Using Ocean Accounting towards an integrated assessment of ecosystem services and benefits within a coastal lake

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Academic editor: Alessandra La Notte

Abstract

Coasts lie at the interface between terrestrial and marine environments, where complex interrelationships and feedbacks between environmental, social and economic factors provide a challenge for decision-making. The knowledge and data needed to link and measure these multiple domains are often highly fragmented and incoherent. Ocean Accounting provides a means to organise relevant ocean data into a common framework, grounded in existing international statistical standards for national and environmental-economic accounting. Here, we test Ocean Accounting within Lake Illawarra, New South Wales (Australia), compiling accounts for the years between 2010 and 2020, inclusive, to measure the extent of coastal vegetation (mangrove, tidal marsh and seagrass) and associated ecosystem services flows (climate change mitigation, eutrophication mitigation) in physical and monetary terms and associated production and employment within sectors of the ocean economy. The accounts show an increase in mangroves by 2 ha and a decrease in seagrass of 80 ha. A net increase was observed in the amount of carbon, nitrogen and phosphorus sequestered across coastal vegetation, due to the expansion of mangroves. Alongside changes in ecosystem extent, a 2-fold increase in full-time ocean-related employment was observed. Fisheries catch also showed significant variation over the 10-year period, where dependencies were observed between commercial species with seagrass and tidal marsh. The relationships and measures derived from accounts provide a cohesive and integrated understanding to provide information for the management and standardised ecosystem service assessments.

Keywords

Introduction

Healthy ocean ecosystems and the services they provide underpin the health, well-being and livelihoods of coastal communities. Coastal ecosystems, such as mangroves, tidal marsh and seagrass, provide ecosystem goods and services (henceforth, 'ecosystem services'), such as food, regulation of nutrient cycles and as landscapes of cultural importance (Liquete et al. 2013, Lau et al. 2019). Many economic sectors (e.g. fisheries, tourism) are dependent on such ecosystems and their services to function (Gacutan et al. 2019). A challenge remains, however, in identifying and measuring the complex relationships between the environment, society and the economy and better recognising dependencies therein (Fenichel et al. 2020). An integrated understanding of coastal systems addresses the call to better value nature's contribution to society (Dasgupta 2021) and more recently, through coherent and standardised methodologies (Jones 2010, Schaltegger and Burritt 2017).

The concept of ecosystems and their provisioning of services have become central in communicating the consequences of ecosystem change on human and societal well-being (Tinch and Mathieu 2011, Luisetti et al. 2014). Ecosystem service frameworks can be used to compartmentalise a system, to trace flows from environmental assets to society and the economy (Harrison et al. 2018, Dunford et al. 2018), where the organisation of ocean systems into 'stocks' and 'flows' lends to their measurement within an accounting framework (Schultz et al. 2015). International accounting standards, such as the UN System of Environmental Economic Accounting (SEEA), provide a coherent structure for physical and monetary data (UN 2012) that aligns with existing national accounts (as defined by the System of National Accounts, SNA) that measure economic activity (UN 2008). Ecosystem accounting within the SEEA framework (as described in SEEA Ecosystem Accounting, SEEA-EA, UNSD 2021) supports a spatial understanding of ecosystems as a function of their location, extent and condition and the resultant supply and use of ecosystem services (see Table 1 for definitions). Accounting frameworks provide a 'data foundation' for evidence-based policy and may be used to evaluate the degree to which coastal management furthers the sustainable, inclusive and equitable use of coasts.

Environmental-economic accounting efforts to date have focused primarily on the terrestrial domain, with limited attention to the applicability of concepts, definitions and classifications to the ocean. Accounting challenges within the ocean include dynamic stocks and flows within a three-dimensional environment and disaggregation of ocean-related economic activity (Jolliffe et al. 2021). The Ocean Accounting Framework

addresses such conceptual challenges by extending the SNA and SEEA statistical standards, providing guidance in classifying and measuring ocean-related economic activity and the underlying ecosystems supporting such activities (GOAP 2021a). Through accounts maintained over time, Ocean Accounts provide a common baseline to monitor ocean ecosystem extent and condition, and subsequently, the ecosystem services supplied and used. This allows the monitoring, reporting and valuation of policies and management interventions, as measured through changes to ecosystems, their services and feedbacks identified through social and economic indicators.

The need for an ocean-centric approach is recognised by the High-Level Panel for a Sustainable Ocean Economy, where all 15 country members have committed to the development of national ocean accounts.[*1] Research commissioned by the panel stressed the need for multiple indicators in understanding the ocean's contribution to society and the environment (Fenichel et al. 2020). There is a need, however, to adapt and extend existing statistical standards towards the ocean, with the UN Statistical Division formally recognising the development of an Ocean Accounting standard.[*2] In support of rapidly growing demand for methods and technical guidance, several pilot studies have been performed, supported by the UN Economic and Social Commission for Asia and the Pacific (UN-ESCAP). The growing global community of practice is supported by the Global Ocean Accounting Partnership (GOAP), which maintains a technical guidance towards the production of Ocean Accounts (GOAP 2021a).

Coastal ecosystems present a prominent, but vulnerable asset to communities and face growing pressures from urbanisation, pollution and over-exploitation. The rapid loss in ecosystems such as mangrove, tidal marsh and seagrass, have been linked to reduced food security, increased exposure to natural hazards and impacts to human health (Singh et al. 2020, Scanes et al. 2020). As such, Ocean Accounting within the coastal domain has largely been used to measure changes to ecosystem extent and condition and their services, given the increasing pressures from human activities, growing coastal populations and climate change (GOAP 2021b). Few accounts, however, have linked changes to ecosystems with subsequent changes to relationships and dependencies with society and the economy, such as production and employment in ocean-related sectors. Here, we describe the compilation of Ocean Accounts for Lake Illawarra, related to coastal ecosystems (seagrass, tidal marsh, mangrove) and their subsequent flows through the valuation of ecosystem services (in physical and monetary terms). The account structure and compilation followed guidance from the Ocean Accounting framework, aligned with SEEA-EA and SNA approaches. We further identify changes to production within fisheries and employment in ocean-related sectors. Lake Illawarra is a coastal estuary within the south coast of New South Wales, Australia, chosen as a case study due to an extensive history of anthropogenic modification (Baxter and Daly 2010) and available data. Ecosystem changes observed within the compiled accounts were then compared to scientific literature to identify potential environmental and economic drivers. Of note is the permanent opening of the Lake entrance in 2007 (Regena 2016), which may have shifted the biophysical characteristics of the Lake.

This study demonstrates the utility of ocean accounts in an integrated understanding of a coastal lake. It provides:

1. an overview of the account compilation strategy,
2. accounts of the extent and provisioning of services for three coastal ecosystems and the ocean economy and
3. draws from literature to identify potential drivers of change identified within the accounts.

