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Review Paper

The value of Australian aquatic ecosystem services

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A R T I C L E I N F O

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A B S T R A C T

Aquatic ecosystems provide valuable ecosystem services to human wellbeing. Nonetheless, anthropogenic pressures cause significant impacts on their environment and biodiversity. Assigning economic value to these services increases awareness for ecosystem protection, informing policies and planning. Currently, there is no comprehensive review of the economic valuation of Australia's aquatic ecosystems, despite it having the world's third largest marine area. This study provides a review of the economic value of ecosystem services in seven aquatic ecosystems in Australia, namely: mangroves, saltmarsh, seagrass, kelp, shellfish reef, freshwater wetlands and open waterways. Over 90% of the economic value estimates in Australia were conducted for kelp, mangroves, saltmarsh and seagrass, whereas limited information was identified for shellfish reef habitats. Available research is concentrated in New South Wales and Victoria, with limited research in Western Australia and the Northern Territory. Provisioning and cultural services represented over 70% of researched ecosystem services in Australia, while habitat and biodiversity services were rarely identified. Typical provisioning and cultural services identified globally, such as raw materials or bequest values were not identified in the Australian literature. Australian economic values were typically below the global 50th percentile for provisioning, cultural and climate regulation services. In contrast, the use of aquatic ecosystems for storm and erosion protection are often one of the highest economic valuations worldwide with a median Australian value over $400,000/ha/year for mangrove, saltmarsh and seagrass habitats. Overall, the compiled results highlight a potential undervaluation of aquatic ecosystem services in Australia and important research gaps for further investigation.

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1. Introduction

Ecosystems services are the "benefits people obtain from ecosystems" and include both the direct and indirect (or noticed and unnoticed) contributions of ecosystems to human wellbeing (Costanza et al., 2017, Millennium Ecosystem Assessment, 2005, Costanza et al., 1997). These services were grouped into four categories in the Millenium Ecosystem Assessment (2005): provisioning, regulating, cultural and supporting services. Although new categorisations have emerged over the past few decades (e.g. supporting services are now integrated into habitat services in The Economics of Ecosystem Services and Biodiversity (TEEB) or not considered as a service in the Common International Classification of Ecosystem Services (CICES) (Sukhdev et al., 2010; Potschin-Young et al., 2017; Haines-Young and Potschin-Young, 2018)), the Millenium Ecosystem Assessment (2005) remains the foundational reference for the subsequent classifications (Costanza et al., 2017). Historically, the natural assets provided by the ecosystems and their associated services tend to be unaccounted in traditional markets. This is primarily because many of these services do not produce a rival and/or excludable benefit and therefore, do not lend themselves to market transactions (Costanza et al., 2017, Chee, 2004, Costanza et al., 1997). However, assigning a quantitative value to these services increases awareness of their value and ecosystem protection, and can also inform policy, management and planning (Costanza et al., 2017). An estimate of the total value of the ecosystem is the aggregate of each service it provides, as a single ecosystem can (and typically does) provide a range of ecosystem services (Brander et al., 2024a, de Groot et al., 2020, De Groot et al., 2012, Costanza et al., 1997). These are often provided concurrently.

There is an increasing body of research that examines the monetary value of ecosystem services worldwide (e.g. Brander et al., 2024a, De Groot et al., 2012, Pascual et al., 2023). The research targets the value of a particular service(s), such as fisheries production or tourism value, from a specific type of ecosystem (e.g. saltmarsh or freshwater wetlands) at a specific location. Several different methods are used to provide the estimated ecosystem service value (e.g. market based, travel cost, avoided cost, contingent valuation, systems modelling, or benefit transfer). Each one of these techniques has been used in the literature to value different aspects of the ecosystem services, however, their application remains complex due to limited data availability, outdated datasets, human preferences and restricted transferability of valuation estimates across regions or globally (Pandeya et al., 2016; Himes-Cornell et al. 2018; Tinch et al. 2019; Pascual et al. 2023). Therefore, the valuation methods may be constrained to locally available information, shaped by regional policy priorities, and the complexity of implementation (Pandeya et al., 2016; Himes-Cornell et al. 2018; Pascual et al. 2023). Although there is no global consensus on the selection of the specific methods to value individual ecosystem services, it is critical to capture their value to increase government and public awareness and promote policies for ecosystem protection. As indicated in Costanza et al. (2017): '*There is not one right way to assess and value ecosystem services. There is however a wrong way, that is, not to do it at all*'.

Aquatic ecosystems provide a wide range of benefits to the community, including provisioning services such as food, drinking water, as well as regulating and cultural services including climate regulation, storm protection, and recreation (Millenium Ecosystem Assessment, 2005, Ferreira et al., 2023). Nonetheless, to satisfy the increasing demands of society, these ecosystems have been heavily impacted by habitat loss, pollution and exploitation (e.g., fishing), causing significant impacts on the natural environment and the biodiversity of aquatic ecosystems (Häder et al., 2020, Culhane et al., 2019, Arthington et al., 2016, Junk et al., 2012). Worldwide, efforts to protect aquatic ecosystems, to reduce their degradation and to promote ocean science-based policies towards sustainable development, include global targets and initiatives such as the United Nations Decade on Ecosystem Restoration, the United Nations Decade of Ocean Science for Sustainable Development and the establishment of protected areas to promote conservation (Guan et al., 2023; Hermoso et al., 2016; Boonzaier and Pauly, 2016; Wood et al., 2008). Australia holds the world's third-largest marine area, covering a wide range of aquatic ecosystems and containing 25% of the global saltmarsh coverage and ranking third in mangrove area distribution (DCCEEW, 2024). Additionally, over 85% of the Australian population lives in proximity to marine environments (Commonwealth of Australia, 2021), making Australian estuarine and marine ecosystems a hotspot for ecosystem services. Therefore, initiatives to protect and promote awareness of aquatic ecosystems in Australia are crucial.

Marine ecosystem service valuations have been conducted globally, including worldwide ecosystem services databases such as the Ecosystem Services Valuation Database (ESVD) (Brander et al., 2024a, De Groot et al., 2012), or reviews of valuations on individual habitats such as mangroves (Salem and Mercer, 2012, Spalding et al., 2010), saltmarsh (Doolan and Hynes, 2023), seagrass (Doolan and Hynes, 2023, Dewsbury et al., 2016), kelp (Eger et al., 2023), or broader assessments including multiple coastal ecosystems (Mehvar et al., 2018, Himes-Cornell et al., 2018, Costanza et al., 2021). Individual studies focusing solely on Australian aquatic ecosystems have also been conducted (e.g. Taylor et al. 2018, Costa et al. 2024, Jänes et al. 2022; Taylor et al. 2024). Nonetheless, to the knowledge of the authors, a comprehensive review of the economic valuation of aquatic ecosystems in Australia is still needed. The lack of valuation for aquatic ecosystems at national and regional scales hinders the promotion of policies to foster aquatic ecosystem protection and ecosystem services.

To overcome the limited and sparse aquatic ecosystem services valuations, this paper provides a review of the economic valuation of seven aquatic ecosystems in Australia (across marine, brackish and freshwater habitats) based on global, national and regional studies. Hereafter, the seven aquatic ecosystems will be defined as 'key fish habitat'. The designation of key fish habitat was established in the *Fisheries Management Act 1994* to conserve and protect fish species in New South Wales (NSW) and includes any aquatic ecosystem vital for the maintenance of native finfish and aquatic invertebrate populations and is applied in the NSW Biodiversity Offsets Policy for Major Projects and the NSW Fisheries Policies and Guidelines (NSW Department of Primary Industries, 2013, NSW Department of Primary Industries, 2014). This paper first discusses the data review methodology considered for this manuscript, followed by a descriptive mapping of the ecosystem services valuation for each key fish habitat in Australia, and identification of knowledge gaps. Finally, the paper includes a comparison of preliminary data, recognition of spatial and temporary variability in ecosystem service valuation estimates, and highlights how this synthesis could aid policy development and decision-making for land use planning and development assessment, or conservation and rehabilitation.

2. Methodology

This study assessed the ecosystem services of seven key fish habitats (Table 1), grouped among: i) **Marine and brackish habitats**: mangroves, saltmarsh, seagrass, kelp and other marine macro-algae, oyster/shellfish reefs, open waterways (e.g. coastal lagoons and estuaries), ii) **freshwater habitats**: freshwater wetlands. Other key fish habitats include snags, riffles, gravel beds and pools but were not included in the present study. For this study, six ecosystem service categories were selected for each key habitat type based on the available literature and key mechanisms through which coastal aquatic ecosystems contribute to human welfare, as indicated in Table 2: provisioning services (food, water, raw materials, genetic resources, medicinal resources and ornamental resources), cultural services (aesthetic information, opportunities for recreation and tourism, inspiration for culture, art and design, spiritual experience, information for cognitive development and existence, bequest values), regulating services (climate regulation, erosion and storm protection, water treatment) and habitat and biodiversity. Note that aquatic ecosystems can also provide additional ecosystem services not included in the analysis such as air quality regulation, local

Table 1
Key fish habitat investigated in this study and corresponding 2024 Ecosystem Services Valuation Database (2024 ESVD) classification.

Habitat	Key fish habitat	2024 ESVD 2.0 classification
Marine and brackish habitat	Mangrove	2.4.2. Mangroves
	Saltmarsh	2.4.3. Coastal salt marshes and reedbeds
	Seagrass	1.1.1. Seagrass meadows
	Kelp and other marine macroalgae	1.1.2. Kelp forests
	Oysters and shellfish	1.1.4. Shellfish beds and reefs
	Open water	2.3.2. Riverine estuaries and bays2.3.3. Coastal lakes and lagoons
Freshwater habitat	Freshwater wetland	3.2.1. Marshes and swamp

climate regulation or biological control. However, these ecosystem services were not considered due to limited available literature. The ecosystem service values were obtained from literature and data review, including the 2024 Ecosystem Services Valuation Database version APRIL2024V1.1 (2024 ESVD) (Brander et al., 2024a) and 24 additional studies that were identified based on keyword search and expert information, representing 1,484 additional estimates identified worldwide (with 80% of studies from Australia). The matrix, including the 2024 ESVD and additional values, is referred as the 'modified ESVD' to distinguish it from the 2024 database (included in Supplementary Material S1). The 2024 ESVD tabulated over 10,800 individual records of ecosystem service values derived from an extensive literature review with 4,700 values externally reviewed and including more than 1,300 studies (Brander et al., 2024a). Note that the values derived from the ESVD may be under- or overestimated for ecosystems with limited available data and may also reflect a geographic bias towards European studies, where the majority of the information has been collected due to funding sources and research interests (Brander et al., 2024b; de Groot et al., 2020). The values reported in the ESDV are further influenced by the type of valuation methods, the context of the valuation, and reporting bias. Therefore, some services estimates may have significant variability across different regions, even within the same country, which are linked to site-specific conditions or method-sensitive values. The larger the number of valuations available, the less likely that the median is skewed by a small number of disproportionately high or low values. However, this does demonstrate that local valuation is necessary in some cases where there are unusual site characteristics. In some cases, multiple valuation methods are applied to a single ecosystem service, increasing potential opportunities for data misinterpretation. Moreover, not all the economic valuation entries in the ESVD have undergone peer-review, resulting in potential inaccuracies in the reported values (Brander et al., 2024b). Nonetheless, for the purpose of comparison with Australian values, the ESVD was selected for this study as it is recognised as the most comprehensive collection and synthesis of economic valuation of ecosystem services worldwide (Amatucci et al., 2024; Brander et al., 2024b; Markanday et al., 2024).

The process to identify the ecosystem service estimates in the 2024

Table 2
Types of ecosystem services considered in this study and corresponding The Economics of Ecosystems and Biodiversity (TEEB) classification. Adapted from Haines-Young and Potschin-Young (2018).

