylor 2002*a*, 2002*b*, 2002*c*). The greatest concentrations of contaminants are generally restricted to the bedded sediments of the upper reaches of embayments and decrease markedly seaward in the Harbour (Birch and Taylor 2004; Dafforn *et al.* 2012*b*). Not only are the fish and the sediments contaminated, some macroalgae within the Harbour contain concentrations of metals that are high enough to cause mortality of associated herbivores (Roberts *et al.* 2008); oysters contain concentrations of metals associated with high cellular stress (Edge *et al.* 2012, 2014; Birch *et al.* 2014) and the grey mangrove *Avicennia marina* found in the upper parts of the Harbour contain high levels of copper, lead and zinc on its roots and leaves (MacFarlane *et al.* 2003). There is also a high frequency of gastropods imposex in Sydney Harbour, associated with high concentrations of tributyltin (TBT) in the water, even after several years of partial ban of TBT-based anti-fouling paints (Wilson *et al.* 1993; Gibson and Wilson 2003).

Most of the Harbour's contamination results from a combination of historical inputs – by the direct disposal of commercial and urban waste into the estuary – and current inputs such as untreated stormwater and urban run-off (Hatje *et al.* 2001; Birch and McCready 2009). Hotspots of metal and TBT contamination are also associated with the Harbour's enclosed marinas (Dafforn *et al.* 2008). Legacy contaminants are a common trend in coasts and estuaries of industrialised countries worldwide (Valette-Silver 1993). In Sydney Harbour, soils may also be an important source of metals to the waterway (e.g. Davis and Birch 2010*b*). In addition, increased concentrations of metals in some areas of the Harbour may be associated with leachate produced in reclaimed lands of the Harbour (Suh *et al.* 2003*a*, 2003*b*, 2004; Fig. 4), although the magnitude of the leaching process has not yet been quantified (Hedge *et al.* 2014*b*).

Chemical contaminants are detrimental to the diversity and functioning of ecological systems (Johnston and Roberts 2009; Johnston *et al.* 2015*b*). In Sydney Harbour, contaminated sediments are associated with increased abundances of opportunistic colonisers such as the green algae *Ulva* spp. and some families of polychaete worms (Borowitzka 1972; Dafforn *et al.* 2013), as well as significant changes in the structure of infaunal assemblages (Birch *et al.* 2008; Dafforn *et al.* 2012*b*) and benthic

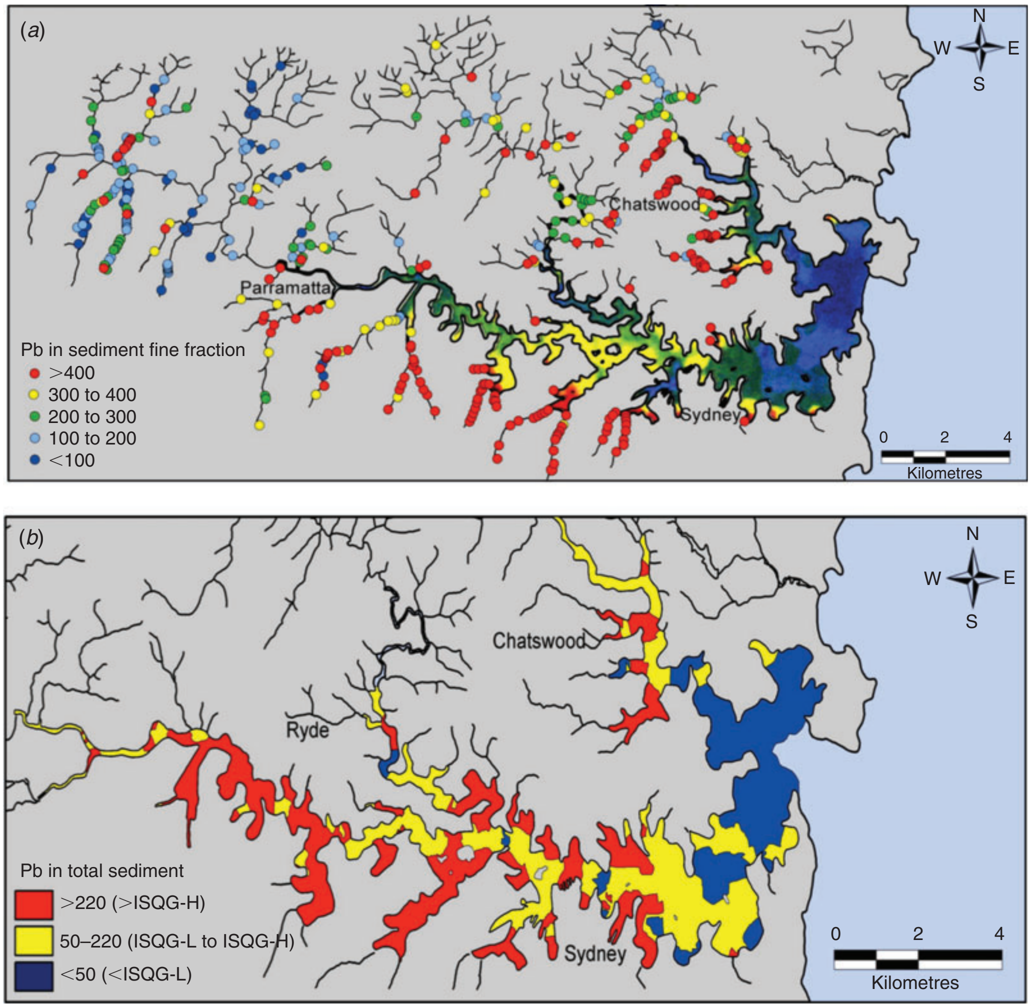

Fig. 3. Lead in sediment fine fractions throughout Sydney Harbour (*a*) and areas of Sydney Harbour in each classification of the International Sediment Quality Guidelines (*b*) (H, high; M, mid; L, low) (from Birch and Taylor 2002*b*).