Accounts were compiled between the years 2010 and 2020 inclusive, with several accounts providing a spatially explicit understanding of ecosystems and their services within the Lake. The identification of relationships and feedbacks derived from accounts provide an integrated understanding to provide information for standardised ecosystem service assessments and management interventions.

Methods

Study site

Lake Illawarra is a wave-dominated barrier estuary (after Roy et al. 2001) located approximately 100 km south of Sydney (Fig. 1). The Lake (max depth ~ 3.2 m) is characterised by a sand barrier at the entrance, where energetic swells on the coast occasionally closed the entrance from the sea entirely. As of 2007, the entrance of the Lake was permanently opened, which increased the intrusion of marine waters and altered the transport of sediments within the Lake. Before the permanent opening of the entrance, freshwater input was limited within the estuary. Lake hydrodynamics were influenced predominantly by entrance condition and tides (when the Lake was open) (Kumbier et al. 2018). The new equilibrium imposed by the built structures has yet to be reached, with changes to the entrance morphology expected to increase into the future (Couriel et al. 2013).

Framework overview and account compilation strategy

Ocean Accounts extend existing accounting standards, where the present study draws upon SEEA-EA and employment from census methods, described in part within the SNA. Environmental and economic components within the Lake Illawarra 'system' could therefore be organised into environmental assets (ecosystem extent and condition), their flows (ecosystem services) and employment within related sectors of the ocean economy (Fig. 2a). The Ocean Accounts align with the structure, concepts and definitions described within the SEEA-EA, which is a spatially explicit approach to measure ecosystem extent, condition and services in both physical (e.g. litres, tonnes) and monetary terms (Fig. 2b). The production of the fisheries sector was explored separately to ecosystem services, with additional analyses performed to partition the contribution of

coastal ecosystems to harvested biomass. Ocean employment was defined as employment in ocean-related sectors, with data sourced from census data.

Account compilation strategy

Following the Ocean Accounts Framework (GOAP 2021b) and SEEA EEA Technical Recommendations (UNSD 2017), account construction followed the following steps:

- Scoping of use-cases to inform coastal management,
- Compilation of a data inventory, literature review and shortlist of key contacts for Lake Illawarra,
- Selection of relevant ecosystem services, constrained by data availability,
- Construction of an ecosystem extent account,
- Valuation of ecosystem services (use, in physical and monetary terms),
- Compilation of ocean economy satellite accounts related to employment within ocean-related economic sectors.

A workshop was held in November 2020 to identify the policy-relevance and management challenges within the Lake, which highlighted the need for accounts concerning coastal vegetation and identified key knowledge and data holders that could facilitate data access (see Table SM1.2 in Suppl. material 1). Specifically, mangrove, tidal marsh*[3] and seagrass were identified as priority assets to regulate biophysical processes and were of concern to the community surrounding the Lake. A literature review was conducted and data inventory compiled, which identified data for ecosystem extent and their services as feasible for account compilation, although a lack of empirical knowledge of relationships and supporting data prevent the compilation of ecosystem condition accounts. The ecosystem services selected for assessment included: (i) climate change mitigation via carbon sequestration and capture and (ii) eutrophication mitigation through nitrogen and phosphorus mitigation and capture. Primary data from Lake Illawarra and values from literature were available to estimate the amount of carbon, nitrogen and phosphorus sequestered or captured within different coastal ecosystems (Table 2).

Ecosystem accounts were compiled for Lake Illawarra for the fiscal years 2010, 2015 and 2020, guided by the Ocean Accounts Framework (GOAP 2021b) and aligned with SEEA (Fig. 2b). Accounts of ocean employment were compiled for ocean-related sectors, aligned with SNA statistical standards for the census calendar years of 2011 and 2016. Spatial data from the accounting area were harmonised into a 1 km discretised grid, which served as the 'basic spatial unit' (UNSD 2021).

Ecosystem accounts of coastal vegetation

Ecosystem extent accounts

The ecosystem extent account dealt with three coastal ecosystem types (mangroves, tidal marsh and seagrass) in Lake Illawarra. For seagrass and tidal marsh, estimates were

calculated for the dominant genera, whilst mangroves were solely of the species *Avicennia marina* (Grey mangrove). Seagrass were composed of two genera (*Zostera* spp. and *Ruppia* spp.) and tidal marsh assemblages were predominantly of the genera *Sarcocornia.* The extent per ecosystem was mapped using an existing spatial dataset for 2015, the spatial borders of which were then modified to estimate the extent for 2010 and 2020. Mangrove, seagrass and tidal marsh extent was previously mapped in 2015, with polygons of spatial boundaries produced through remote sensing ('NSW macrophytes' layer, projected to WGS 84 / UTM zone 56S, see Suppl. material 1). The 2015 data were a composite of aerial images, many of which were taken during Austral winter (June - August). To estimate extent in 2010 and 2020, the existing spatial data was duplicated and manipulated to match the spatial boundaries observed visually across the Lake using high-resolution aerial imagery from Nearmap*[4] (0.075 m per pixel). The lateral extent and distribution of intertidal saltmarshes, mangrove forests and seagrass meadows were further aided through previous high-resolution mapping of ecosystem change (Wiecek et al. 2016, Dixon 2017) and ground-truthing in 2020. To match the 2015 dataset, aerial images were used to map ecosystems from July of each year to minimise the influence of seasonal variability. The polygon area for each ecosystem was separated and calculated per grid (i.e. spatial unit).

Ecosystem asset and ecosystem service accounts

The supply of the identified ecosystem services from coastal vegetation were estimated in physical terms (e.g. tonnes) through relating empirical estimates of ecosystem extent with 'ecosystem service' factors, based on empirical data from both Lake Illawarra and other similar estuaries. Detailed methods to calculate the physical flow of each ecosystem service per ecosystem type are presented in Suppl. material 2. Ecosystem services were then valued in monetary terms and related to an economic activity. Carbon and nutrient sequestration and capture into long-term storage relate to the health and well-being of society and could, therefore, be considered a service to the 'owners' of the Lake (i.e. local government, representing the community). The flow of ecosystem services was calculated as the accumulation of a service within an accounting year representing the contribution of the ecosystem to human benefit (climate change mitigation).

The valuation of ecosystem services was conducted in a manner aligned, where possible, with information in national accounts. This allows for the comparison of ecosystem service supply with the supply and use of goods and services described within existing national accounts. The monetary ecosystem services account records the monetary value of ecosystem service flows during the accounting period (e.g. one year), while the monetary asset account estimates the value of the ecosystem service for the entire lifetime of the asset. Valuation by flow or asset varies by ecosystem service. Therefore, this study makes the distinction between the annual flow of an ecosystem service and the service provided by the existence of an environmental asset, which is captured in the monetary ecosystem service and asset accounts, respectively. For example, a portion of the carbon sequestered by coastal vegetation is 'captured' into long-term storage annually (flow), while the majority is stored within the biomass of the

vegetation (asset) and a net loss is observed with the reduction in ecosystem extent or condition.