Ecosystem services included in this study	Definition	Ecosystem service type			TEEB value classification
		Provisioning	Regulation and maintenance	Cultural	
Provisioning value	This typically accounts for the nutritional contribution of the habitat to commercial fisheries. In some cases, this might include values for aquaculture or raw materials, where relevant.	x			Food Water Raw materials Genetic resources Medicinal resources Ornamental resources
Climate regulation value	The importance of vegetated coastal ecosystems to carbon storage has been recognised in Australia and globally, and a net loss of these habitats has the potential to contribute to changing global climates (Serrano et al., 2019)		x		Climate regulation
Storm and erosion protection value*	Aquatic ecosystems provide protection to coastal, estuarine and freshwater infrastructure against storms and erosion, including dampening of waves (wind or swell generated), slowing water velocities, or providing a protective surface to prevent erosion of underlying soils.		x		Moderation of extreme events Erosion prevention
Water treatment value	Numerous aquatic ecosystems, such as wetlands, are recognised for their ability to remove nutrients (Schmidt, 2008) including nitrogen and phosphorus. Nutrient enrichment of waterbodies degrades aquatic health, leading to significant risks to the health of people using water bodies for recreational activities (Ruprecht et al., 2021)		x		Waste treatment
Habitat and biodiversity value	Key fish habitats provide important long-term support of biodiversity in rivers and estuaries. Many of the identified ecosystems offer important nursery habitats for aquatic species, and support various terrestrial wildlife, including migratory birds.		x		Maintenance of life cycles Maintenance of genetic diversity
Cultural value	This accounts for tourism and recreational related benefits, including recreational fishing.			x	Aesthetic information Opportunities for recreation and tourism Inspiration for culture, art and design Spiritual experience Information for cognitive development Existence/bequest values

* Storm and erosion protection have been combined as there is often little distinction between the two services in the literature in the context of key fish habitats.

ESVD involved filtering two parameters: the ecosystems, and the ecosystem services. The ESVD classified the ecosystems based on the 2024 ESVD 2.0 classification (considering the Food and Agriculture Organization of the United Nations (FAO) Global Ecological Zoning framework (IIASA/FAO, 2012) and the 2020 International Union for Conservation of Nature (IUCN) Global Ecosystem Typology (Keith et al., 2020)), and were selected based on the classification filter for the key fish habitat type (Table 1) (e.g. mangroves were denoted with the 'Ecosystem code' of 2.4.2 in the 2024 ESVD). For entries with more than one ecosystem, only the first ecosystem was considered in the analysis. The ecosystem services in the 2024 ESVD were classified into several categories (e.g. System of Environmental-Economic Accounting (SEEA), TEEB and CICES). In this study, the ecosystem services were selected following the TEEB, as it was most consistently used among different studies (e.g. climate regulation ecosystem service was denoted with the 'TEEB Ecosystem Service' code of 8 in the 2024 ESVD). Note that entries into the original 2024 ESVD with multiple ecosystem services type were not considered in the present study. A summary diagram of the filtering and selection criteria considered in this manuscript is included in Supplementary Material S2. This research did not establish new values for any individual ecosystem service, and no primary data collection was conducted.

To standardise the analyses, the typical unit for ecosystem service valuations of dollars-per-hectare-per-year ($/ha/year) was selected, as the habitats considered can provide value continuously and indefinitely (as most ecosystems are self-maintaining). This unit aligns with commonly identified practices in the literature, where ecosystem service values are typically reported as annual estimates per hectare (Brander et al., 2024b). However, this spatial unit may be incompatible for the valuation of some ecosystem services, particularly those measured per unit of length, or services that cannot be measurable in a spatial unit or have limited data availability, constraining the ability to capture the value of some ecosystem services (Brander et al., 2022; 2024b). In addition, ecosystem services can be temporally and spatially specific, and even minor variations can significantly influence their economic valuation (Farber et al., 2002; Barbier, 2007; Johnson et al., 2012). This variability leads to dynamic economic values across spatial units and should be explored when comparing ecosystem service valuations at different sites. Frameworks such as the Ecosystem Condition Account, developed under the SEEA, provides guidance to assess temporal changes in the overall condition of the ecosystem asset (UN, 2024). It is assumed that the ecosystem can provide this value to society in perpetuity. If existing literature used alternative currency and/or valuation year, the ecosystem service values were converted to 2020 dollars by using the World Bank GDP deflator (available at data.worldbank.org/indicator/NY.GDP.DEFL.ZS) based on the country of valuation. They were subsequently converted to international dollars using the World Bank Purchasing Power Parity converter (available at data.worldbank.org/indicator/PA.NUS.PPP) based on the country of valuation. Finally, the values were converted to Australian dollars using World Bank Purchasing Power Parity converter. In this study, the statistical analysis of the economic valuation was conducted using the median value to minimise the influence of outliers in the valuation estimates, as identified in previous studies where outliers were removed from the analysis or median values were selected for skewed distributions (Brander et al., 2024a, De Groot et al., 2012). Results were then rounded to the nearest whole number.

3. Results

3.1. Ecosystem service values in Australia and the world

The ecosystem service valuations for the key fish habitats were estimated based on the modified ESVD (i.e. comprising the 2024 ESVD and 1,484 additional estimates). Fig. 1 and Table 3 present the total number of valuation estimates per key fish habitat and aquatic ecosystem services in the world and in Australia. Worldwide, the total number of estimated ecosystem valuations was 3,175 (Fig. 1), with kelp containing the largest number of studies (1,534 values, accounting for almost 50 % of the estimates) followed by mangrove habitats containing 671 values, accounting for more than 20 % of the recorded values. This was followed by freshwater, seagrass and open water habitats, each comprising approximately 9 % of the records (Fig. 1). Other key fish habitats had less than 5 % of the records individually, with shellfish comprising only 1 % (Fig. 1). Note that although kelp accounts for nearly 50 % of the estimates, almost 90 % of this data was provided by the recent global study conducted by Eger et al., (2023). Overall, the worldwide assessment of ecosystem services in key fish habitat ecosystems highlight the significant amount of research conducted on kelp and mangroves, while limited investigations and data recordings were identified for shellfish habitat worldwide.

The findings also revealed variations in the number of studies and estimates for the ecosystem services provided by the key fish habitats (Fig. 1). From the available studies, provisioning and cultural services covered 65 % and 22 % of the records for all key fish habitats investigated, representing 2,048 and 684 estimates, respectively. Regulating services represented 14 % of the modified ESDV, with climate regulation, erosion protection, and water treatment each comprising 4 % of the estimates. Habitat and biodiversity values were the least identified ecosystem services in the available database, representing only 2 % of the identified estimates.

While the assessment of ecosystem service valuation for key fish habitat around the world had 3,175 estimates, only 8 % of the estimates in the modified ESVD assessed the valuation records in Australia (267 estimates). Kelp has the largest number of estimates (63 %), followed by mangroves, seagrass and saltmarsh as the most investigated key fish habitats in Australia, with approximately 11 % of the estimates, respectively. The other key fish habitats, which were investigated, represented less than 1 % of the database with only four studies identified for open water, three for freshwater waterways and two studies for shellfish. In agreement with the worldwide findings, provisioning services had the highest number of estimates (75 %), followed by regulating services (13 %), and cultural services (11 %). Climate regulation was the regulating service with highest number of estimates, representing 6 % of the Australian database. An assessment of the national and regional valuation records for each key fish habitat in Australia is presented in the following sections.

3.2. Mangroves

A total of 666 ecosystem service values for mangroves is provided in the modified ESVD, featuring 27 values from Australia. Fig. 2a illustrates the spatial distribution of these valuation estimates for mangroves in Australia and the locations where research has been undertaken. Most of the estimates in Australia are for provisioning services (only considering commercial fishing) with values ranging from $20 to $897/ha/year and a median value of $56/ha/year. The median value was one order of magnitude below the global value of $363/ha/year, ranking the Australian value in the 28th percentile (Table 4). The studies estimated the value of mangroves in commercial fishing based on the trophic connectivity (stable isotope analysis) to apportion primary productivity to exploited species, expected commercial catch volumes, and fish market prices (Raoult et al., 2022, Jänes et al., 2022, Jänes et al., 2019, Carnell et al., 2019, Taylor et al., 2018, Heimhuber et al., 2023). These studies acknowledged that their recorded values are conservative, as stable isotopes mostly focused on adult fish (missing nursery and juvenile species) and were limited to a subset of commercial caught fish species (excluding the value for recreational fish) (Jänes et al., 2022, Jänes et al., 2019, Carnell et al., 2019, Taylor et al., 2018). While all the studies quantified the provisioning services of mangroves using stable isotope methodology, the median value differed between Australian states ($265, $56 and $21/ha/year for NSW, Victoria (VIC) and

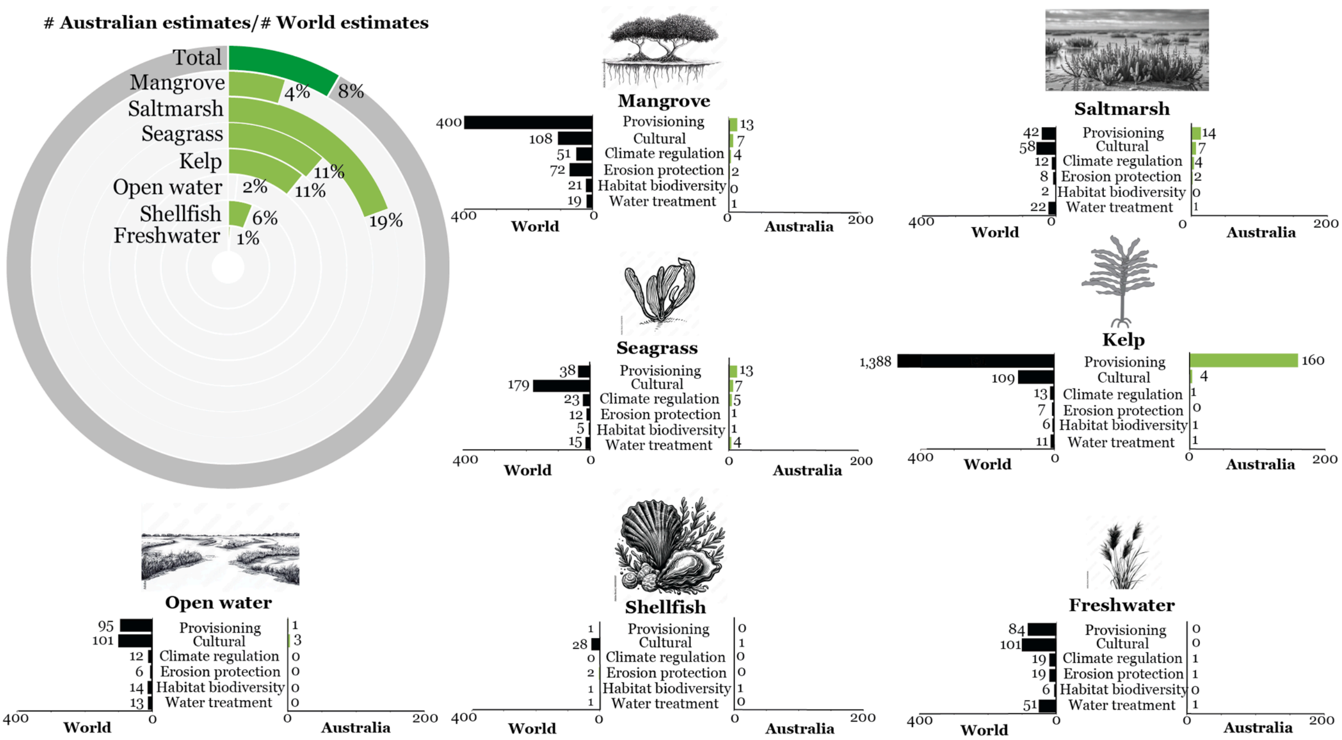


Fig. 1. Number of ecosystem services valuation estimates per key fish habitat type and ecosystem in the world and in Australia.