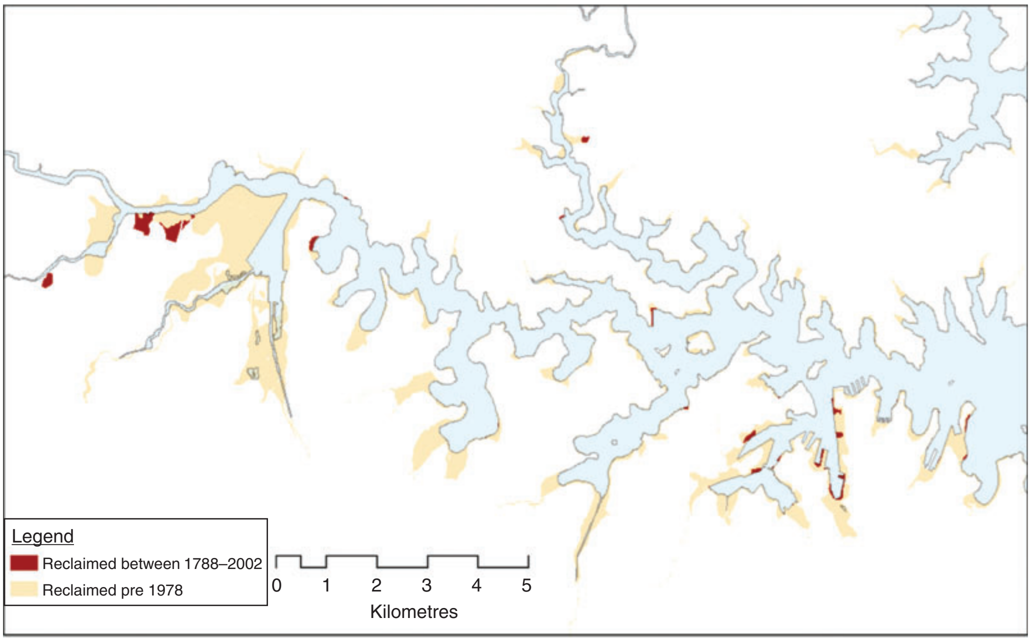

Fig. 4. Reclaimed land in Sydney Harbour since colonisation by Europeans in 1788 (from Birch *et al.* 2009).

larval fish assemblages (McKinley *et al.* 2011*b*). High concentrations of contaminants are linked to changes in sediment bacterial communities within the Harbour (Sun *et al.* 2012, 2013). Increases in the frequency of occurrence of sulphur-liking bacteria, as well as bacteria that are associated with oil spills, are observed in contaminated sediments (M. Sun, K. A. Dafforn, M. V. Brown and E. L. Johnston, unpubl. data). Changes in the structure of microbial communities are expected to have functional consequences that can have substantial consequences for the entire ecosystem of the Harbour, for example, changes to the nitrogen (N) cycle and decreases in primary productivity (Sun *et al.* 2013).

The potential short- and long-term impacts of emerging contaminants, such as micro-plastics and pharmaceuticals are significant, but we have little understanding of how such contaminants affect the Harbour or indeed other coastal environments. Research is needed to characterise their sources and pathways to the Harbour, and to define and quantify processes that determine their transport, fate and ecological effects.

Elevated nutrients and turbidity

Eutrophication is defined as an ‘increase in the rate of supply of organic matter to an ecosystem’, in particular increases in N and phosphorus (P) (Nixon 1995). Increases in the nutrient load of systems is often due to human activities such as land clearing, fertiliser application and sewage discharge (Cloern 2001) that mobilise dissolved and particulate materials (e.g. N and P). An excess of nutrients and changes to nutrient ratios (stoichiometry) have contributed to widespread changes in the ecology of coastal habitats, resulting in harmful algal blooms, loss of seagrasses and depletion of oxygen in the water (Smayda 1990; Walker and McComb 1992; Diaz 2001; Kemp *et al.* 2005).

In Sydney Harbour, large loads of total suspended solids (TSS) and nutrients are delivered during high river flow conditions (Birch and Rochford 2010), whereas under ‘baseflow’ conditions TSS is lower and high levels of total nitrogen (TN) and phosphorus (TP) dominate (Beck and Birch 2012*a*, 2012*b*). This can lead to complex responses because impacts of nutrients in estuarine systems depend on a range of factors such as the mode and timing of delivery, the residence time and the type of sediments present in the systems. Estuaries with fine sediments, for example, can have lower primary productivity despite nutrient enrichment due to higher levels of turbidity blocking light in the water column (Cloern 2001).

Modelling of overflows and discharges suggest that sewage contributes just over 50% of TN and TP loads to the Sydney estuary (Birch *et al.* 2010). By comparison, in Chesapeake Bay, USA, a highly affected system, the main contributors of TN and TP inputs are diffuse watershed sources, oceanic inputs and direct atmospheric deposition (Kemp *et al.* 2005). The type of TN and TP inputs in systems have important implications for management – it is easier to decrease direct inputs, such as those occurring in Sydney Harbour, than indirect inputs (e.g. Chesapeake Bay), which are harder to control and manage. The annual TN, TP and TSS load for Sydney estuary has been determined by modelling and analyses of field samples as 475, 63.5 and 34 300 Mg (megagrams or tonnes) respectively (Birch *et al.* 2010). These amounts are not large when compared with other disturbed catchments around the world and in Australia (see details in Birch *et al.* 2010). Suspended sediment in Sydney Harbour exhibit TP concentrations less than the world average of suspended material being delivered to estuaries (Birch *et al.* 1999).