The provision of habitat and nursery services to commercial fish species by coastal vegetation was estimated in physical terms and converted to monetary terms through their exchange value at market price. For ecosystem services which are not directly marketed, approaches consistent with the concept of exchange values, as underpinning the SNA, were employed. For example, there is no exchange value for carbon sequestration and capture for coastal vegetation, although the auction price of carbon abatement (per tonne C) in August 2020 of the Australian Government Emissions Reduction Fund was used.

Nutrient sequestration by coastal vegetation is highly variable and dependent on biophysical and chemical characteristics of the estuary that can impact estuarine health, such as eutrophication and algal blooms. As no nutrient trading schemes were present (and thus exchange values), an 'avoided cost' was calculated (See Suppl. material 2). The value of nutrients sequestered by vegetation were based on the estimated cost of investment into infrastructure and maintenance to a tonne of nitrogen and phosphorus. The economic value of nutrients sequestered for Lake Illawarra were estimated from the studies of similar coastal lakes.

Links to ocean economy satellite accounts

Fisheries production

Commercial fisheries landings within the Lake, in both physical and monetary terms (Gross Value Product, GVP), were used to develop accounts pertaining to fisheries production. As per the Ocean Accounts technical guidance (GOAP, 2021a) and SEEA-EA, landed fish were treated within the ocean economy satellite accounts, in order to avoid double counting. Catch in physical terms (e.g. tonnes of exploited species landed) does not measure the entire service of enhancement, which includes the biomass remaining within the environment. It does, however, reflect enhancement by ecosystems to some degree, given that catch volume is impacted by the functioning and services provided by these ecosystems. The monetary value of catch also conflates ecosystem contribution with that of the labour and produced capital required to land the catch and, thus, should be assessed separately (GOAP 2021a). This study proportioned the production accounts of fisheries (i.e. catch landed) within Lake Illawarra to identify the contribution of ecosystems to catch. Each ecosystem has an 'isotopic signature' of a specific ratio of carbon and nitrogen isotope, that could be used to track the energy flow through the food web, from species that initially consume biomass from these ecosystems into the harvested biomass of commercial species.

Dietary information from previous studies using stable isotopes to track energy flow in similar estuarine ecosystems was used to apportion the harvested biomass of commercial species amongst the ecosystems being considered (see Jänes et al. 2020,

Taylor et al. 2018b). We focused our assessment on a subset of eight species, binned into three taxonomic groupings, that comprised about 65% of the total commercial harvest in Lake Illawarra (Suppl. material 3). The use of stable isotopes within harvested commercial species facilitates the attribution of economic value to specific mangrove, tidal marsh and seagrass ecosystem. It is limited, however, in that estimates of dietary contributions from similar seagrass-dominated systems were not available for all species harvested in Lake Illawarra.

Ocean employment

In line with the SNA, the Australian Government, public and private institutions maintain records of industry activities, such as employment, production volumes and production values. National accounts include a range of economic activities that intersect with the ocean, both in industry and geography (Colgan 2004), which may be disaggregated to identify production and employment of ocean industries and further subset for specific statistical areas (e.g. Lake Illawarra). Key ocean industries in Lake Illawarra were identified from a universal list of ocean industries (Colgan 2004, Kildow and McIlgorm 2010, Park and Kildow 2014), which were used to subset relevant categories from the Australian and New Zealand Standard Industrial Classification (ANZIC). The ANZIC contains a hierarchical structure of four levels, namely division (e.g. agriculture, forestry and fishing), subdivision (e.g. fishing, hunting and trapping), group (e.g. fishing) and class (e.g. prawn fishing). Data randomisation is performed at the lowest level (class), to abide by confidentiality agreements. Therefore, this study disaggregated to the 'group' level (level 3), which included fisheries, water transport and boat building.

The Australian Bureau of Statistics (ABS) census data record employment by industry at place of work, based on the physical location or the address of their workplace. Those with a fixed workplace address who journeyed to an alternate address for work (i.e. depot) were coded to the depot. Data were aggregated to the smallest statistical spatial unit within census reporting, Statistical Area Level 2 (SA2)[*5] with seven SA2 areas contiguous to the Lake used to calculate employment for the 2011 and 2016 census years (Fig. 1). Employment within the ocean economy is highly volatile due to seasonality in ocean industries, such as fishing (including transport and processing), which is rarely captured in official statistics. Ocean industries also have non-traditional working arrangements (i.e. informal and self-employment) that result in inconsistent working hours. Thus, full-time equivalent (FTE) employment was calculated, which accounts for both full-time, part-time and casual employment, which addressed the seasonality and non-traditional patterns of work.

Results

Ecosystem accounts (extent and services)

The present study observed an expansion of mangroves and contraction of seagrass extent in Lake Illawarra between 2010 and 2020, increasing by 2 ha (1197%) and decreasing by 82 ha (-9%), respectively (Table 3). Mangrove expansion occurred primarily near the entrance channel, with single trees and shoots establishing to the west and south of the estuary (Fig. 3). Of the seagrass lost between 2010 and 2020, 76% occurred adjacent to the entrance channel and flood-tide delta, while the marginal expansion of tidal marsh is concentrated at the southern foreshore of the Lake.

The flow (annual sequestration) of carbon (C), nitrogen (N) and phosphorus (P) into the biomass of mangroves, tidal marsh and seagrass for 2020 are presented in Table 4 , where only C flows could be estimated across all three ecosystems. For 2020, the three ecosystems were estimated to sequester 174.07 tonnes C, with a monetary value of A$2783. The stock of C, N and P within the biomass of the three coastal ecosystems are presented in Table 5. An estimated 845 tonnes C was estmated across the three ecosystems in 2020, with seagrasses accounting for 43% of total carbon. The net carbon balance between 2010 and 2020 was a gain of 142.67 tonnes C within biomass, despite a loss of 38 tonnes C captured within biomass due to the contraction of seagrass.

The capture of N and P into biomass was estimated to increase by 13% and 9%, respectively between 2010 and 2020 (Table 5). The contraction of seagrass decreased capture of N by 2.37 tonnes N, which was offset by the expansion of mangroves and tidal marsh, leading to a net change of 3.87 tonnes N. Similarly, P capture in biomass increased by 0.35 tonnes P, with mangroves estimated to increase P capture by 1110% between 2010 and 2020. The largest net change in N and P capture was observed in the woody component of mangrove biomass (Fig. 5, see Table SM2.7 of Suppl. material 2).