Queensland (QLD), respectively) (Fig. 3a). The variance in value between estuaries and Australian states can be attributed to fish species investigated, the species targeted by estuarine fisheries, the per-unit market price and the extent and proportion of other primary producing habitats (Jänes et al., 2019, Taylor et al., 2018, Heimhuber et al., 2023, Raoult et al., 2022). As previously indicated, Australian studies of provisioning services focused mostly on commercial fisheries, with no studies assessing the raw material service of mangroves, which are highly valued worldwide (Table 3). Further research is required to ensure that additional ecosystem services of mangroves in Australia are not overlooked, and the mangrove services provided to First Nation communities and in remote areas are also accounted for in broader conservation efforts, as suggested in the approach to capture cultural services for First Nations in Australia (Nursey-Bray et al., 2024).

Australian literature on cultural services provided seven estimates ranging from $4 – $14,717/ha/yr, with a median value of $62/ha/yr. The median value was one order of magnitude below the global value of $297/ha/year, ranking the Australian value in the 34th percentile (Table 4). Most valuations of mangrove recreational services were based on recreational fishing, assessed using stable isotope analysis, recreational fisheries expenditure surveys and recreational catch data (Taylor et al., 2024, Costa et al., 2024), or by the travel cost (willingness of people to travel for fishing and bird watching) (Carnell et al., 2019). Cultural service valuations were identified only for NSW and VIC, with median values of $7,783/ha/year and $62/ha/year, respectively (Fig. 3a). The wide variability in cultural service values is related to the type of cultural service assessed (i.e. bird watching, recreational fishing), the type of valuation method (i.e. travel cost or market price), survey data sets (i.e. date of the study, data sample, data collection, etc.), as well as estuary-specific attributes (Taylor et al., 2024). Importantly in most instances these two or more values can occur concurrently. Estuarine water quality and hydrology significantly influence species composition and productivity, leading to substantial variation in valuation estimates. This influence was evident in the Clarence River and Hunter River estuaries (both located in NSW), where valuation estimates, conducted during the same research period and using the same method, differed by almost a factor of 20—likely in part due to the impacts these attributes have on recruitment processes, and the concomitant effects on fisheries productivity and recreational harvest (Taylor et al., 2024). Overall, the cultural services of mangroves in Australia were limited to recreational activities (aligned with the most represented estimates identified in the global data, Table 3). Nonetheless, additional cultural services such as information for cognitive development and bequest values were not identified in the Australian literature, despite being researched in the mangrove ecosystem service literature worldwide.

Seven estimates were identified for mangrove regulation services. The climate regulation valuation services provided by mangroves in Australia ranged from $92 to $17,805/ha/year, with a median range of $197/ha/year. The median value was almost three times below the global value of $514/ha/year, ranking the Australian value in the 31st percentile (Table 4). These values were estimated based on the carbon market price and carbon sequestration rates (Costa et al., 2024, Serrano et al., 2019, Carnell et al., 2019), and the avoided carbon emissions costs obtained by conserving mangroves (Serrano et al., 2019). While both Carnell et al., (2019) and Costa et al., (2024) estimated the carbon sequestration service of mangroves in VIC, the latter reported a value almost five times higher. This discrepancy may be attributed to differences in the estimation of carbon sequestration potential, the extent of mangrove sequestration, as well as the carbon pricing datasets used (i.e. although both references used the same carbon sequestration method, they used different carbon pricing estimates). Serrano et al., (2019) reported carbon sequestration estimates that were two orders of magnitude higher compared to other Australian studies. The substantial difference may be attributed to the broader area of analysis in Serrano et al., (2019), which covered the entire Australian region, including the Australian tropics, a hotspot for carbon sequestration. A key factor driving variance in these valuations is the selected value of carbon, which can vary substantially depending on the chosen standards, and often undervalues the carbon sequestration value of estuarine habitats given its' perceived 'premium' value over terrestrial carbon.

No Australian studies were identified for assessing habitat and

Table 3
Number of Australian and global estimates identified in The Economics of Ecosystems and Biodiversity (TEEB) ecosystem service classification per each key fish habitat (Numbers highlighted in bold represent ecosystem services with five or more estimates).

Ecosystem service				Ecosystem sub-service	Ecosystem sub-service code	Number of Australian estimates (Number of global estimates*)						
Provisioning	Regulating	Habitat	Cultural			Mangroves	Saltmarsh	Seagrass	Kelp	Shellfish	Freshwater	Open waterways
X				Food	1	**11** **(242)**	**12** **(26)**	**12** **(36)**	**160** **(1379)**	– (1)	– **(36)**	1 **(51)**
X				Water	2	– (3)	– (2)	– (–)	– (1)	– (–)	– **(14)**	– **(9)**
X				Raw materials	3	– **(122)**	– **(11)**	– (2)	– **(6)**	– (–)	– **(19)**	– **(25)**
X				Genetic resources	4	– (–)	– (1)	– (–)	– (–)	– (–)	– (–)	– (–)
X				Medicinal resources	5	– (1)	– (–)	– (–)	– (1)	– (–)	– (1)	– **(5)**
X				Ornamental resources	6	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)
	X			Air quality	7	– (2)	– **(7)**	– (–)	– (3)	– (–)	– **(6)**	– (1)
	X			Climate	8	4 **(51)**	4 **(12)**	**5** **(23)**	1 **(12)**	– (–)	1 **(19)**	– **(12)**
	X			Moderation of extreme events	9	2 **(40)**	2 **(8)**	1 **(9)**	– (4)	– (1)	1 **(16)**	– **(6)**
	X			Water flows	10	– (2)	– (–)	– (–)	– (1)	– (–)	– (4)	– (1)
	X			Waste treatment	11	1 **(19)**	1 **(22)**	4 **(15)**	1 **(11)**	– (1)	1 **(51)**	– **(13)**
	X			Erosion prevention	12	– **(27)**	– (–)	– (3)	– (3)	– (–)	– (2)	– (–)
	X			Maintenance soil fertility	13	– **(5)**	– (1)	– (2)	– (1)	– (–)	– (4)	– (2)
	X			Pollination	14	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)	– (–)
	X			Biological control	15	– (–)	– (–)	1 (–)	– (–)	– (–)	– (1)	– (–)
		X		Maintenance of life cycles	16	– **(11)**	– (1)	1 (1)	1 **(5)**	– (–)	– (4)	– **(12)**
		X		Maintenance genetic diversity	17	– **(10)**	– (1)	– (3)	– (1)	– (–)	– (2)	– (2)
			X	Aesthetic information	18	– (1)	– **(12)**	– (2)	– **(10)**	– (–)	– **(19)**	– **(19)**
			X	Opportunities for recreation and tourism	19	**7** **(73)**	**7** **(27)**	**7** **(158)**	4 **(65)**	1 **(7)**	– **(19)**	3 **(55)**
			X	Culture, art and design	20	– (1)	– **(5)**	– (–)	– **(8)**	– (–)	– **(17)**	– **(7)**
			X	Spiritual experience	21	– (–)	– (1)	– (1)	– (–)	– (–)	– (–)	– (3)
			X	Information for cognitive development	22	– **(6)**	– **(9)**	– (2)	– **(9)**	– (–)	– **(5)**	– **(6)**
			X	Existence, bequest values	23	– **(18)**	– (1)	– **(16)**	– **(10)**	– **(21)**	– **(9)**	– (3)

* Excluding entries that addressed more than one TEEB ecosystem sub-service.

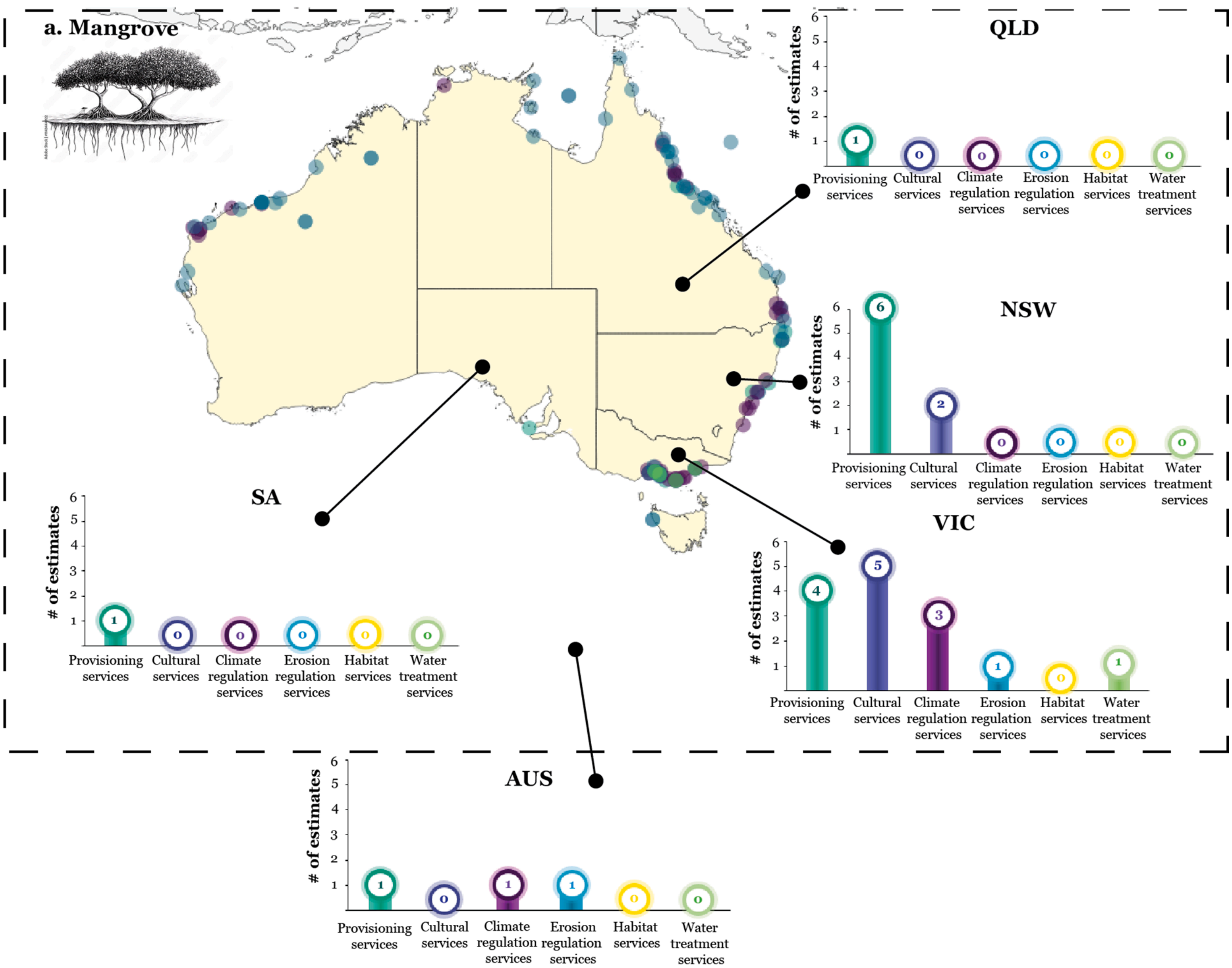
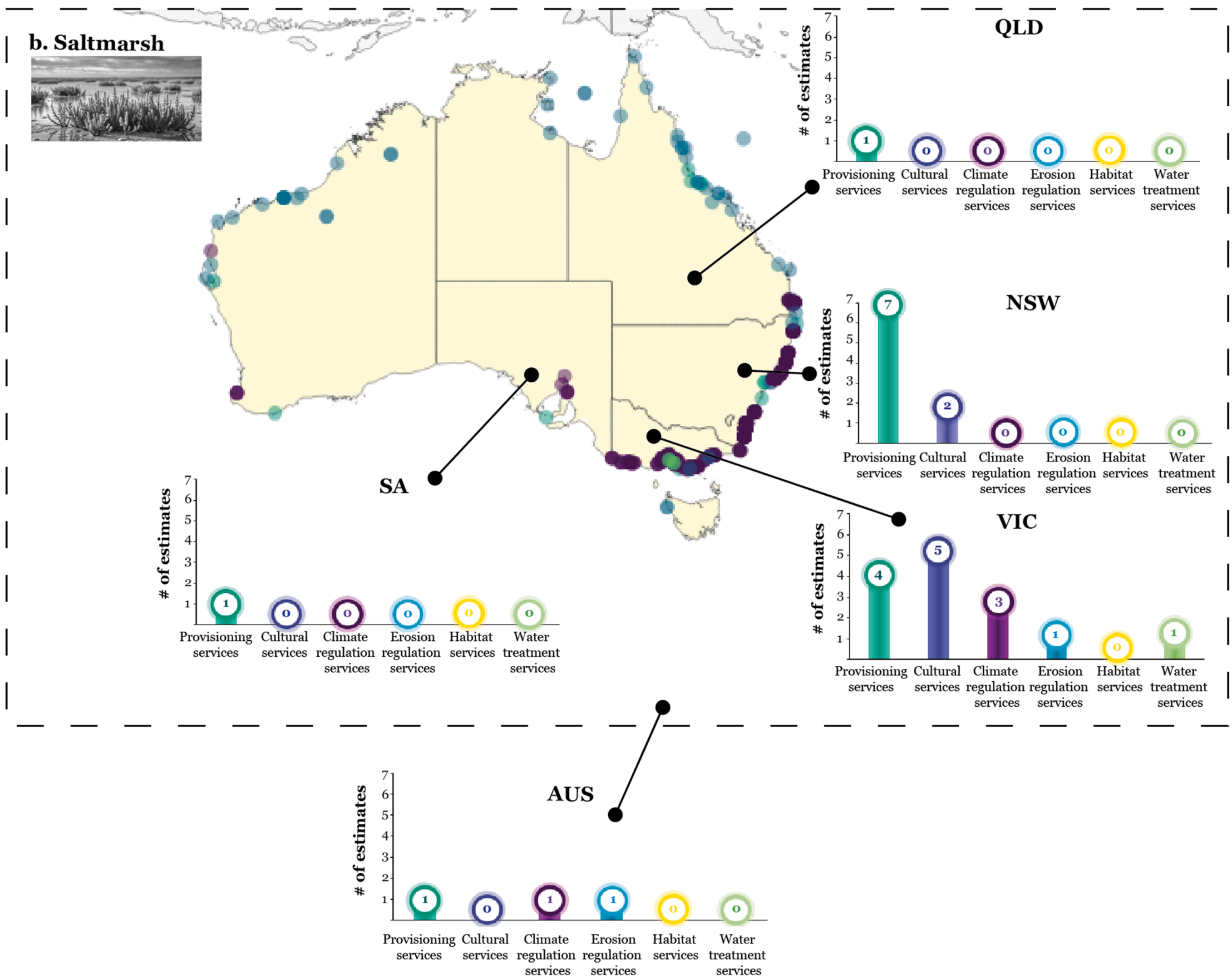