The fate of nutrients in Sydney Harbour is strongly dependent upon water flow. Under high rainfall conditions ($>$50 mm day^{-1}), the estuary becomes stratified and nutrients are either removed from the estuary directly in a surface plume or indirectly by advective or dispersive remobilisation (Lee *et al.* 2011). Under low to moderate rainfall (5–50 mm day^{-1}), low flushing rates present favourable hydrological conditions for nutrients (and contaminants) to be chemically and biologically incorporated into the food web (Förstner and Wittmann 1981) and deposited into adjacent estuarine sediments close to discharge points and thereby remain in the estuary (Birch and McCready 2009; Birch 2011).

Although Sydney Harbour sediments contain high nutrient concentrations, more research is needed to determine whether they contribute substantially to primary production in the Harbour (Birch *et al.* 1999). The high delivery of TSS into the Harbour, however, affects the quantity of contaminated suspended material in the water column and availability to filter feeding animals (Birch and O’Hea 2007) and reduces the quality of light available for photosynthesis, which can have substantial negative knock-on consequences for this system, potentially affecting its functioning (Robinson *et al.* 2014).

Marine debris

Marine debris (or marine litter) is defined as any persistent, manufactured or processed solid material discarded, disposed of, or abandoned in the marine and coastal environment. Plastics – synthetic organic polymers – make up most of the marine litter worldwide (Derraik 2002) and reach the marine environment by accidental release and indiscriminate discard (Derraik 2002; Wright *et al.* 2013). Plastic debris can harm organisms physically and chemically, by releasing toxic substances that they either absorb or contain (Rochman and Browne 2013). Large pieces of plastic can kill and injure several marine species such as marine mammals and sea birds by ingestion or entanglement (Rochman and Browne 2013). Marine debris has, therefore, the potential to greatly affect the diversity and functioning of Sydney Harbour and marine and estuarine systems worldwide.

Although there are not many published data on marine debris in Sydney Harbour (but see Smith and Edgar 2014), the NSW Roads & Maritime collects ~3500 m^3 of litter per year in the Harbour, ranging from large objects such as trees and tyres, household debris and small items left behind on beaches and other foreshore locations by members of the public (NSW Roads & Maritime, accessed 12 August 2015). Cunningham and Wilson (2003) found that the abundance of marine debris within the Greater Sydney region was comparable to some of the most polluted beaches in the world and Smith and Edgar (2014) reported that fishing-related items were the most common types of debris found in estuaries in NSW, including Sydney Harbour. There is, however, an obvious gap in the knowledge related to debris in the Harbour. Not only more sampling needs to be done to address this issue, but a more thorough and rigorous sampling protocol needs to be applied, including: (1) temporal and spatial replication; (2) standardised measurements of quantity;

and (3) experimental tests about processes that cause accumulation of debris and their impacts (Browne *et al.* 2015). Only then we will have a better understanding of the potential impacts of debris in Sydney Harbour and be able to devise effective management plans.

Non-indigenous and novel species in Sydney Harbour

Invasive species are a major global source of losses of biodiversity and economic value – estimated to be up to US$120 billion per year in the US alone (Pimentel *et al.* 2005). Native systems can be affected through the displacement of native biota, changes to predation and herbivory rates, introduction of new diseases and parasites and the destabilisation of microenvironments (Ruiz *et al.* 1999; Byers 2000). Invasion can be categorised as a four-step process – transport, establishment, spread and impact (Lockwood *et al.* 2005). Transport processes have been well studied globally and the transfer of the large majority of introduced species – both between and within countries – occurs through shipping (in ballast water or as hullfouling; Carlton 1985; Ruiz *et al.* 2000*a*). However, the translocation of species for aquaculture or the aquarium trade is also an important vector (Naylor *et al.* 2001). A more recent phenomenon is the rapid expansion of many native species within (Zhang *et al.* 2014; Glasby *et al.* 2015) and outside their traditional range (Booth *et al.* 2007). Far less is known about the establishment processes of these species, although propagule pressure (Lockwood *et al.* 2005), changes in resource availability (e.g. reduced competition) (Stachowicz and Byrnes 2006), a reduction in natural enemies (deRivera *et al.* 2005) and disturbance (Clark and Johnston 2009; Zhang *et al.* 2014) have all been implicated in the success of invasive species in their introduced range. For instance, traits of invasive tropical fish species such as large body size, high swimming ability, large size at settlement and pelagic spawning behaviour favour establishment in temperate locations such as Sydney (Feary *et al.* 2014).

As in most major ports, many NIS have established in Sydney Harbour. Unlike some harbours such as San Francisco Bay, where invasions have been studied on a systematic basis for more than 60 years (Carlton 1996), the study of NIS in Sydney Harbour is relatively new (~2 decades). NISs occur in most habitats within the Harbour such as artificial substrata (e.g. the tunicate, *Styela plicata*), natural intertidal (e.g. the Pacific oyster, *Crassostrea gigas*) and subtidal rocky reefs (e.g. the tropical goby fish *Abudefduf vaigiensis* and the introduced bryozoan *Membranipora membranacea*), soft sediment substrata (e.g. the green alga, *Caulerpa taxifolia* and mantis shrimp, *Oratosquilla oratoria*) and upper intertidal plant communities (e.g. the saltmarsh plant, *Juncus acutus*). A more detailed list of NIS known to occur in Sydney Harbour can be found in a report by the Australian Museum (AM 2002).