The monetary value of ecosystem services for coastal vegetation were estimated for both stock (lifetime of the asset) and flow during the accounting period. The monetary value of carbon stock within Lake Illawarra was estimated at A$13,522 in 2020, increasing by 20% for the accounting period. The monetary value of N and P stock was estimated at A$70 million and A$50 million, respectively Table 5.

Ocean Economy Satellite Accounts

Significant variations in catch, by total volume and composition were observed between 2010 and 2020. The highest catch by weight and value was observed in 2010, landing over 200 tonnes with a value estimated at A$1.14 million (Table 6). The composition of the catch shifted between accounting periods, with almost 60 tonnes of prawns landed in 2010, relative to 12.5 tonnes in 2020 and 27.8 to 6.1 tonnes of crab between 2010 and 2020. The net change in total catch within the accounting period was 74 tonnes, with prawn catch decreasing by 47 tonnes, while crab and finfish decreased by 22 tonnes and 26 tonnes, respectively.

In estimating the contribution of ecosystems to the diet of target species of commercial size, the biomass of crab, prawn and mullet species showed reasonably strong attribution to seagrass ecosystems (based on food web modelling from other seagrass-dominated systems) (Fig. 4). Using diet as an indicator of energy flow, the 60 - 70% of the composition of crab, mullet and prawn biomass were traced to seagrass biomass (see Suppl. material 3), where the value of seagrass supporting crab, prawn and mullet catch was estimated at A\$451,425 and A\$255,152 in 2010 and 2020, respectively. Tidal marsh contribution to commercial catch was valued at A\$135,228 and \$55,744 in 2010 and 2020, respectively. While biophysical conditions can influence fisheries productivity, changes to value are also influenced by catch composition, fishing intensity and market price.

Ocean employment in Lake Illawarra increased by 112% from 34 to 72 FTE employees between 2011 and 2016 (Table 7). Almost all sectors increased in employment, with water transport support services increasing by 227%, which included jobs such as stevedoring, water freight transport and terminal operations and other support services. Over the 5-year period, fishing only increased by 1 FTE (10%). The census data reported 'boat building' and 'ship building' for 2011 and 2016, respectively, where aggregating both activities identified a 67% increase in employment.

Discussion

Ecosystem extent, services and asset accounts were compiled for Lake Illawarra and linked to accounts of fisheries catch, to identify and measure the contribution of ecosystems to society and the economy between 2010 and 2020. Ecosystem accounts were compiled for mangroves, tidal marsh and seagrass, in estimating the impact of net changes in extent to the supply and value of eutrophication and climate change mitigation ecosystem services. Accounts were also compiled for fisheries production and employment within ocean-related sectors. By collating environmental and economic data into accounts, trends within the system may be observed and linked to potential drivers.

Monitoring and evaluating trends in ecosystems and their services

Changes in coastal vegetation within Lake Illawarra were observed between 2010 and 2020, inclusive. Mangrove extent increased by 2 ha, tidal marsh extent increased by 5 ha, whilst seagrass contracted by 82 ha (Fig. 3, Table 3). The change in seagrass extent occurred predominantly around the flood-tide delta near the entrance of the estuary, whilst the increase in mangrove extent was observed predominantly near the Lake entrance.

The change in biophysical characteristics of Lake Illawarra, such as mangrove expansion, sediment erosion and deposition, have been linked to the permanent opening of the Lake entrance in 2007 (Regena 2016). The permanent opening increased the influence and retention of marine waters within the estuary, which provides ideal conditions for the establishment of mangroves (Woodroffe et al. 2016, Rodríguez et al.

2017). In parallel, the permanent opening increased the velocity of tidal currents, especially within the entrance channel, leading to scouring (i.e. erosion) and transport of sediment into the estuary basin, burying seagrass beds (Regena 2016). The entrance continues to deepen and scour, suggesting an equilibrium has not yet been reached, with increased sediment deposition and seagrass burial expected to continue (Young et al. 2014).

Coastal carbon stocks and flows

Carbon (C) is sequestered into the living biomass of ecosystems, of which a proportion may subsequently be transferred into sediments and captured through burial into long-term geological storage (Kelleway et al. 2016). A net increase of 143 tonnes C was estimated between 2010 and 2020. While mangroves only composed 0.2% of extent across the three ecosystem types in 2020, it was linked to 18% of carbon sequestered into biomass, where its expansion led to the net increase. Of the three ecosystems within this study, mangroves have the greatest capacity for carbon capture, estimated at 263 times and 11 times tonnes C per hectare relative to seagrass and tidal marsh, respectively (See Suppl. material 2).

Lunstrum and Chen (2014) suggest that, while the total carbon captured in mature mangrove forests is higher, the rate at which carbon is sequestered could be higher in younger forests. Further, mangroves within Lake Illawarra are encroaching on tidal marsh extent and Kelleway et al. (2016) suggest the substitution to mangroves may lead to a net gain in carbon sequestration and capture over longer timescales. Therefore, reductions in carbon capture and sequestration due to seagrass loss may be balanced by the expansion of mangroves within Lake Illawarra. Evaluating the service of climate change mitigation, however, should identify and account for the production and release of greenhouse gases, such as methane from mangroves, which may impact the net sequestration and capture of carbon (Rosentreter et al. 2018).

Eutrophication mitigation

A net increase in nitrogen (N) and phosphorus (P) was observed across the Lake due to the expansion of mangroves and tidal marsh, despite the contraction of seagrass. The loss of seagrass decreased N and P capture by 2.37 tonnes N and 0.31 tonnes P, respectively. The loss of nutrients (both N and P) as stock within seagrass biomass was valued at A\$ 5.43 million in eutrophication mitigation services between 2010 and 2020. The expansion of tidal marsh and mangrove, however, led to a net increase in nutrient stock within biomass across Lake Illawarra, at 3.87 tonnes N and 0.35 tonnes P, for which it was valued at A\$ 8.68 million (Table 5). As with C, mangroves contain greater stocks of N and P within foliage, wood and root biomass, relative to tidal marsh and seagrass (Fig. 5). Thus, the continued expansion of mangroves may increase the stock of N and P within biomass into the future.

The removal of N and P from the water column and into biomass limits its availability to the algae responsible for eutrophication. Algal blooms were a motivating factor for public

support for the permanent opening of the Lake in 2007, where eutrophication led to a loss of amenity, such as swimming areas and navigation of personal watercraft. Advocates of the permanent opening believed it would increase tidal flushing and, thus, water quality (Regena 2016). Some areas have shown improvement in water quality, although areas to the north-west of the Lake still experienced elevated nutrient loads (WCC 2021).