Fig. 2. Spatial distribution of ecosystem services studies around Australia for the seven key fish habitats: a. Mangrove; b. Saltmarsh; c. Seagrass; d. Kelp; e. Shellfish; f. Freshwater waterways; g. Open waterways. Dots represent the locations from where research was undertaken considering Australian wide (i.e. one single study may include multiple locations), and the bar chart represent the number of estimates identified in the modified ESVD. Abbreviations: AUS – Australia; NSW – New South Wales; QLD – Queensland; SA – South Australia, TAS – Tasmania; VIC – Victoria; WA – Western Australia. Note in this figure bar charts are not included for Australian States and Territories without identified estimates.

biodiversity ecosystem services. Erosion and protection services accounted for the highest valuation services of mangroves, with values ranging from \$4,533 to \$1,507,774/ha/year and a median value of \$756,153/ha/year. The median value was almost three orders of magnitude higher than the global value of \$1,437/ha/year, ranking the Australian value as one of the highest based on the global estimate (Table 4). The studies assessed the avoided damages due to the storm protection provided by mangroves in VIC based on the property and infrastructure price (Costa et al., 2024) and the avoided damages in Australia during cyclones based on Bayesian methods considering wind and wetland areas (Mulder et al., 2020). The avoided damage due to storm protection in Victoria presented by Mulder et al., (2020) was over two orders of magnitude below the value provided by Costa et al., (2024). While all the studies analysed the avoided damages to infrastructure, Mulder et al., (2020) conducted an Australian-wide analysis of avoided damages (including densely and non-densely populated areas) while Costa et al., (2024) assessed the damage in densely populated areas in Victoria, including Port Phillip and Western Port. Therefore, the valuation of Mulder et al., (2020) may be more appropriate for a national average while Costa et al., (2024) could guide the valuation in densely populated urban areas. Only one study estimated the economic value of water treatment service based on the nitrogen sequestration rate and nitrogen price in VIC, providing a value of \$3,298/ha/year. This value was similar to the global median value of \$2,892/ha/year. In comparison with the regulating services worldwide (Table 3), there is lack of Australian research on mangrove ecosystem services related to soil fertility and habitat and biodiversity.

The review of available data and information on the valuation of mangrove ecosystem services in Australia revealed that most research has been conducted in VIC and NSW, with minimal or no research in other Australian states. The global valuation of mangrove ecosystem services, considering the sum of all the ecosystem services, is \$7,921/ha/year, which is similar to the valuation in NSW (although some ecosystem services are not quantified) and lower than the valuation in VIC (Fig. 3a). Given the variation of valuation estimates depending on location and region, it is recommended that mangrove ecosystem service valuations in other Australian regions are investigated to quantitatively estimate the value of mangrove ecosystems continent-wide. Until this is done, we caution against using valuations from one state for another, given how variable the valuations can be among jurisdictions and even



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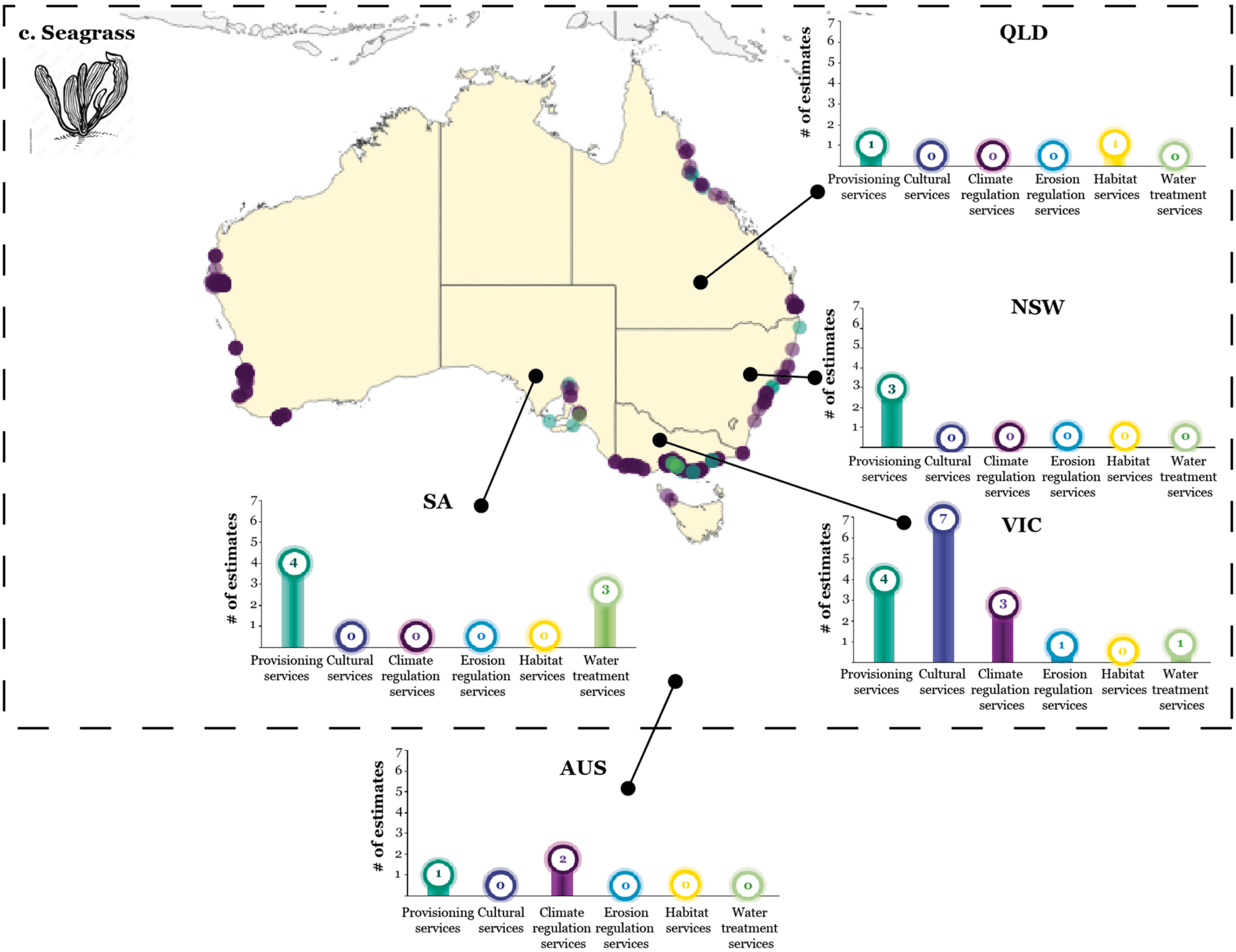
estuaries.

3.3. Saltmarsh

The modified ESVD included 144 ecosystem valuation estimates for saltmarsh ecosystems, with 19 % of these estimates corresponding to Australian studies. Fig. 2b presents the spatial distribution of saltmarsh ecosystem services studies and the regional estimates. Provisioning services were the most frequently identified ecosystem service in Australia, with values ranging from $7 to $4,662/ha/year, and a median value of $235/ha/year. The median value was approximately a third of the global value of $646/ha/year, ranking the Australian value in the 40th percentile (Table 4). All values were determined using stable isotope analysis, expected commercial catch volumes, and fish market prices, as also identified in mangrove ecosystems. NSW had the largest number of estimates with a median value of $1,119/ha/year, followed by VIC with a median value of $7/ha/year and QLD only had one estimate of $19/ha/year. The variation in values for each estuary may be explained by differences in commercially targeted species, the catch size, the spatial extent of saltmarsh, and the market price, as previously highlighted (Jänes et al., 2019, Taylor et al., 2018, Heimhuber et al., 2023, Raoult et al., 2022). Stable isotope data also suggest that saltmarsh composition (e.g., saltmarsh succulents or saltmarsh grasses) may play a role in the contribution of this habitat to the food web, and as a result, its value (Raoult et al., 2022). Despite the global use of saltmarsh as a raw material service (Table 3), no Australian study was found for this service. Further research is required to explore the extent of provisioning services provided by saltmarsh beyond commercial fishing.