The mechanisms behind NIS establishment in the Harbour, post arrival, remain unclear and are likely to vary between taxa and habitat. Nevertheless, increases in non-indigenous propagule pressure, caused by increases or changes in commercial and recreational shipping traffic, are likely contributing to the establishment of NIS (Carlton 1985; Floerl and Inglis 2003; Hedge *et al.* 2012). Subsequent continual mechanical disturbance by vessels docking, or by cleaning activities, may also increase the dominance of these early colonising NIS (Clark and Johnston 2005; Clark and Johnston 2009). In addition, artificial structures in the Harbour (see 'Habitat modification' section below) probably exacerbate the invasion processes, by artificial shading and unnatural surface orientations (Glasby *et al.* 2007; Dafforn *et al.* 2012*a*; Hedge and Johnston 2012). In Sydney Harbour, the abundance of NIS on artificial structures can be more than twice that found on natural sandstone reefs (Glasby *et al.* 2007; Dafforn *et al.* 2012*a*), with these structures also serving as 'stepping stones' to NIS, facilitating their spread (e.g. Bulleri and Airoldi 2005). Metal contamination is a further facilitator of NIS establishment and competitive dominance, with exposure to standard anti-fouling paint contaminants associated with increased NIS dominance within the Harbour and beyond (Piola and Johnston 2008; Dafforn *et al.* 2009).

The ecological and economic impacts of NIS within Sydney Harbour are poorly quantified although several NIS found in the Harbour have significant negative impacts elsewhere. For example, *C. taxifolia*, first discovered in Sydney Harbour in 2002, can affect the feeding behaviour and distribution of benthic fishes (Levi and Francour 2004; Longepierre *et al.* 2005) or support assemblages of fish (York *et al.* 2006) and invertebrates (McKinnon *et al.* 2009; Gallucci *et al.* 2012) that differ from those in adjacent native habitats. *C. taxifolia* has large negative direct and indirect effects (by modifying habitat quality) on native biota (Wright and Gribben 2008; Gribben *et al.* 2009; Wright *et al.* 2012; Gribben *et al.* 2013). Although its impacts on seagrass beds are of potential concern, recent research indicates *C. taxifolia* does not have an impact on intact seagrass beds in NSW (Glasby 2013).

One of the important knowledge gaps is establishment and the impacts of invasive microbes in Sydney Harbour. It is likely that coastal systems, especially harbours, are frequently invaded by microorganisms from ballast water (Ruiz *et al.* 2000*b*). Chesapeake Bay, on the US East Coast, for instance, receives ~10 billion litres (~10 GL) of foreign ballast water each year, with each litre containing ~1 billion bacteria and seven billion virus-like particles (Ruiz *et al.* 2000*b*). Given the risks that invasions of that magnitude pose to local ecosystems, this is an important knowledge gap to fill.

Climatic changes are also increasingly contributing to the spread of some species (e.g. Verges *et al.* 2014). The incursion of tropical marine fish into NSW, for example, has been growing in frequency and intensity, with several species now with regular 'overwintering' adults (Figueira and Booth 2010). In some circumstances, these species have been referred to as invasive species in their extended range. In Sydney Harbour, studies have shown the presence of tropical fishes (Booth *et al.* 2007), which has been linked to the southward strengthening of the East Australian Current (i.e. the occurrence of warmer waters further into south-eastern Australia; see section on climatic changes). The full consequences of such range expansions, coined 'tropicalisation', are likely to alter Harbour ecosystems, resulting in community phase shifts (Verges *et al.* 2014).

Habitat modification

Habitat modification is one of the primary global causes of biodiversity loss (e.g. Didham *et al.* 2007). In urbanised coastal areas, the most common types of modification of habitats are: (1) addition of artificial structures such as pier pilings and pontoons; (2) replacement of natural habitats by artificial structures such as seawalls and breakwaters; (3) land reclamation and infill; and (4) fragmentation of habitats, mostly as a result of the disturbances mentioned above. In some areas of Europe, the US and Australia more than 50% of estuarine coastlines are modified by artificial structures (Bulleri *et al.* 2005; Dugan *et al.* 2011) with associated loss of natural habitats, e.g. soft sediments, wetlands and seagrasses.

Sydney Harbour has been extensively modified since European settlement over 200 years ago, and the Harbour is probably one of the best studied places in the world regarding the impacts of artificial structures on biological assemblages (see references below). Approximately 77 km of the 322 km of its original shoreline has been removed due to reclamation and infilling (Pitblado 1978). Furthermore, ~22% of the total 50 km^2 area of the estuary has been reclaimed, mainly for industrial, recreational and residential uses (Birch 2007) and more than 50% of the shoreline has been replaced with artificial structures such as seawalls (Chapman and Bulleri 2003). Artificial structures have inherently different features from natural habitats such as the material with which they are built (Glasby 2000; Moreira 2006), their orientation (Connell 1999), shading (Glasby 1999*b*; Blockley and Chapman 2006; Marzinelli *et al.* 2011) and their distance to the sea floor (Glasby 1999*b*; Glasby and Connell 2001). As a consequence, these structures often support assemblages that differ in many ways from those on natural substrata (see examples below).