The changing Ocean Economy

Accounts detailing fisheries production, in terms of the amount landed and its value, could be used to identify feedbacks with changes to ecosystems that are supporting exploited species. Within Lake Illawarra, the accounting period saw a change in prawn and crab catch, at -79% and -78%, respectively, between 2010 and 2020. Crustacean landings are generally highly variable and 2010 happened to represent a particularly productive year for Lake Illawarra, so the catch values reported for 2010 could be considered atypical. Year-to-year variability in crustacean fisheries can arise from fishery decisions and market values, variability in temperature, spawning and recruitment processes, growth and survival, amongst other things. Factors such as rainfall (and drought) can have a substantial influence on prawn biomass, growth and survival (Dall et al. 1990). Prawn species that comprise the majority of catch within the Lake may benefit from the permanent lake opening as they have a juvenile phase within the estuary, but are ocean spawners (Dall et al. 1990). Thus, while it may be tempting to attribute this difference to changes identified within the ecosystem accounts, there are several other contextual factors that need to be considered.

Changes to the value of gross value product (GVP, Fig. 4) are also impacted by unrelated factors to ecosystem extent and condition, including market forces impacting demand, supply, imports and exports. For example, while finfish decreased by 26 tonnes landed, the value of the catch increased by A$ 54 thousand. As such, while catch in physical and monetary terms represents benefits supported by ecosystems, the trends over time need to be interpreted with caution and are not a direct measure of the supply of ecosystem services (GOAP 2021a).

An alternate method is the use of diet (measured via stable isotopes) to link the biomass of ecosystems to catch landed. Diet indicators have been suggested as an indirect means to measure dependency, where commercial species may depend on ecosystem biomass, although may not intersect spatially (Taylor et al. 2018a). For example, 65% of the biomass of mullet were dependent on tidal marsh, while 86% of the biomass of crab species were dependent on seagrass. There is a clear spatial disconnection between ecosystem dependency and residence of commercially-important species. Crabs are found largely along intertidal areas although they demonstrate a dependency on seagrass. Conversely, subtidal fish species were observed to be dependent on tidal marsh, which are rarely submerged within the region and thus limited in providing habitat for such species (Saintilan 2009).

Ocean-related employment within Lake Illawarra was estimated to grow from 34 to 72 Full-time equivalent (FTE) jobs between 2011 and 2016. Despite the significant reduction in prawn and crab catch within the accounting period, FTE employment within the overall fisheries sector remained stable (Table 7). A decline in the employment of a specific sub-fishery (e.g. prawn, crab fisheries) could not be observed directly due to aggregation to the general 'fishing' classification in both 2011 and 2016 censuses and estuary catch of all species examined within this study were mostly managed and reported under a single fishery. The increase in FTE employment was attributable to the 'water transport' sector, which could be linked to the expansion and maintenance of water transport infrastructure (e.g. docks and jetties) (Fletcher et al. 2020). The permanent opening of the Lake entrance increased navigability, which may be a driver of increased water transport and boating traffic, with observed increases in visitation (Baxter and Daly 2010).

Use of ocean accounts in coastal decision-making

The immediate use of ocean accounts is in the monitoring and evaluation of trends across the environment and economy, to provide information for management interventions. Accounts could be used to demonstrate the impacts of changes to ecosystem extent, to flows such as climate change and eutrophication mitigation. If accounts are maintained over longer timescales, accounts could trace relationships with economic sectors, to better demonstrate trade-offs between ecosystem change and impacts to their services and their benefits to society and the economy. For example, large amounts of seagrass were lost, which would have significantly reduced carbon, nitrogen and phosphorus capture, but this is somewhat offset by the expansion of mangroves. Seagrasses, however, were identified as an important source of primary production, supporting the food webs in which exploited species fed (Fig. 4), where mangroves and their services may not necessarily act as a substitute (c.f. nutrient removal) for supporting the production of these species. Such accounts provide evidence for the contribution of these cosatal ecosystems and could be used as evidence towards their role as nature-based solutions in providing carbon a carbon sink and addressing excess nutrients within the water column (Nesshöver et al. 2017).

A strength of ocean accounting is the ability to support integrated coastal decision-making (and evaluate the outcomes of decisions), which requires knowledge derived from multiple domains. Ocean accounts facilitate this process by providing a 'common set of facts,' relevant to several coastal policy processes, such as supporting:

1. the evaluation of policies and management interventions and
2. providing information for planning processes.

Accounts that are maintained over time may trace the impacts of policy across ecosystems, society and the economy (Ruijs et al. 2019), where the accounts support the framing of the system through a Driver-Pressure-State-Impact-Response (DPSIR) approach (see Grondard et al. 2021). When combined with empirical studies, accounts may be used to identify drivers and the potential impacts of management interventions. The efficacy and unintended impacts of the 'response' may be monitored

by ocean accounts, through both data and the production of statistics and indicators (Fenichel et al. 2020, Farrell et al. 2021).

Ocean accounts further support planning processes, including the development of ocean-based sectors (i.e. blue economy) or area-based planning (Gacutan et al. 2022). The last decades have seen the widespread adoption of Integrated Coastal Zone Management (ICZM), where some jurisdictions have further extended area-based management to both the coastal and marine domain through Coastal and Marine Spatial Planning processes (CMSP, Halpern et al. 2012). Both ICZM and CMSP may utilise an ecosystem-based approach, which endorses consideration of both social and ecological components of the system. Similar sentiments are found within the Lake Illawarra Coastal Management Program (2019 – 2029), which aims to 'protect and enhance natural processes', while also considering social, cultural and economic values (BMT 2019). The accounts compiled within this study directly contribute to the monitoring of ecosystem state and future account extensions may consider ecosystem services and social indicators that explore the links between ecosystems (and their health) and amenity and recreational values. In summary, accounts provide a standardised means of monitoring multiple system components.

Limitations and future work

Integrated and standardised assessment of ecosystems and their services pose a significant conceptual and data challenge. Even for a data-rich and well-studied area such as Lake Illawarra, the compilation of several accounts required several iterations to refine the classifications used. The process also required a multi-disciplinary collaboration across the fields of coastal ecology, geographical information systems (GIS), ecosystem services, environmental-economic and national accounting. During account compilation, it was clear that ecosystem condition accounts could not be compiled and several 'condition' and ecosystem service 'factors' identified within literature could not be applied directly to Lake Illawarra and warranted further testing against empirical data.

Ecosystem condition and how it affects services, is often overlooked due to complexity and data limitations. It is vital, however, in refining estimates of ecosystem service supply, by considering the functioning of biotic and abiotic ecosystem components. For example, the emergence of young (< 5 years) mangrove ecosystems within Lake Illawarra may significantly increase the rate at which carbon is incorporated into biomass (Lunstrum and Chen 2014), although the lack of structures (i.e. woody biomass, aerial roots) may significantly limit the provisioning of nursery habitats for commercial fish species at the 'mangrove fringe' (sensu Aburto-Oropeza et al. 2008) and hence their omission from the present study. Another challenge was the accuracy and reliability of the parameters (i.e. ecosystem service 'factors') that translate the extent (and condition) of ecosystems to their provisioning of services. The parameters were sourced from Lake Illawarra where possible, but other estimates were sourced from studies of different estuaries (see Suppl. material 2). This highlights the need for a robust compilation of 'factors' at local scales, to

increase the accuracy and reliability of ecosystem service estimates. It demonstrates, however, that the accounting exercise provides a useful means of identifying the priority knowledge and data gaps for future research and investment.