Seven estimates were identified in the Australian literature for the saltmarsh cultural valuation, ranging from $1 to $58,068/ha/year and a median value of $16/ha/year. The median value was two orders of magnitude below the global value of $1,447/ha/year, ranking the Australian value in the 19th percentile (Table 4). Similar to mangrove cultural studies, the majority of cultural valuations estimated recreational fishing based on the stable isotope analysis and recreational fisheries expenditure surveys and recreational catch (Taylor et al., 2024, Costa et al., 2024) or by the travel cost (willingness of people to travel for fishing and bird watching) (Carnell et al., 2019). Most cultural valuation estimates were identified in VIC with a median value of $9/ha/year, followed by two studies in NSW with a median value of $31,184/ha/year. As indicated above, the interstate and regional variability in the valuation of the cultural services is linked to the type of recreational service, the valuation methods, data input and models for survey data, and estuary-specific attributes (Taylor et al., 2024). It is noteworthy that the same studies assessing mangrove cultural services also measured saltmarsh cultural services. Also, as observed in mangrove cultural services, saltmarsh cultural services were also limited to recreational activities. However, worldwide cultural services of



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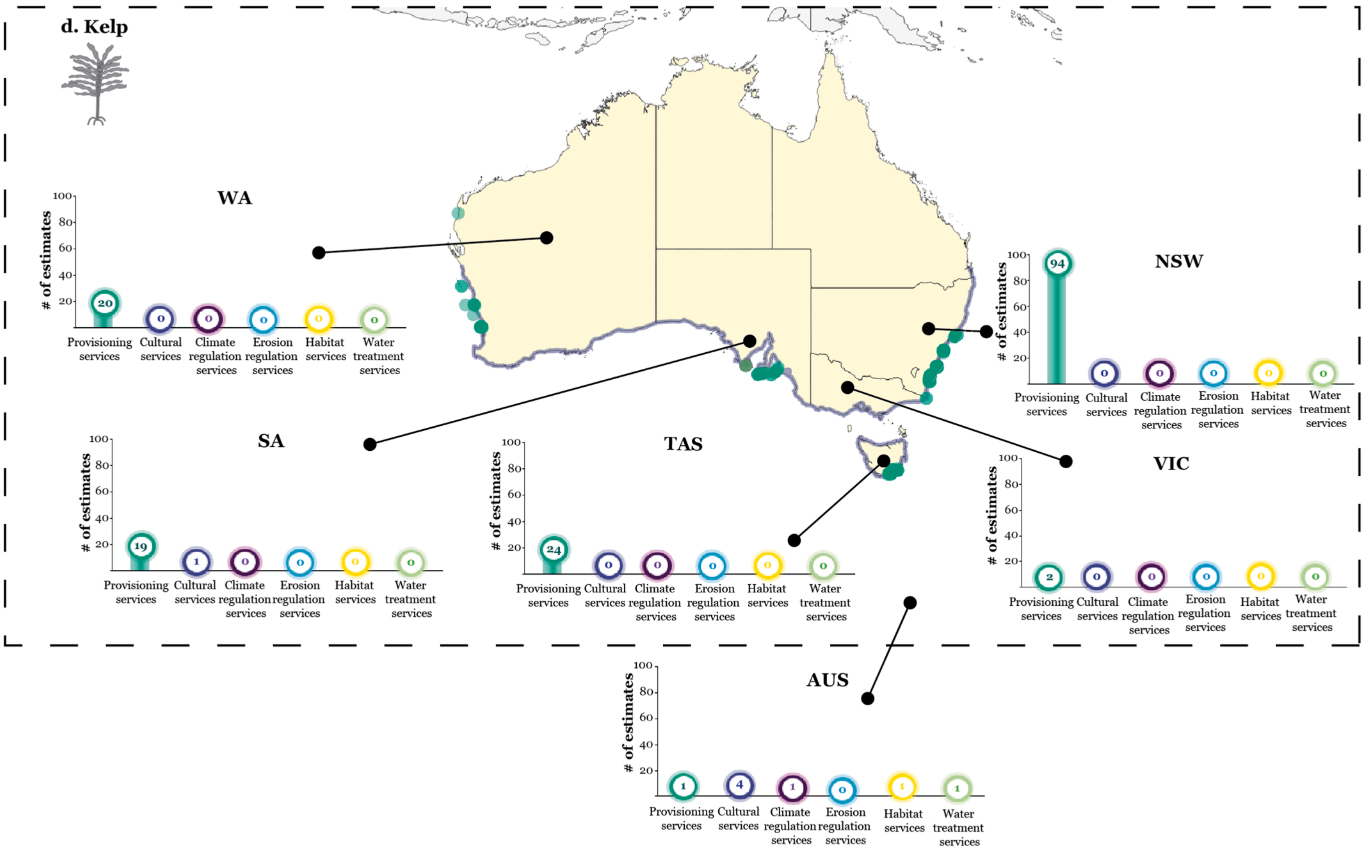
saltmarsh also include aesthetic information, culture, art and design and information for cognitive development. Further research is recommended to ensure the cultural services of Australian saltmarsh are assessed and considered in the future economic valuations.

Four studies identified the climate regulation services of saltmarsh, with a range from $34 to $5,193/ha/year and a median value of $77/ha/year. The median value was almost half the magnitude of the global value of $164/ha/year, ranking the Australian value in the 17th percentile (Table 4). These studies estimated the valuation of climate regulation services based on the carbon market price and carbon sequestration rates (Costa et al., 2024, Serrano et al., 2019, Carnell et al., 2019) and the avoided carbon emissions costs obtained by conserving saltmarsh (Serrano et al., 2019). Both Carnell et al., (2019) and Costa et al., (2024) estimated the carbon sequestration potential for the same region in VIC. Nonetheless, the estimate from Costa et al., (2024) was three-times higher, which may be related to differences in the measured extent of carbon sequestration and the carbon pricing datasets used (as explained above). For saltmarsh habitat, Serrano et al., (2019) reported carbon sequestration estimates that were one order of magnitude higher compared to other Australian studies, potentially due to their covering of the entire Australian region, including regions with higher sequestration potential. No Australian estimates were identified for habitat and biodiversity services. Only two Australian estimates were identified for saltmarsh storm protection with a value ranging from $4,533/ha/year (considering the avoided damage in Australia during cyclones) to $3,274,143/ha/year (considering avoided damage in the infrastructure located 1 km distance from the saltmarsh ecosystem) (Costa et al., 2024, Mulder et al., 2020). The significant variability in avoided damage between the Australia-wide analysis and the Victorian dataset may be related to the considered infrastructure price, as well as the extent of damage, suggesting that the valuation of Mulder et al., (2020) may be more appropriate for the estimation of an Australian national average valuation of storm protection. The median value was two orders of magnitude above the global value of $16,229/ha/year, ranking the Australian value in the 93rd percentile (Table 4). The study of Costa et al., (2024) provided the only estimate of water treatment services by saltmarsh in Australia with a value of $6,737/ha/year. The estimate was calculated based on a nitrogen sequestration rate and the nitrogen price in VIC. This value was four times the global value of $1,872/ha/year, ranking Australia in the 81st percentile (Table 4). Saltmarsh has also been recognised for its air quality regulation services worldwide (Table 3), although no Australian studies have reported on this service.

The median of the global ecosystem service valuation of saltmarsh is $22,455/ha/year which is similar to the NSW valuation (although some ecosystem services were not included), substantially higher than the QLD valuation (which only estimated the saltmarsh provisioning services) and substantially lower than the VIC valuation, likely due to the high storm protection valuation estimated in Victoria) (Fig. 3b). Based on the available studies, further research is required to assess the economic value of saltmarsh in Australia. While the current studies provide



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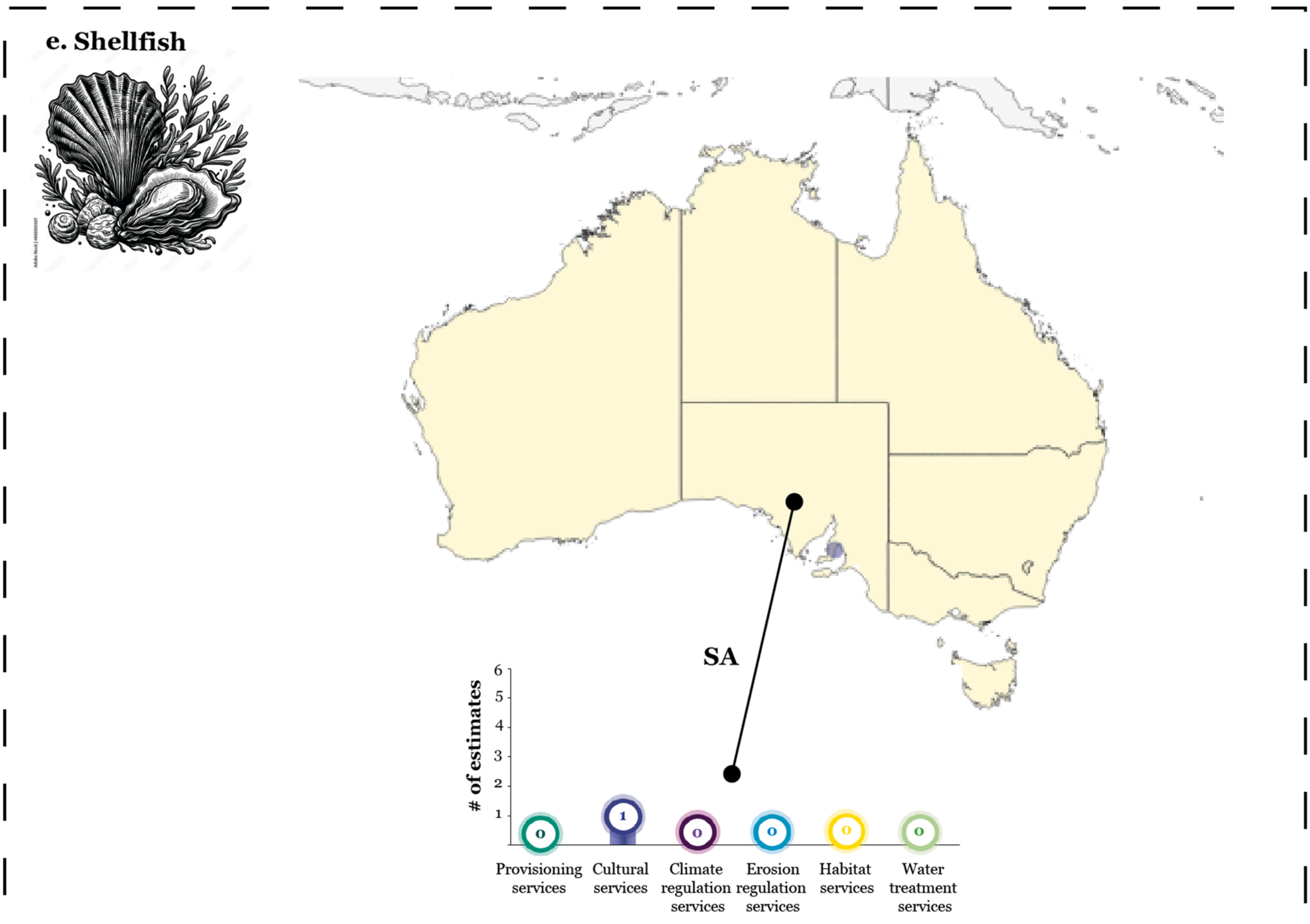
an overview of some ecosystem services provided in Australia, specifically in VIC and NSW, there are data gaps for services such as habitat and biodiversity that have not been quantified or have limited information. Additionally, there is limited information of saltmarsh valuation for most of Australian states.

3.4. Seagrass

A total of 272 valuation estimates for seagrass ecosystem services were identified in the 2024 ESVD, with 31 estimates from the Australian literature. Fig. 2c presents the spatial distribution of seagrass ecosystem services studies and the regional estimates. Provisioning services represented the seagrass service with the highest number of estimates in Australia, with values ranging from $7 to $242,815/ha/year and a median value of $40/ha/year. This value was similar to global value of $51/ha/year, ranking Australia in the 42nd percentile (Table 4). These provisioning services were estimated based on commercial fishery production, considering the support of seagrass to secondary production (commercial fishing), the enhancement on fish biomass, and the market value of fisheries in the location of interest (Costa et al., 2024, Jänes et al., 2022, Blandon and zu Ermgassen, 2014, McArthur and Boland, 2006). Four estimates were identified in VIC with a median value of $40/ha/year, followed by two estimates in NSW with a median value of $558/ha/year and one estimate in QLD with a value of $7/ha/year. The variability in the estimated range reflects differences in the fish market price, fish species (as previously explained in Section 3.2), the area of seagrass habitat in the system, and variations of fishing methods along estuaries impacting the catch volume (Jänes et al., 2022). It is important to note that these studies only estimated values from a limited number of important commercial fisheries species and would be larger if all commercial fish catches were included. In agreement with worldwide research on provisional services of seagrass (Table 3), the most reported service is food.