In Sydney Harbour, intertidal seawalls support fewer organisms than adjacent natural rocky shores (e.g. Chapman 2003; Bulleri 2005; Bulleri *et al.* 2005). Chapman (2003, 2006) found that this difference in diversity is mainly due to the absence of several species of mobile organisms on seawalls, including some gastropods commonly found on natural shores. Important ecological processes and interactions among organisms occurring on seawalls such as competitive interactions and recruitment, also differ from those occurring on natural rocky shores (e.g. Bulleri 2005; Moreira *et al.* 2006; Jackson *et al.* 2008; Ivesa *et al.* 2010; Klein *et al.* 2011), leading to differences in the composition of assemblages compared to natural shores. Furthermore, these structures impair the reproductive output of limpets (Moreira *et al.* 2006), which are important structuring agents of intertidal assemblages (e.g. Underwood and Jernakoff 1981; Hawkins and Hartnoll 1983).

In subtidal systems, the most common types of artificial structures found in Sydney Harbour are pier pilings and floating pontoons in marinas and wharves. The composition of assemblages and the relative abundance of organisms living directly on these structures also differ from those on natural rocky reefs (Connell and Glasby 1999; Glasby 1999*a*; Glasby 2001; Dafforn *et al.* 2012*a*). Pilings not only affect organisms living directly on them, but also in their surroundings. Fish assemblages surrounding pier pilings in marinas often differ from those in natural reef habitats (Clynick *et al.* 2008). Furthermore, important habitat forming species growing on artificial structures such as kelps have been shown to support different species and greater cover of epibiota (e.g. encrusting bryozoans and hydroids) than those on adjacent natural reefs (Marzinelli *et al.* 2009; Marzinelli 2012).

One of the greatest impacts of the addition of artificial structures on coastal systems is the fragmentation of habitats, the division of large natural patches of habitat into smaller patches of smaller total area, isolated from each other by a matrix of habitats unlike the original (Wilcove *et al.* 1986). In Sydney Harbour, most natural shores are currently fragmented by seawalls (Goodsell *et al.* 2007). Goodsell (2009) found a greater abundance of several taxa on natural shores than on mixed (bordered at one end by artificial habitat and at the other end by natural shore) or complete (bordered by artificial habitats at both ends) fragments. A study that experimentally manipulated sizes and isolation of patches of algal beds in Sydney Harbour, however, found an increased abundance of some taxa of mobile invertebrates on small and isolated patches (Roberts and Poore 2006). These results indicate that patchy landscapes should not necessarily be considered poor habitats and suggest that a range of patch sizes may be necessary to maintain species diversity in certain systems.

In addition to all the hard artificial structures, several beaches in Sydney Harbour have swimming enclosures constructed with hanging nets (Clynick 2008; Hellyer *et al.* 2011), designed to exclude sharks from popular swimming beaches. These nets are a suitable habitat for seahorses in Sydney Harbour – especially when manipulated to construct a more structurally complex net habitat – supporting a greater density of the species *Hippocampus whitei* than that found in natural habitats (Clynick 2008; Hellyer *et al.* 2011). However, the nets are often removed during winter or when being repaired (Clynick 2008). The removal or cleaning of the nets reduces local seahorse abundance, but whether nets are actually increasing seahorse populations (by providing new habitat) or acting as sinks, taking these organisms away from their natural habitats, it is still not known (Harasti *et al.* 2010).

Despite their numerous impacts on the diversity of systems, the construction of artificial structures on coastal systems, including Sydney Harbour, is likely to increase in response to predicted global climatic changes such as sea level rises and increases in intensity and frequency of storms (Thompson *et al.* 2002; Bulleri and Chapman 2010), making the development of better ways to build and manage such structures a global imperative (Dafforn *et al.* 2015). Furthermore, the consequences of such modification on the functioning of systems and their provision of services are not yet understood and need to be assessed.

Habitat modification – through reclamation and dredging – is possibly one of the culprits of the significant decline of saltmarshes in Sydney Harbour since colonisation (e.g. McLoughlin 2000*a*). Although it appears that mudflats and saltmarshes communities dominated much of the intertidal zone of the Harbour in the 19th century (McLoughlin 2000*a*), in 2005 they occupied an area of less than 37 ha (Kelleway *et al.* 2007). The exact cause of this decline – a consistent pattern observed across Australia – is still uncertain and may vary from place to place, but it has been linked to habitat modification, sea level rise and elevated concentrations of atmospheric carbon dioxide (Saintilan and Rogers 2013). Saltmarshes provide several important ecosystem services such as coastal protection and filtering of sediments and nutrients (Pennings and Bertness 2001). Such significant changes in the extension of these systems can therefore have serious implications for the functioning of the Harbour.

Fishing

Worldwide demand for seafood products drives very high levels of wild harvest and aquaculture in marine systems (80 and more than 90 Mg in 2012 respectively; FAO 2014). Although there are a variety of fisheries in open waters, most of catch is typically from the coastal regions and estuaries of the world (Blaber *et al.* 2000). These regions are not only more productive, but also much easier to access by commercial, recreational, artisanal and subsistence fishers as well as developers of aquaculture operations. With over 85% of the Australian population living within 50 km of the coast, fishing has long been an important activity. Owing to their close proximity to population centres, estuaries have been host to the majority of this activity. Within NSW, ~45–50% of total commercial effort (days fished) and 30–35% of landings (by weight) come from estuaries (authors' unpubl. data).

Sydney Harbour is home to over 580 species of fish (Hutchings *et al.* 2013), and although commercial fishing was banned in 2006 due mainly to fish contamination concerns (Ghosn *et al.* 2010), recreational fishing is still allowed and fishing pressure can be intense in some areas of the Harbour (Ghosn *et al.* 2010). Prior to 2006, commercial fisheries were generally described as 'artisanal' with fisheries dominated by smaller boats (Hedge *et al.* 2014*a*). From 1980 to 1982, 108 000 kg of fish were caught commercially. By contrast, in the same period, the recreational catch exceeded the commercial catch by ~50%, removing 164 700 kg of fish (Hedge *et al.* 2014*a*).