Ocean accounting and environmental-economic accounting, generally, have several limitations that should be considered when managing the coastal domain, namely the biases in selecting the contents within accounts and the identification of tipping points. As explored by Chen et al. (2020) and Perkiss et al. (2022), the choice of system components for compilation will bias the values represented within the accounting area. For example, the omission of mangroves as a relatively limited ecosystem would have excluded the estimated contributions to nutrient and carbon capture and further limited a key impact linked to the permanent lake opening. Accounts are also limited in predicting rapid changes in the system (i.e. tipping points), related to measures of thresholds and irreversibility (Chen et al. 2020). For example, accounts compiled prior to the Lake opening would have been limited in predicting any rapid changes to the Lake system (e.g. ecosystem extent and employment).

Conclusions

This study presents a process to compile several accounts on ocean ecosystems and economy, aligned with existing technical guidance and standards. Through an assessment of policy needs and data availability, coastal vegetation was identified as a priority for account compilation. Measured changes in ecosystem extent allowed for estimates of changes to ecosystem service supply, in parallel to compiling accounts for fisheries production and ocean-related employment. The accounts showed changes in seagrass and mangrove extent across a decade. The expansion of mangroves led to an estimated net increase in carbon, nitrogen and phosphorus sequestration and capture across Lake Illawarra and has the potential to increase carbon and nutrient capture into the future.

Whilst not all components of the system could be accounted for, the set of accounts that could be compiled provided a means of linking ecosystems (and their services) to the ocean economy and considering the implications of changes to ecosystems. The accounts support holistic and integrated decision-making and expand the consideration of ecosystems within cost-benefit analyses in measuring the value of ecosystem services in parallel to the ocean economy. Decision-makers may, therefore, use the data contained within accounts, alongside other considerations (e.g. social values) to monitor and better manage Lake Illawarra. Future policy processes supported by accounts could include spatial planning, coastal management and area-based protection measures.

Acknowledgements

Author contributions

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Conflicts of interest

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

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Endnotes

[1] Members of the High Level Panel for a Sustainable Ocean Economy include Australia, Canada, Chile, Fiji, France, Ghana, Indonesia, Jamaica, Japan, Kenya, Mexico, Namibia, Norway, Palau, Portugal and the United States of America. Commitments are made through each country's respective leader (i.e. presidential/ prime ministerial level).

[2] United National Statistical Commission, Report on the fifty-second session (1–3 and 5 March 2021), Economic and Social Council Official Records, 2021 Supplement No. 4, E/2021/24-E/CN.3/2021/30, accessed online: https://unsta_ts.un.org/unsd/statcom/52nd-session/documents/2021–30-FinalReport-E.pdf

[3] Existing literature within Lake Illawarra and New South Wales estuaries uses the term 'saltmarsh', which we consider analogous to 'tidal marsh' for this paper.

[4] Nearmap: https://www.nearmap.com/au/en

[5] SA2s have a population range of 3,000 to 25,000 persons with an average population of about 10,000 to represent a community that interacts together socially and economically. See: https://www.abs.gov.au/statistics/standards/australian-statistical-geography-standard-asgs-edition-3/jul2021-jun2026/main-structure-and-greater-capital-city-statistical-areas/statistical-area-level-2
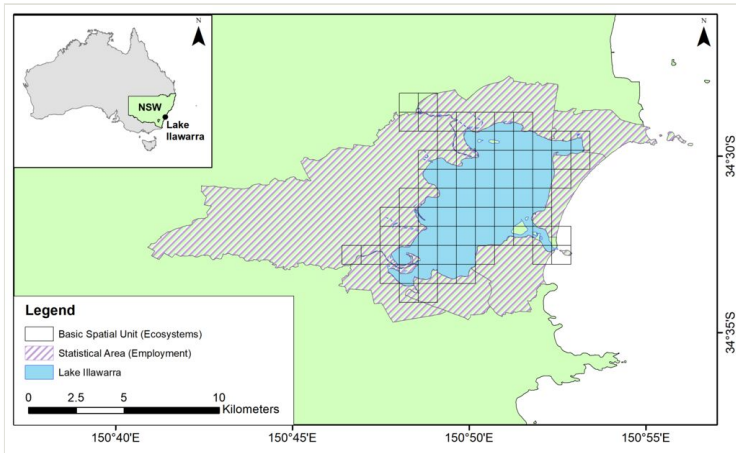
Figure 1.

Location of Lake Illawarra in New South Wales (NSW) Australia (inset) and the basic spatial units (1 km^2 grid, n = 73) used to measure mangrove, tidal marsh and seagrass in ecosystem accounting and (c) the seven level 2 statistical areas (SA2s) used in Australian Bureau of Statistics (ABS) census data used to estimate full-time equivalent employment (FTE).
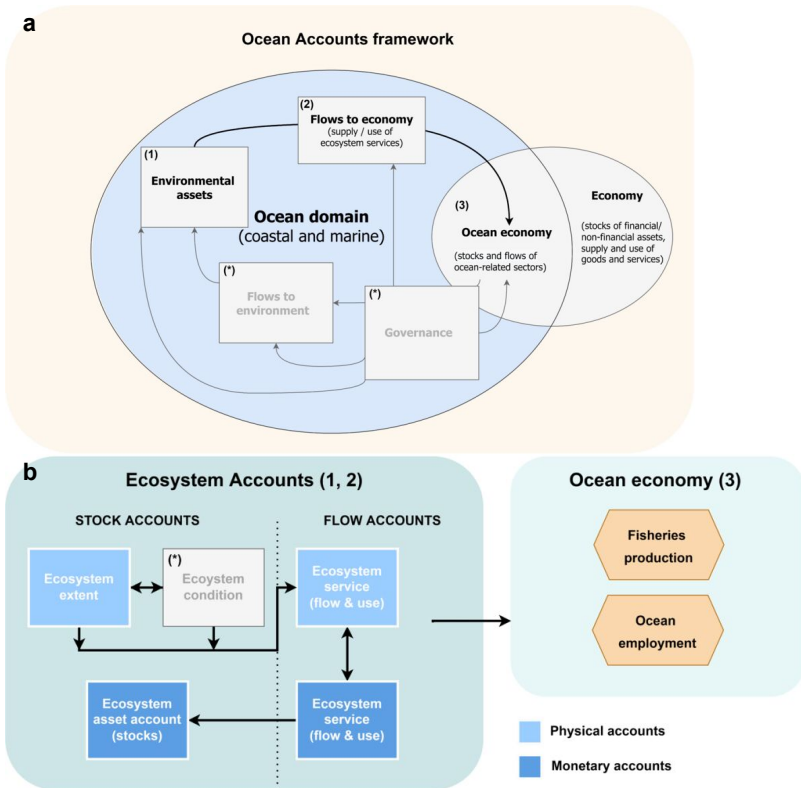
Figure 2.