Seven estimates were identified for cultural services provided by seagrass, with a range from $2 to $6,749/ha/year, and a mean value of $1,161/ha/year. This value was more than one order of magnitude above the global value of $86/ha/year, ranking Australia in the 71st percentile (Table 4). The cultural services were estimated based on the travel cost for recreational fishing trips (Huang et al., 2020; Carnell et al., 2019), recreational catch models (Costa et al., 2024; Huang et al., 2020; Carnell et al., 2019) and stable isotopes model (Costa et al., 2024, Carnell et al., 2019). Although all seven estimates were conducted in VIC, the difference in the estimated valuation is linked to variations in valuation methods (i.e. travel cost, recreational catch model and stable isotope model), survey data sets (i.e. date of the study, data sample, data collection, etc.) and estuary-specific attributes (Note the studies were conducted in the same two bays: Western Port and Port Phillip Bays in VIC, apart from Costa et al., (2024) who included two additional bays). In general, the recreational value associated to the travel time was two orders of magnitude higher (average of $4,025/ha/year) compared to the recreational catch estimates ($55/ha/year). While recreation is the most frequently investigated seagrass ecosystem service, global literature also identifies bequest values as a relevant cultural service, which was not identified in the Australia literature (Table 3).

The climate regulation estimates ranged from $2 to $3,338/ha/year, with a median value of $24/ha/year. This value was four times below the global value of $86/ha/year, ranking Australia in the 19th percentile (Table 4). The valuation of climate regulation services was estimated based upon the carbon market price and carbon sequestration rates (Costa et al., 2024, Carnell et al., 2019, Lavery et al., 2013) and the avoided costs of carbon emissions (Serrano et al., 2019). Three estimates were conducted in VIC (Costa et al., 2024, Carnell et al., 2019), while the additional studies assessed the climate regulation services across Australia. The estimated value in Costa et al., (2024) was almost four



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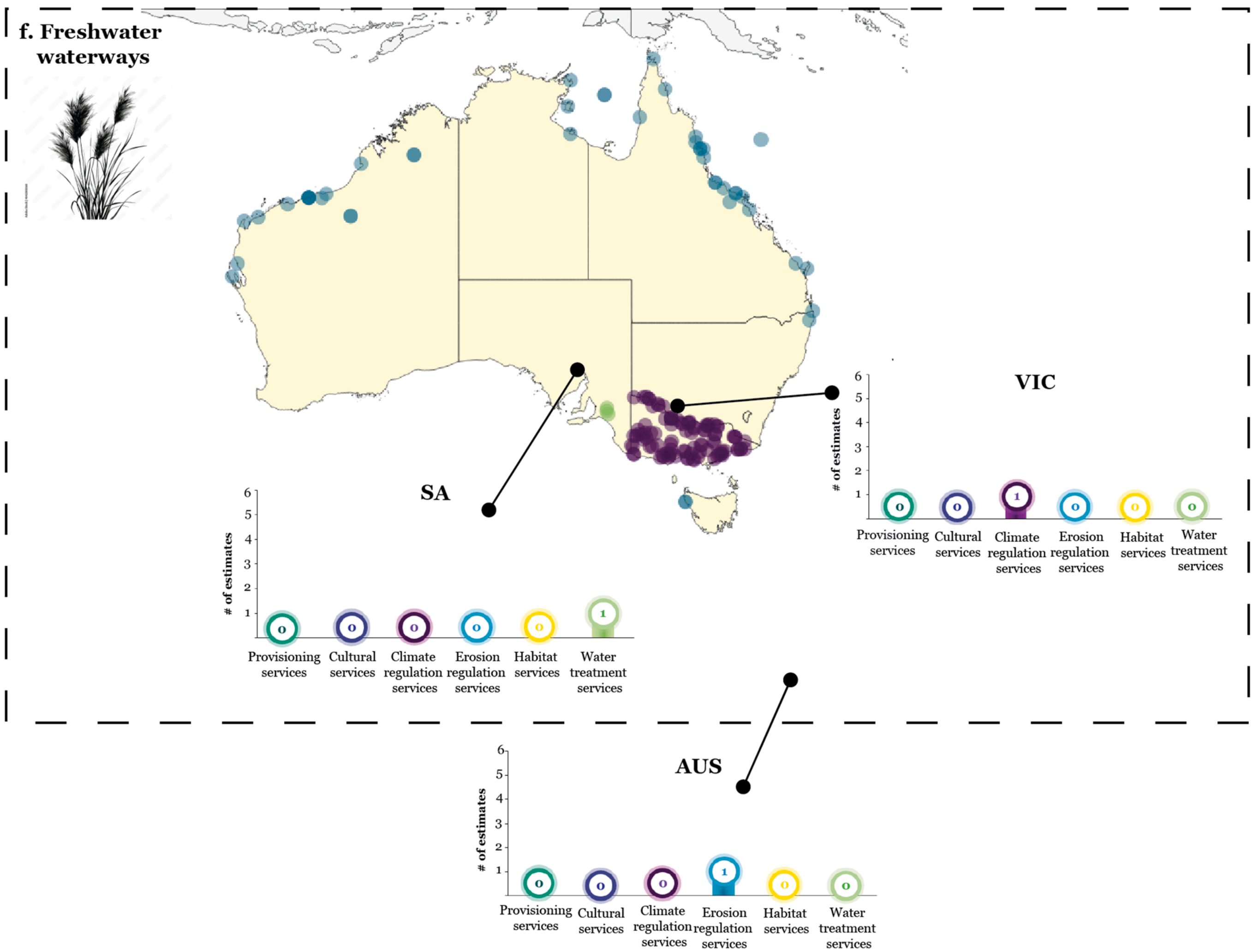
times higher, which may be attributed to differences in the estimation of carbon sequestration potential, the extent of seagrass, as well as the carbon pricing dataset used. A single estimate was identified in the modified ESVD for habitat and biodiversity services in QLD with a value of $2,548/ha/year. This study estimated the yield and landed value of commercial prawns in Cairns (Watson et al., 1993). The study of Costa et al., (2024) presented the only value of storm protection of seagrass, corresponding to $463,104/ha/year. This value was almost two orders of magnitude higher than the global value of $6,780/ha/year, ranking Australia in the highest percentile (Table 4) This estimate was assessed considering the avoided damages provided by seagrass in VIC based on the cost of the properties located within 1 km from the coastal wetlands, and may not necessarily represent an average value for other regions in Australia. Four estimates were identified for water treatment services, ranging from $754/ha/yr to $1,846/ha/yr, with a median value of $1,448/ha/year. This value was similar to the global value of $1,889/ha/year, ranking Australia in the 32nd percentile (Table 4). These estimates were based on the replacement costs of nitrogen treatment in a wastewater treatment plant in South Australia (SA) for three different levels of treatment (Gaylard et al., 2023) and the nitrogen sequestration capacity of seagrass and nitrogen price in VIC (Costa et al., 2024). Although the water treatment estimates were conducted in different states, they presented a similar average value of $1,289/ha/year.

Overall, in contrast with mangroves and saltmarsh, seagrass presented a valuation estimate for all the ecosystem services considered in the present study. Nonetheless, there is limited information of ecosystem service valuation for most Australia states. The median of the global seagrass ecosystem service valuation is $8,892/ha/year, which is above the NSW and QLD valuations of $558/ha/year and $2,555/ha/year, respectively and significantly below the VIC valuation ($465,956/ha/year) which included a broader range of ecosystem service valuations (Fig. 3c). More research is needed to cover the wider range of Australian states, and to identify whether the storm protection values vary across different regions in Australia, as observed worldwide.

3.5. *Kelp*

In the modified ESVD, 1,534 estimates for kelp habitat were identified, from which 167 were Australian estimates. As previously indicated, nearly 90 % of the kelp estimates were identified in the recent study by Eger et al., (2023). Fig. 2d presents the spatial distribution of kelp ecosystem services research. 160 provisioning estimates were identified in the Australian literature for kelp, ranging from $5 to $195,351/ha/year, with a median value of $25,404/ha/year (Eger et al., 2023, Eger et al., 2022). The median value was slightly above the global value of $17,777/ha/year, ranking the Australian value in the 61st percentile (Table 4). Provisioning services of kelp ecosystems were estimated based on the gross value of production of commercial fisheries and harvest rate (Eger et al., 2023, Eger et al., 2022). Additionally, two recent reports suggested annual gross value of seaweed and kelp farming production of <$3 million, although the production is currently small and fragmented (Kelly, 2020) and an average value of potential fisheries production for the *Ecklonia* genus (the dominant kelp genus along the Australian coast) of $41,045/ha/year, assuming a harvest rate of 38 %. Nonetheless, the latter appears to be skewed by a small number of sites with particularly high associated fishery biomass. Without further clarity on the



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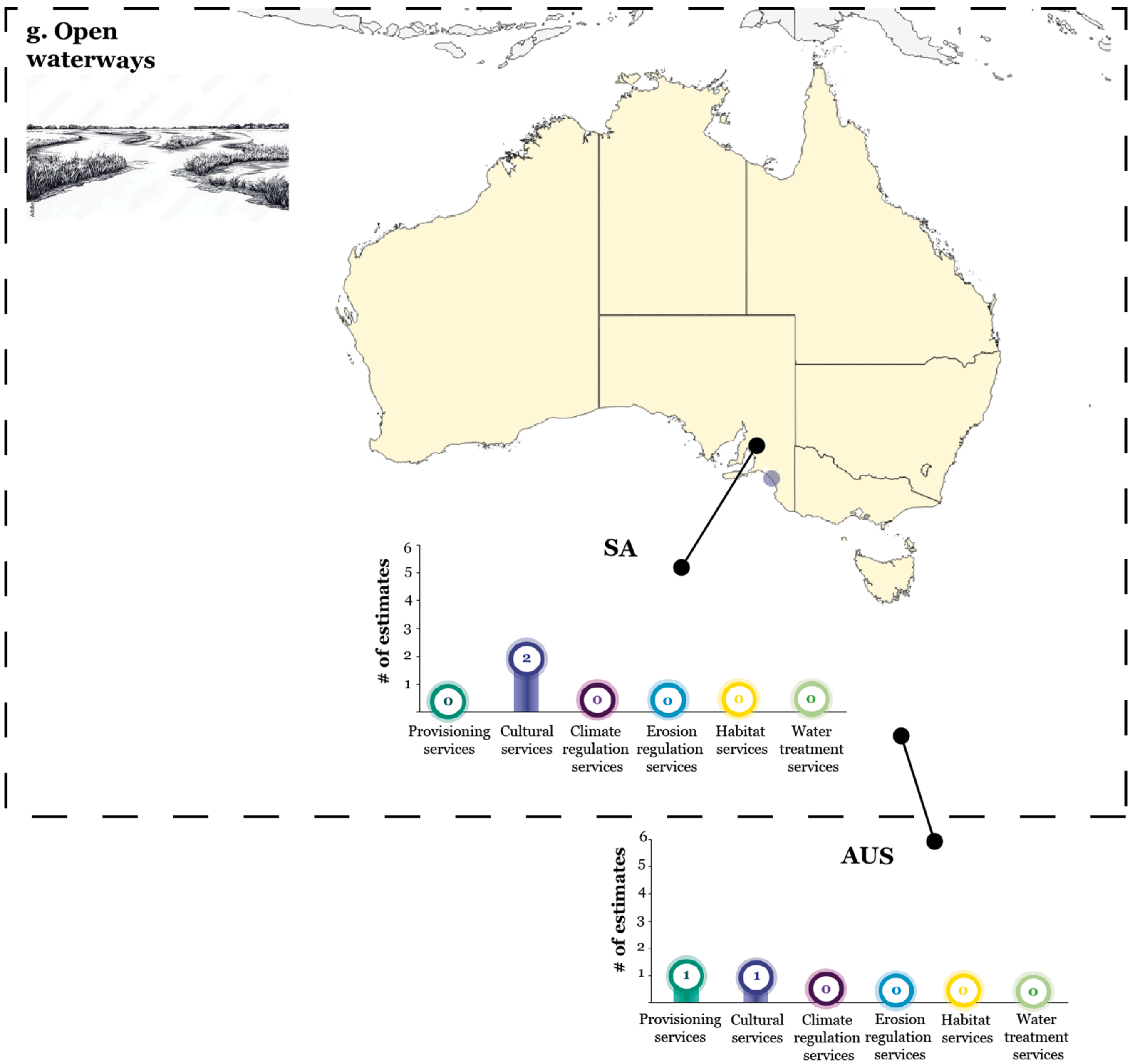
appropriateness of using the average values from a new study, these values have been noted but not yet relied upon for this review. Worldwide, kelp is also identified as a source of raw material for provisioning services (Table 3), however, no Australian study assessed this provisioning service.