Several species commonly targeted and caught in Sydney Harbour such as mulloway (*Argyosomus japonicus*), kingfish (*Seriola lalandi*), snapper (*Pagrus auratus*) and yellowfin bream (*Acanthopagrus australis*), have been listed as overfished or growth overfished in NSW (NSW Fisheries 2014). These species have a large recreational component (>50%) to their catch (NSW Fisheries 2012; Ghosn *et al.* 2010). Although published data on the recreational fishing sector in NSW are limited, on-site surveys indicate that Sydney Harbour experiences approximately twice the effort and catch of other estuaries in the state (Ghosn *et al.* 2010). Unlike recreational fisheries in the Greater Sydney region (Steffe and Murphy 2011), the fishery in Sydney Harbour is dominated by local residents fishing from shore (Ghosn *et al.* 2010).

Information on the impacts of by-catch from recreational fisheries in the Harbour is limited to a study demonstrating ~15% mortality of angled-and-released yellowtail kingfish *Seriola lalandi* (Roberts *et al.* 2011). In addition, by-catch and catch ratios of ~2 : 1 were found in the Harbour, which was less than nearby Botany Bay (Liggins *et al.* 1996). Data on directed recreational fisheries in the Harbour would suggest a relatively healthy fishery based on catch per unit effort but it does have a higher proportion of undersized catch than other estuaries surveyed (Ghosn *et al.* 2010).

The establishment of marine reserves is one of the management strategies commonly used to protect some ecologically and economically important species from overfishing (e.g. Lester *et al.* 2009; Harrison *et al.* 2012). Within Sydney Harbour, the North (Sydney) Harbour Aquatic Reserve (260 ha) was established in 1982. Although, line fishing is allowed in the park, spearfishing and mollusc collecting is prohibited. This reserve has been used as part of a larger study, which demonstrated that protection can enhance the abundance of targeted fish species (McKinley *et al.* 2011*a*). However, more detailed studies are required to determine the efficacy of marine parks and reserves, where they should be located, how large to make them, and how to manage them effectively to meet the multiple competing ecological, economic and sociological needs.

Climate change

Climate change simultaneously alters many environmental parameters (e.g. temperature, pH, physical water column structure, storm and wave action, nutrient bioavailability) that regulate the biodiversity and function of marine ecosystems (Boyd 2010). Although the drivers of ecological impacts of climate change operate globally, they vary in their intensity depending on region and habitat. Estuaries are exposed to changes in climate by changes to freshwater inputs, atmospheric influences and oceanic systems (e.g. Najjar *et al.* 2010). Moreover, human settlements are often located on estuaries and hence most of human adaptation to climate change (e.g. coastal armouring) will affect estuaries. However, many estuarine organisms have evolved mechanisms to withstand large fluctuations in environmental conditions and may therefore be less sensitive to changes in water chemistry than oceanic organisms.

Sydney Harbour is located in the western Tasman Sea, a region known to be warming relatively quickly compared to the global average (Wu *et al.* 2012), with the water temperature regime shifting 350 km southwards due to the increasing extent of the East Australian Current (EAC; Ridgway 2007). Some of the observed consequences of the strengthening of the EAC are a drop in concentrations of dissolved silicate (an essential element for growth of silicifying phytoplankton such as diatoms) over the last 30 years, alongside a decade long (1997–2007) drop in the size of the spring phytoplankton bloom and its growth rate (Thompson *et al.* 2009). Such observations come from a substantial water quality time series collected from Port Hacking, 27 km south of the Harbour's entrance. These changes suggest that water entering the Sydney estuary from the ocean is becoming warmer as well as less productive, with potential implications for recruitment of organisms into the Harbour and other processes.

Figueira and Booth (2010) showed the range expansion of tropical fish species being transported southwards in the EAC. Although these species rarely overwinter when sea surface temperature (SST) drops below 17°C, future scenarios suggest that overwintering may become an annual event in future with the predicted increase in temperature, and may facilitate substantial range shifts. This issue is discussed in greater detail within the Non-Indigenous and Novel Species section above.

Ocean acidification, one of the consequences of climate change, is likely to result in reduced capacity for marine calcifiers such as corals, molluscs, and some plankton to produce their skeletons (Ferrier-Pagès *et al.* 1998; Diaz-Pulido *et al.* 2007). Under such conditions, non-calcifying species (e.g. ascidians and siliceous sponges) may have a competitive advantage over calcifying species such as habitat forming invertebrates and commercially important shellfish (e.g. mussels and

Table 1. Predicted interactions between threats and stressors in Sydney Harbour

Antagonistic interactions result in one stressor negating the effect of the other. Synergistic stressors are predicted to enhance the effects of each stressor to levels above what would be expected by simply adding the effects of each stressor. Question marks represent areas where predictions are made difficult due to limited data

Contamination	Contamination	NIS	Habitat modification	Nutrients and turbidity	Fishing and aquaculture	Climate change
NIS	Synergistic					
Habitat modification	Synergistic	Synergistic				
Nutrients or turbidity	Antagonistic	Synergistic	Synergistic			
Fishing and aquaculture	Synergistic	?	Variable	Antagonistic		
Climate change	Synergistic	Synergistic	Synergistic	Synergistic	?	

oysters respectively). Although there is little data on how estuarine ecosystems, in general, will respond to these changes, research on the Sydney rock oyster, *Saccostrea glomerata*, has shown that this organism may have the capacity to acclimate or adapt to elevated carbon dioxide (pCO_2) over the next century. Larvae spawned from adults exposed to elevated pCO_2 were larger and developed faster, but displayed similar survival compared with larvae spawned from adults exposed to ambient pCO_2 (Parker *et al.* 2012). Furthermore, selectively bred *S. glomerata* larvae were more resilient to elevated pCO_2 than wild larvae, suggesting that this species may be able to 'keep up' with rates of climate change.