The Ocean Accounts framework, adapted from the technical guidance (GOAP 2021a), with specific focus on ecosystem accounts and their links to the ocean economy.

a: An overview of the Ocean Accounts framework, subset to three accounting table groups relevant to the Lake Illawarra study, namely: (1) environmental assets, (2) flows to the economy and (3) the ocean economy. *Tables from framework that were not compiled for this study.

b: The table groups from the Ocean Accounting framework may be disaggregated to ecosystem accounts, following guidance from the System of Environmental-Economic Accounting Ecosystem Accounts (SEEA-EA) and measures of the ocean economy, aligned with the Ocean Accounts technical guidance. In aligning with the Ocean Accounts Framework, Ecosystem Accounts encompassed: (1) environmental assets and (2) flows to the economy, with tables concerning (3) the Ocean Economy compiled separately.
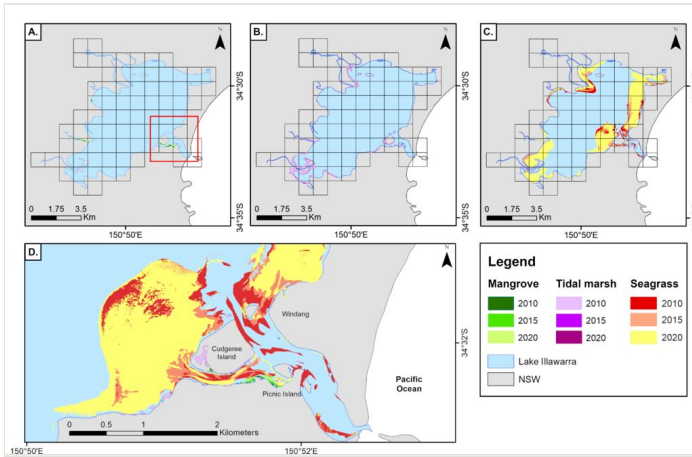
Figure 3.

Ecosystem extent for the (A) mangrove, (B) tidal marsh and (C) seagrass coastal ecosystems for the 2010, 2015 and 2020 accounting periods. Basic spatial units used in ecosystem accounting overlayed. The (D) change at the Lake entrance and flood-tide delta is shown for all three ecosystems, with the location indicated in the red within (A).
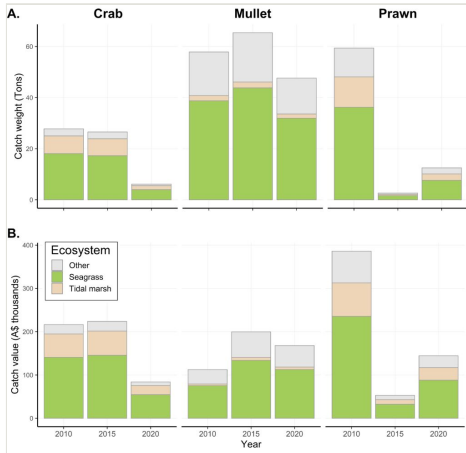
Figure 4.

The amount of catch landed in (A) physical (tonnes) and (B) monetary (A$ thousands) values, apportioned amongst seagrass, tidal marsh and other ecosystems for crabs, mullet and prawn species. Trophic modelling of stable isotope data in published studies was used to estimate the energy transfer from producers to consumers. Raw data tables for the Figure is presented in Table SM 3.2 of Suppl. material 3.

Figure 5.

Capture (in tonnes) of (A) nitrogen and (B) phosphorus into the biomass of three coastal vegetation ecosystem types (mangroves, tidal marsh and seagrass) for Lake Illawarra across the three accounting years. Note that seagrass is presented as *Ruppia sp.* and *Zostera sp* . Raw data tables for the Figure are presented in Table SM 2.7 of Suppl. material 2.

Table 1.

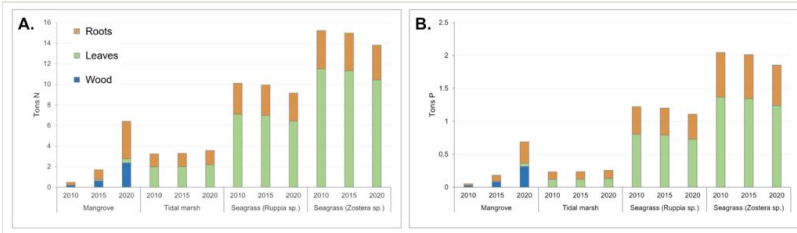Definitions of terms used within the study, as used within the Ocean Accounting Framework (GOAP 2021b) and aligned with SEEA-EA (UNSD 2021) and SNA (UN 2008) statistical accounting standards.

Term	Definition	Example	Source
Ecosystem	A contiguous space of a specific ecosystem type characterised by a distinct set of biotic and abiotic components and their interactions.	Mangrove, tidal marsh, seagrass	SEEA EA (UNSD 2021)
Basic Spatial Unit	The subdivision of the accounting area spatially to align data.	The present study uses a 1 km^2 grid (see Fig. 1).	SEEA EA (UNSD 2021)
Environmental asset	Environmental components that are stores of value that, in many situations, also provide inputs to society and the economy (e.g. production processes).	Abiotic and biotic environmental components	Ocean Accounts Framework (GOAP 2021b)
Ecosystem extent	The range and extent of ecosystems within an accounting area.	Landcover of mangroves (in hectares). Ocean Accounts endorse the use of the IUCN Global Ecosystem Typology (Keith et al. 2020).	SEEA EA (UNSD 2021)
Ecosystem condition	The quality of an ecosystem measured in abiotic and biotic characteristics.	Mangrove tree height, above ground biomass. Note that there are no standardised indicators for each ecosystem, although the SEEA-EA provides guidance for the development of condition accounts.	SEEA EA (UNSD 2021)
Ecosystem services	The contributions of ecosystems to the benefits that are used in economic and other human activity. Services are categorised broadly into provisioning, regulating and cultural services. Services are measured either as a good or intangible product of the system.	Enhancement of exploited species stock (provisioning service), climate change mitigation through carbon sequestration (regulatory service), cultural significance of mangroves to traditional owners (cultural services)	SEEA EA (UNSD 2021)
Ocean-related sectors	Sectors with spatial intersection or dependent on ocean resources, including activities that use ocean resources as an input (e.g. fishing) and produce products and services for use in the ocean environment (e.g. shipbuilding).	Coastal and marine fishing, water transport (coastal and marine), shipping and ports.	Ocean Accounts Framework (GOAP 2021b)
Ocean economy satellite accounts	Accounts that measure economic activity dependent on oceans, including activities that use ocean resources as an input (e.g. fishing), produce products and services for use in the ocean environment (e.g. shipbuilding) or use ocean space due to geographic proximity (e.g. warehouses that service ports).	Production, employment accounts for ocean-related sectors.	Ocean Accounts Framework (GOAP 2021b)

Table 2.