Two studies measured the cultural services of kelp in the Australian "Great Southern Reef", an area dominated by kelp forests and hotspot for biodiversity and tourism, including recreational activities such as recreational fisheries, diving and snorkelling (Eger et al., 2022). Kelp values ranged from \$57 to \$1,498/ha/year, with a median value of \$247/ha/year (Eger et al., 2022, Bennett et al., 2016). The median value was close to the global value of \$361/ha/year, ranking Australia in the 47th percentile (Table 4). Note these values considered all marine habitats located in the "Great Southern Reef", where kelp is dominating species (Bennett et al., 2016). Additional cultural services of kelp have been investigated worldwide, including aesthetic information, culture, art and design and bequest values. While none of these services were identified in the Australian literature, further research is recommended to ensure the cultural services of kelp are properly assessed.

Only one estimate was identified in the Australian literature values for the climate regulation services provided by kelp, with a value of \$5/ha/year, which is one order of magnitude below the global value of \$76/ha/year. While some Australian studies acknowledge its value for sequestration in Australia (Kelly, 2020, Sondak et al., 2016), there is a debate regarding magnitude and significance of carbon sequestration potential of kelp ecosystems (Gallagher et al., 2022, Pessarrodona et al., 2024). Eger et al., (2022) was the only study assessing the value for habitat and biodiversity services contributed by kelp and other marine macro-algae in Australia, estimating a value of \$154/ha/year. This is significantly lower than the global value, which exceeds one trillion dollars. The study of Eger et al., (2022), assessed the value of habitat and biodiversity service in the Great Southern Reef applying the benefit transfer method to the willingness to pay for kelp replanting. Apart from Eger et al., (2022), the only global study assessing the value of habitat and biodiversity services was Hynes et al., (2021), identified in the 2024 ESVD. This study provided the willingness to pay per person per year for kelp restoration in Norway with an average value of a trillion dollars per hectare per year. Therefore, due to the absence of additional global data, the global data may be biased (Brander et al., 2024b) and the Australian value is significantly below the global median value. It is important to note that the study of Hynes et al., (2021) consistently provided high median values for all ecosystem services, suggesting the willingness to pay method applied in Norway may be skewed compared to other ecosystem service valuation methods conducted worldwide. Additional regulating services of kelp identified in the global literature include air quality, storm and erosion protection, but these were not identified in the Australian literature (Table 3). Only one study assessed the water treatment services of kelp based on the avoided costs of nitrogen entering marine ecosystems in the Great Southern Reef due to nitrogen uptake in kelp areas (Eger et al., 2022). The avoided cost was \$913/ha/year which represents almost a third of the global value of \$2,519/ha/year (Table 3), ranking Australia in the 30th percentile.



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Only two studies assess the economic value of kelp in Australia based on a thorough analysis conducted in the Great Southern Reef. The median of the global kelp ecosystem service valuation is $1.3 trillion/ha/year, which is well above the Australian value of $26,724/ha/year. While the studies of Eger et al., (2022; 2023) have provided a comprehensive overview of the economic valuation of kelp ecosystems in Australia, some services identified in the global literature were not evaluated, such as the use of kelp for raw materials, aesthetic information, culture, art and design and bequest values. Additionally, there is no segregation of kelp ecosystem services per state.

3.6. Shellfish reef

The number of estimates for shellfish habitat was substantially lower than other ecosystems, with only 32 studies identified in the modified ESVD and only two in the Australian literature. Fig. 2e presents the spatial distribution of Australian studies on shellfish reef ecosystem services. One study on oyster provisioning services was identified in White (2001), who assessed three key threats and pressures on the oyster industry and identified that the average gross value production of oysters in NSW was $13,211/ha/year. Nonetheless, these estimates are not considered in the present analysis because the NSW oyster industry is based on commercially grown oysters, not wild harvest oysters collected from natural reefs. The only study assessing cultural value of oyster reefs in Australia was conducted in SA and provided an approximate value of $34,003/ha/year (considering interstate recreational fishers) and $7,137/ha/year (excluding interstate visitors) (Rogers et al., 2018). This study considered the annual willingness to pay of intrastate and interstate recreational fishers, the annual benefit derived from educational tourism and additional profit expected to be made by commercial charter boat operators. It is noteworthy that worldwide, the bequest value of a shellfish reef is the most researched ecosystem service, although no Australian study has captured this service.

No monetised values were found in the modified ESVD for the

Table 4
Median ecosystem services valuation for key fish habitats worldwide and in Australia (Percentile ranks above 70th percentile are highlighted in bold).

Key fish habitat	Ecosystem service	Median – World data ($/ha/yr)	Median – Australia ($/ha/yr)	Australian median value percentile rank relative to global distribution of estimates for this service
Mangrove	Climate Regulation	513.52	196.70	31st
	Erosion Protection	1,342.79	756,153.8	**99th**
	Water Treatment	2,892.23	3,298.26	56th
	Habitat and Biodiversity	2,513.47	–	–
	Provisioning	362.62	56.28	28th
	Cultural	296.88	62.15	34th
Saltmarsh	Climate Regulation	163.59	77.18	17th
	Erosion Protection	16,228.87	1,639,338.06	**93rd**
	Water Treatment	1,872.00	6,737.25	**81st**
	Habitat and Biodiversity	2,097.70	–	–
	Provisioning	645.59	235.16	40th
	Cultural	1,447.49	15.64	19th
Seagrass	Climate Regulation	85.57	23.97	19th
	Erosion Protection	6,779.74	463,103.88	**100th**
	Water Treatment	1,889.44	1,447.64	32nd
	Habitat and Biodiversity	0.21	2,548.42	**75th**
	Provisioning	50.73	40.35	42nd
	Cultural	86.27	1,161.05	**71st**
Shellfish	Climate Regulation	–	–	–
	Erosion Protection	2,197.09	–	–
	Water Treatment	8,269.72	–	–
	Habitat and Biodiversity	–	–	–
	Provisioning	8,418.78	–	–
	Cultural	2,126.80	34,003.11	**96th**
Kelp	Climate Regulation	75.60	5.32	1st
	Erosion Protection	196.99	–	–
	Water Treatment	2,518.52	913.24	30th
	Habitat and Biodiversity	> 1 trillion	154.37	1st
	Provisioning	17,776.97	25,404.14	61st
	Cultural	360.76	246.76	47th
Open water	Climate Regulation	7.25	–	–
	Erosion Protection	1,347.27	–	–
	Water Treatment	276.11	–	–
	Habitat and Biodiversity	111.82	–	–
	Provisioning	133.25	190.27	59th
	Cultural	1,003.26	489.19	37th
Freshwater	Climate Regulation	247.59	86.04	22nd
	Erosion Protection	1,423.35	4,533.51	67th
	Water Treatment	57.66	9,764.54	**98th**
	Habitat and Biodiversity	1,420.24	–	–
	Provisioning	36.50	–	–
	Cultural	208.84	–	–

climate regulation services contributed by shellfish reefs. Some research suggests that these systems may be net producers of carbon (Ahmed et al., 2017, Munari et al., 2013), and subsequently reefs may not provide climate regulation services. No Australian studies of the value of habitat and biodiversity and erosion protection provided by shellfish reefs were found. While no Australian studies of the value of water treatment services provided by oyster reefs were identified, research has demonstrated their importance in the purification of estuaries (Ferreira and Bricker, 2015, Kellogg et al., 2014). Indeed, it is estimated that NSW oysters may remove over one million tonnes of suspended material in their lifetime (White, 2001). Overall, research touching on ecosystem service valuations in shellfish is scant in Australia (and worldwide). The median of the worldwide shellfish reef ecosystem service is $21,157/ha/year, which is similar to the cultural value estimated in SA. Further research is required to identify the additive ecosystem service of shellfish in Australia, as well as identify the variation of ecosystem service values among the Australian states.

3.7. *Freshwater wetlands*

A total of 280 freshwater wetland estimates were found in the modified ESVD, with only three related to Australian literature. Fig. 2f presents the spatial distribution of research on ecosystem services on freshwater wetlands—no Australian studies were identified that assessed the value of provisioning, cultural, habitat and biodiversity provided by freshwater wetlands. Globally, extensive research has been conducted in diverse provisioning services for freshwater wetlands, including food, water and raw materials. Further research is needed to capture the valuation of provisioning services of freshwater wetlands in Australia. In addition, while cultural service valuations for freshwater wetlands were not identified in Australia, many valuation estimates dealing with aesthetic information, recreation, culture, art and design, information for cognitive development and bequest values of freshwater wetlands were identified elsewhere. This highlights the relevance of the cultural services of freshwater wetlands worldwide.

Carnell et al., (2018) was the only Australian study that estimated the value of carbon sequestration in Australia based on carbon trading prices, suggesting an estimate of $86/ha/year in VIC. However, it is acknowledged that this value is likely an underestimation of the total climate services considering carbon stored in freshwater wetlands across the state are worth approximately $3 billion ($6,500/ha) in carbon dioxide equivalents if the wetland is lost (Carnell et al., 2018). The estimated Australian value was three times below the global value of $248/ha/year, ranking Australia in the 22nd percentile (Table 4). One study was identified assessing the storm protection services by wetlands in Australia based on the avoided damages during cyclone events, providing a median value of $4,531/ha/year (Mulder et al., 2020). This value was almost three times the global value of $1,423/ha/year, ranking Australia in the 67th percentile (Table 4). Freshwater wetlands are known to play a valuable role in removing nutrients, particularly nitrogen and phosphorus. In the last few decades, this value of wetlands has led to an increase in constructed wetlands in urban areas to improve stormwater quality (Wu et al., 2023, Zhi and Ji, 2012). Schmidt (2008)