Sea level rise, as a result of climatic changes, has been of most concern to governments worldwide, particularly in view of dramatic shifts in beach sands as a result of climate-driven storms (Short and Trembanis 2004). Waters along Australia's eastern seaboard are rising in line with global averages – 3.1 ± 0.6 mm year^{-1} (1993–2009) (White *et al.* 2014) and are acting in opposition to vertical accretion of sediments in near-shore habitats. Rogers *et al.* (2005) showed that the surface elevation increase at sites within Sydney Harbour exceeded the 85-year sea level trend, suggesting that mangrove forest would not be inundated under future estimated sea level rise. However, given the limited opportunities for shoreward migration in some parts of the Harbour, sea level rise is likely to diminish key habitats in the Harbour such as saltmarsh, mangrove and seagrass. Nonetheless, to fully understand the whole range of impacts that the predicted climatic changes will have on the systems in Sydney Harbour, further research is required on the impacts of these stressors in the Harbour's ecosystems and biota, at relevant temporal and spatial scales.

Research is required to improve modelling tools that investigate the impacts of climate change on the hydrology of the estuary. For example, changes in freshwater inflow are likely to have profound impacts on estuarine habitats and ecosystems (e.g. Azevedo *et al.* 2014) and research is required to predict changes in circulation, biogeochemistry, flushing and residence times. Flushing timescales may increase if, for example, flushing is reduced by smaller volumes of freshwater inflow. This could have a potentially detrimental impact on water quality through increased residence leading to stagnation. Conversely, with an increase in rainfall, flushing timescales may decrease, i.e. the estuary may flush more quickly. However, the impacts of these changes on water quality and primary and secondary production are currently difficult to predict. This uncertainty warrants a substantial new effort to model estuary processes through space and time. Fine-scale climate modelling studies (some already available online) will be valuable tools that can be used to anticipate and mitigate severe environmental consequences, and will readily feed into management and adaptation strategies.

Interactions among stressors

Sydney Harbour is subject to multiple threats that affect biodiversity and ecosystem function. The identification of individual threats and how they vary in their relative importance for each habitat is a first step and essential to understand some of the impacts. However, many of these stressors occur simultaneously and the study of individual stressors may inform little about their realised impacts if stressors interact in ways that cannot be predicted by their individual study, i.e. if their interactive effects are non-additive. It is often assumed that impacts of multiple stressors are additive (Crain *et al.* 2008). However, recent reviews and meta-analyses suggest that synergistic and antagonistic effects between stressors are also common and complex (Crain *et al.* 2008; Darling and Cote 2008).

Although many of the predicted stressor interactions in Sydney Harbour are considered to be synergistic, most interactions have not been investigated directly (Table 1). So, although we have some understanding of the impacts of each stressor in isolation, multiple stressor research is urgently needed, both in Sydney Harbour and for urbanised estuaries worldwide.

Of the research on multiple stressors that has been carried out in Sydney Harbour, experimental studies demonstrated the facilitative effects of metal contamination on the competitive dominance of NIS (Piola and Johnston 2008; Dafforn *et al.* 2009). Increased copper and tin contamination results in recruitment and growth of various NIS above that that occurs 'naturally' in the high traffic areas of the Harbour. Interestingly, reduced native recruitment was also observed. Increased NIS recruitment and increased metal contamination may therefore have acted synergistically to affect native species abundance. Similarly, habitat modification can increase the recruitment of NIS species (Glasby *et al.* 2007). In the Mediterranean Sea, for example, habitat modification caused an increase in propagules supply of the invasive mussel *Brachidontes pharaonis*, leading to a shift in dominance of the near-shore habitats. This happened, even though *B. pharaonis* was competitive inferior than the native mussel *Mytilaster minimus* – the dominant mussel before the habitat degradation (Rilov *et al.* 2004; Didham *et al.* 2007).

In areas with both high levels of metal contamination and nutrient input, we might predict an ameliorating relationship between the two types of contamination, depending on the concentrations of each type of contaminant. Metals may bind to organic matter making them less bioavailable and masking potential effects of these contaminants (e.g. Krumgalz 1989). However, the biogeochemistry of metal availability in sediments is complex and dependent on several other parameters (e.g. Chakraborty *et al.* 2015), so our general prediction may not hold in all circumstances. If interactions do occur, there are important implications for management; as we reduce sources of organic enrichment to the Harbour, the effective toxicity of historically contaminated sediments may increase.

Climate change interactions with other stressors are predicted to be largely synergistic. For example, increased temperature and decreased pH may increase the toxicity of many common contaminants (Crain *et al.* 2008). Changes in natural environmental variables such as the increased frequency and intensity of storms will likely lead to greater disturbance regimes that can facilitate NIS recruitment (Clark and Johnston 2009). The advantageous effects of heavy metals on biofouling NIS recruitment and growth are known (see above), so increased disturbance that mobilises sediment bound metal contamination may further exacerbate such effects (Knott *et al.* 2009). In addition, human responses to sea level rise are likely to result in increasing rates of foreshore modification as communities seek to protect valuable real estate and infrastructure. Owing to the complexity and importance of understanding how multiple stressors interact, such investigation should be a priority research goal and used to inform managers and stakeholders for better conservation practices of the natural environments of Sydney Harbour.