The measurement and valuation of ecosystem services related to mangrove, tidal marsh and seagrass, assessed in this study. C = carbon, N = nitrogen, P = phosphorus

Ecosystem services	Ecosystem service factors (units)	Units	Valuation technique	Account type for valuation*
Climate Change mitigation	Carbon sequestration into living biomass	Tonnes C	Auction price of carbon 'credits'	Asset (stock)
	Carbon burial	Tonnes C		Service (flow)
Eutrophication mitigation	Nitrogen sequestration	Tonnes N	Avoided cost	Asset (stock)
	Phosphorus sequestration and burial	Tonnes P		Service (flow) and asset (stock)

Table 3.

Lake Illawarra change in extent (Ha) account (2010 to 2020) for mangrove, tidal marsh and seagrass ecosystem types.

Accounting entries	Mangrove	Tidal marsh	Seagrass	Total
Opening stock	0.17	51.02	878.90	930.09
Additions to stock	1.99	5.25		7.24
Reduction to stock		(0.18)	(82.24)	(82.42)
Net change in stock	1.99	5.07	(82.24)	(75.14)
Closing extent	2.16	56.10	796.65	854.91
Additions to stock (%)	92.29%	10.29%		0.78%
Reduction to stock (%)		(0.35%)	(9.4%)	(8.86%)
Net change in stock (%)	1197.07%	9.94%	(9.4%)	8.08%

Table 4.

Ecosystem service supply in 2020 related to climate change mitigation and eutrophication mitigation, through the capture of carbon, nitrogen and phosphorus within ecosystem biomass within Lake Illawarra. *Annual nitrogen and phosphorus sequestration and capture into biomass could not be estimated.

Ecosystem Service Supply		Unit of measure	Mangrove	Tidal Marsh	Seagrass	Total supply
Climate change mitigation	Of which carbon	Tons	3.02	27.65	143.4	174.07
Eutrophication mitigation	Of which nitrogen		*	*	*	*
	Of which phosphorus		0.05	*	*	0.05

Table 5.

Change in stock of carbon, nitrogen and phosphorus within the biomass of mangrove (M), tidal marsh (TM) and seagrass (SG) ecosystems between 2010 and 2020, in physical (tonnes) and monetary ($ AUD) terms.

	Accounting entry	Units	Carbon				Nitrogen				Phosphorus		
			M	TM	SG	Total	M	TM	SG	Total	M	TM	S
Physical terms	Opening stock	tonnes	11.71	300.97	400.39	713.07	0.49	3.25	25.33	29.07	0.05	0.23	
	Addition to stock		140.15	40.99		181.14	5.92	0.34		6.26	0.64	0.02	
	Reduction in stock			(1.02)	(37.45)	(38.47)		(0.02)	(2.37)	(2.39)			
	Net change in stock		140.15	39.97	(37.45)	142.67	5.92	0.32	(2.37)	3.87	0.64	0.02	
	Closing stock		151.86	330.87	362.94	845.67	6.42	3.57	22.96	32.95	0.69	0.26	
Monetary terms	Opening stock	A$ (thousands)	0.19	4.81	6.40	11.40	1051.25	6900.30	53821.09	61772.64	68.56	300.40	
	Addition to stock		2.24	0.66	0.00	2.90	12584.29	722.43	0.00	13301.19	820.72	29.86	
	Reduction in stock		0.00	(0.02)	(0.60)	(0.62)	0.00	(42.50)	(5035.75)	(5078.25)	0.00	0.00	
	Net change in stock		2.24	0.64	(0.60)	2.28	12584.29	679.93	(5035.75)	8222.94	820.72	29.86	
	Closing stock		2.43	5.29	5.80	13.52	13635.54	7586.28	48784.69	70006.51	889.28	330.26	

Table 6.

Change in landed catch from the fisheries sector (ANZIC 041) in Lake Illawarra between 2010 and 2020, in physical (tonnes) and monetary ($AUD) terms.

	Accounting entry	Unit	Crab	Prawn	Finfish	Other	Total
Physical terms	Opening stock	tonnes	27.78	59.38	112.14	1.12	200.42
	Addition to stock					10.32	10.32
	Reduction in stock		(21.65)	(46.88)	(26.26)		(84.47)
	Net change in stock		(21.65)	(46.88)	(26.26)	10.32	(74.15)
	Closing stock		6.13	12.50	85.88	11.44	115.95
Monetary terms	Opening stock	A$ (thousands)	223.80	451.22	460.26	8.80	1144.08
	Addition to stock					10.32	10.32
	Reduction in stock		(21.65)	(46.88)	(26.26)		(84.47)
	Net change in stock		(21.65)	(46.88)	(26.26)	10.32	(74.15)
	Closing stock		83.90	144.45	515.15	98.75	842.25

Table 7.

The full-time equivalent (FTE) employment for ocean-relevant sectors for the 2011 and 2016 accounting periods. *Defined as the direct use of ecosystem service provided by ecosystems explored within this study (climate change mitigation, eutrophication mitigation). #Estimated change in employment was combined for ship and boat-building and repair services.

ANZIC code	Subdivision (Level 2, ANZIC)	Group (Level 3, ANZIC)	Uses ecosystem services*	2011	2016	% Change (2011 to 2016)
041	Fishing	Fishing	Yes	10	11	10
2391	Other transport equipment manufacturing	Shipbuilding and Repair Services	No	0	5	67#
2392		Boat-building and Repair Services	No	3	0	
48	Water transport	Water Freight Transport	No	10	14	40
521	Water transport support services	Water transport support services	No	11	36	227
Total				**34**	**72**	**112**

Supplementary materials

Suppl. material 1: Definitions and data sources used

Authors: J. Gacutan
Data type: Word
Brief description: Definitions and data sources used for the study.
Table SM1.1 - Definitions of international accounting standards.
Table SM1.2 - Primary and spatial data used in the study.
Download file (29.13 kb)

Suppl. material 2: Ecosystem service assessment methods

Authors: J. Gacutan
Data type: Word
Brief description: Methods for the assessment of ecosystem services (climate change mitigation, eutrophication mitigation).
Download file (123.46 kb)

Suppl. material 3: Fisheries - stable isotope calculations

Authors: J. Gacutan
Data type: Word
Brief description: Methods for the use of stable isotope calculations to partition fish catch to ecosystems.
Download file (25.13 kb)