Science and management

Like many other highly urbanised harbours around the world, the major management challenges for Sydney Harbour arise from conflicting uses. There exists a need to balance the requirements and aspirations of residents, visitors, industry, shipping and other users. In addition, Sydney has to deal with an ongoing legacy of past activities that have occurred since European settlement in the late 18th century (Hoskins 2010).

The Federal and NSW governments have legislation and regulations in place to deal with these management issues, such as: the *NSW Protection of the Environment Act* 1979 and the *Environment Protection and Biodiversity Conservation Act* 1999 – to regulate the quality of the Harbour's water; the *Fisheries Management Act* 1994 – to regulate the catch of species that are harvested for food and to protect marine biodiversity, habitats and ecological processes, and Local Environmental Plans – to control the types of development permitted on the Harbour's foreshores (under the *Environmental Planning and Assessment Act* 1979). However, these Acts are often enforced in a piecemeal fashion and there has been a lack of coordination and strategy to guide the management of the Harbour's natural, social and economic resources.

Current NSW government is in the process of conducting spatially explicit risk assessments that consider threats to social, economic and environment values (MEMA). This process will feed into an EBM strategy. Ecological Risk Assessment (ERA) and Spatial Management and Prioritisation are tools by which complex natural resources can be effectively managed. A recommendation of the NSW Independent Scientific Audit of Marine Parks (Beeton *et al.* 2012) was to manage marine resources within a risk assessment framework. A comprehensive risk assessment of Sydney Harbour has yet to be conducted, in part because there is a lack of spatially explicit information on the environmental social and economic benefits derived from the system. As demonstrated in this review, however, there are clearly issues of threat and risk within the Harbour and we have some knowledge on the most affected areas and most pressing threats. Such knowledge could be used in the implementation of spatially explicit risk assessments and EBM plans albeit with some substantial information gaps. Undertaking such a project for the Sydney Harbour estuary is a large task, but one that we believe is long overdue.

It is not that the Harbour is entirely without environmental management plans. For example, in 2005 a Regional Environmental Plan was produced for the Sydney Harbour Catchment (http://www.austlii.edu.au/au/legis/nsw/num_epi/srephc20052005590587.pdf, accessed July 2015). However, this plan appears to have limited expression through current management authorities. One notable example of an established management plan was developed in the mid-1990s by the Sydney Olympic Park Authority for the protection of the shoreline marine habitats under its jurisdiction. This included a major reconstruction of tidal flats followed by saltmarsh replanting. However, this plan is an exception. Even the North Sydney Aquatic Reserve – established over a decade ago to protect a representative component of the Harbour's biodiversity – lacks a management plan. Also, there are no comprehensive management strategies for important plant habitats within the Harbour such as mangroves, seagrass and saltmarsh. This, despite the recorded decline in seagrass and saltmarsh habitats (McLoughlin 2000*b*), the listing of threatened populations of *Posidonia australis* and the suggestion that Harbour mangroves are threatened by low genetic diversity (Melville and Burchett 2002).

Some protections are afforded under the *Fisheries Management Act 1994*: harm to vegetation (including all three macrophyte types) is illegal and removal or damage can result in fines. Further, 'Habitat Protection Guidelines' (Fairfull 2013) aim to minimise disturbance to mangroves, but at the same time allow public access. However, even the building of walkways can affect the local biota. For example, the abundance of the semaphore crab, *Heloecius cordiformis*, can be higher closer to boardwalks than further away due to the environmental changes (e.g. changes in sediment structure) associated with the boardwalks (Kelaher *et al.* 1998). There is arguably a need for more plans like this, particularly in light of concerns surrounding boat moorings and anchoring in the small remnant patches of *Posidonia australis* in this part of the Harbour. In other countries – substantial management plans covering aspects of water quality, biotic diversity, habitat, threats and connectivity have been developed for major estuaries (e.g. Chesapeake Bay Program and Chesapeake Bay Watershed Agreement 2014, see http://www.chesapeakebay.net/documents/FINAL_Ches_Bay_Watershed_Agreement.withsignatures-HIres.pdf, accessed July 2015;

San Francisco Bay National Estuarine Research Reserve Management Plan 2011–2016) and have resulted in substantial improvements to ecosystem management.

Conclusions

Here, we have provided the first comprehensive synthesis of published information regarding anthropogenic threats to the natural habitats of Sydney Harbour. The impacts of human activity in the Harbour have significantly changed the ecology of the system. The structure and functioning of biological communities within Sydney Harbour are threatened by contaminated sediments, extensive habitat modifications, resource extraction and the potentially serious direct and indirect effects of NIS. How the biota and habitats present in the Harbour will respond to the predicted climatic changes is a major source of uncertainty and we lack a sophisticated understanding of the interactive and cumulative effects of stressors on ecosystem functioning and the provision of services. It is clear that further research is needed to fill knowledge gaps and holistic risk assessments and IM strategies must be developed. It is hoped that the establishment, in 2013, of the Marine Estate Management Authority for the state of New South Wales (http://www.marine.nsw.gov.au, accessed July 2015) will result in better coordination of science and management for Sydney Harbour, one of the world's largest urbanised estuary.

The threats and impacts outlined for this heavily modified estuary are common to major urban and industrialised estuaries around the globe. The exact scale and extent of impacts will vary as a function of estuary geomorphology and the history and scale of development. It would be worthwhile conducting similar systematic reviews of threatened waterways in order to highlight critical management concerns and knowledge needs.

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