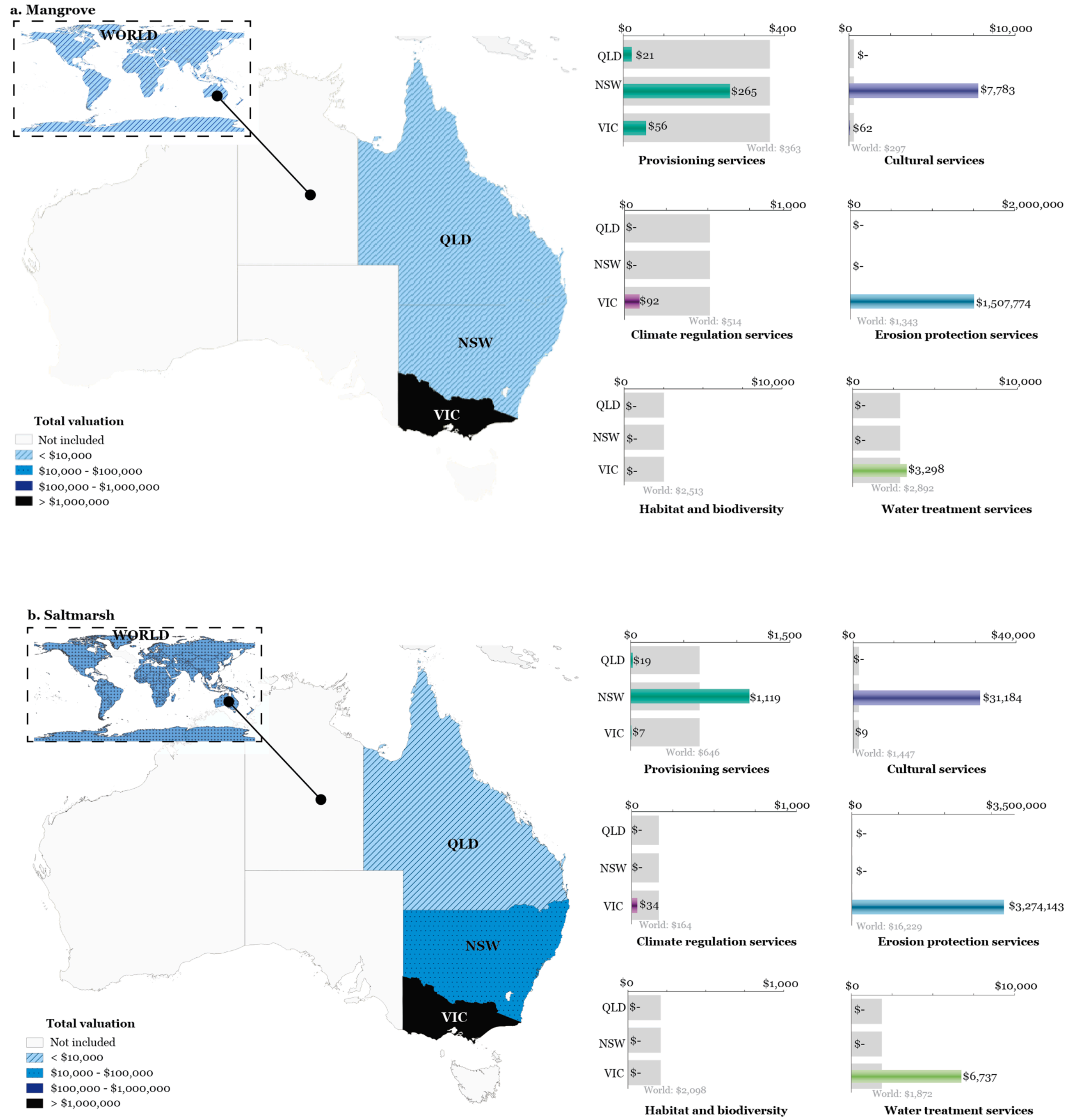

Fig. 3. Median valuation of ecosystem services for: a. Mangrove; b. Saltmarsh; c. Seagrass. Abbreviations: NSW – New South Wales; QLD – Queensland; VIC – Victoria.

estimated the value of water treatment provided by dairy swamps of \$9,764/ha/year based on the avoided costs of artificial water filtration plants in South Australia, considering that natural wetlands have 50 % of the filtration efficiency of a purpose-built constructed wetland and that the wetland is permanently connected to the river system. This value was two orders of magnitude higher than the global value of \$58/ha/year, ranking Australia in the 98th percentile (Table 4). A comparison with the global analysis of regulating services offered by freshwater also informed habitat and biodiversity and air quality as researched services in freshwater wetlands (Table 3).

The median value of global ecosystem services of freshwater wetlands is \$3,394/ha/year, which is below the median value that just two services—erosion protection services and water treatment services—provide in Australia (Fig. 3d). Considering the relevance and abundance of freshwater wetlands in Australia, expansion of ecosystem service valuation in these ecosystems is a high priority for future

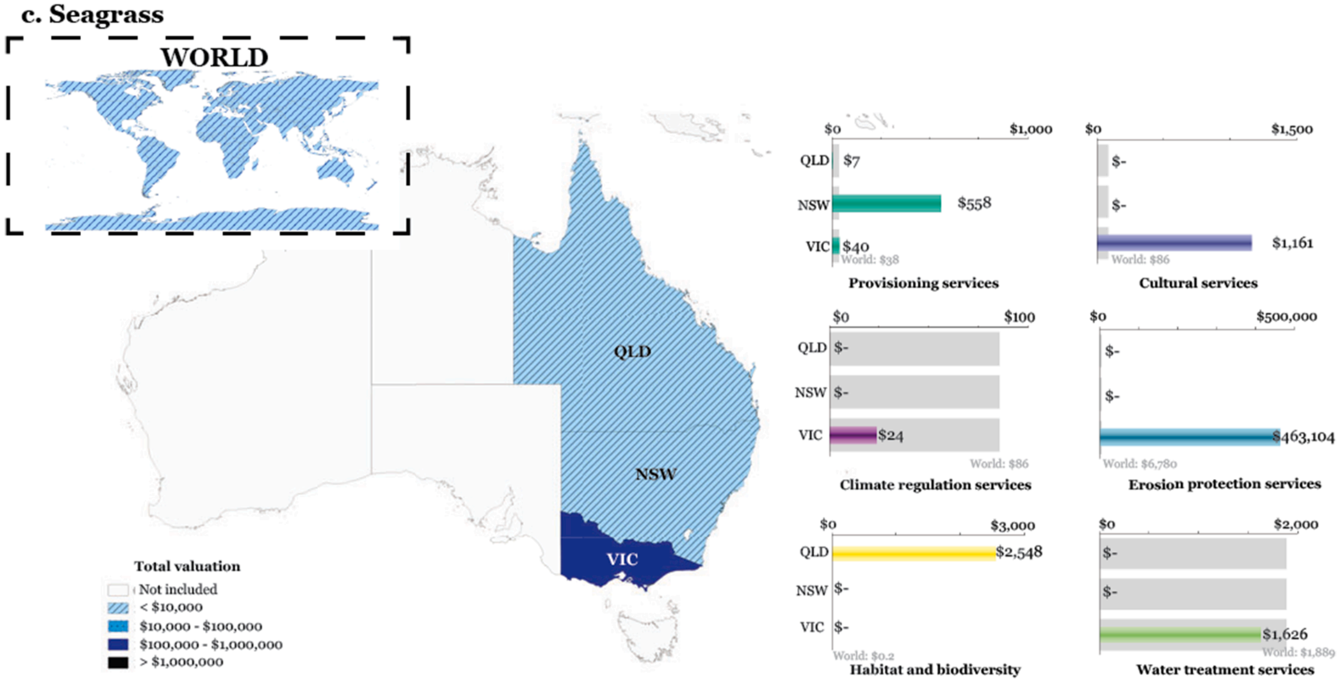

Fig. 3. (*continued*).

research.

3.8. Open waterways

A total of 241 estimates for open waterways (lagoons and estuaries) were found in the modified ESVD, with only four related to Australian literature. Robinson (2001) was the only study that identified provisioning services in open waterways. This study assessed the value of estuarine dependent fisheries in 2001 to be $432 million annually, based on four commercially significant species (oysters, prawns, barramundi, and crabs). While it is acknowledged that this value is not solely reliant on the open waterways in estuaries (e.g. the other coastal ecosystem, such as mangroves and saltmarsh also contribute), it provides an Australian-based estimate to compare with international literature. Assuming estuarine waterways in Australia cover approximately 40,000 km^2 (CSIRO, 2015), this equates to a value of $190/ha/year. While commercial fisheries were the only service identified in the Australian literature, worldwide provisioning services of open waterways also include water, raw materials and medicinal resources (Table 3). Waterways also act as critical transport 'infrastructure' for many heavy industries (e.g., mining). Further exploration of additional provisioning services of open waterways and the habitats in them such as snags and gravel beds is recommended to improve understanding of the benefits of open waterways.

Three Australian estimates were identified for cultural services provided by open waterways based on recreational fishing, with a median value of $489/ha/year. The cultural services were estimated using the travel cost and contingent valuation methods (Clara et al., 2018) and the recreational fishing expenditure (Robinson, 2001). The 2024 ESVD also identified open waterways cultural services for aesthetic information, culture, art and design, spiritual experience, information for cognitive development and bequest values (Table 3), and none of them were identified in the Australian literature. No Australian studies dealt with the ecosystem service value of climate regulation, erosion protection, and water treatment in open waterways. The global median value for open waterways habitats is $2,879/ha/year. Further research is required to fully identify the Australian valuation of open waterways for different ecosystem services and its variation at a national and regional scale.

4. Discussion

4.1. Further research of ecosystem services in Australia

The valuation of ecosystem services increases awareness for ecosystem protection and rehabilitation, highlights the diverse range of beneficiaries, and informs policy, management and planning. Several studies have quantitatively assessed the ecosystem services of key fish habitats in Australia. However, most of these studies have been predominantly conducted in NSW and VIC, thereby limiting development of a continent-wide picture of the ecosystem services and associated values across Australia. In addition, the valuation of provisioning services has been limited to commercial fisheries, with no available quantification of the valuation of fish key habitats used for construction, tools, timber or fuel, as typically considered in the ecosystem service analysis worldwide (Brander et al., 2024a, Millennium Ecosystem Assessment, 2005). This means that provisioning service estimates in Australia are likely undervalued. Further research should explore key fish habitat ecosystem services for these additional services providing evidence-based information of the benefit of the ecosystems and informing the development of ecosystem service frameworks to integrate findings with policy planning (Costanza et al., 2017). Also, some important aquatic ecosystems such as snags and gravel beds have not been evaluated for their services.

Cultural services have also been limited to recreational fisheries, overlooking the identification of bequest values and cognitive development, which has been reported in other studies around the world (Brander et al., 2024a, Millennium Ecosystem Assessment, 2005). Therefore, to ensure a thorough identification and understanding of the key fish habitat ecosystem services in Australia, and to prevent underestimation of their benefits, future research should focus on assessing a broader range of provisioning and cultural services and expanding analyses to encompass other regions across Australia. Note that while this manuscript highlights the need for extensive valuation of cultural services across Australia, previous global reviews on cultural services have highlighted the limitations on cultural ecosystem services knowledge due to their methodological barriers such as spatial and temporal discontinuities, overlapping ecosystem services, as well as ambiguity in the classification of cultural services (Cheng et al., 2019; Hirons et al., 2016). Therefore, it is suggested that future research aiming to describe these services in Australia (and worldwide) should follow a defined framework to provide reliable, accurate and comparable cultural services valuations, such as the guideline to account Indigenous cultural values in Australia (Nursey-Bray et al., 2024). A summary of the data gaps identified in the present review is included in Fig. 4.

4.2. Sensitivity analysis of evolution of the ESVD

The assessment presented in this manuscript was conducted using the 2024 ESVD, based on 10,874 records of the valuation of ecosystem service and derived from more than 1300 studies (Brander et al., 2024a). The 2020 ESVD was an earlier version of the database containing 2900 records of ecosystem service valuations and derived from 693 studies. Given the significant increase in the ecosystem service studies and estimates over a four year-period, it is expected that these numbers will continue to grow. Noting the recent increase in data volume, the influence of this additional data on the current assessment is of interest. Consequently, an assessment of the variation between the 2020 and 2024 ESVD datasets is included below (excluding additional references identified in the modified ESVD). Note that the ecosystem service valuation records in the 2020 ESVD were standardised to international dollars/ha/year for 2020 price levels. Therefore, the values of the 2020 ESVD were not updated.

The filtering of data in the 2020 ESVD database followed the same procedure used in the 2024 ESVD, namely:

i. Any entry that addressed more than one of the six ecosystem services defined in this study was not considered;
ii. Only key fish habitats with available information in both databases were included in this assessment: seagrass, mangrove, saltmarsh, open water and freshwater wetland (i.e. shellfish and kelp were excluded since they only had one estimate in the 2020 ESVD);
iii. The ecosystem services considered were based on the TEEB categorisation.

Note that the biome(s) and ecosystem(s) classifications were different between the 2020 ESVD and the 2024 ESVD. The former used the TEEB classification, while the latter used the IUCN Global Ecosystem Typology 2.0 and the FAO Global Ecological Zoning Framework (Brander et al., 2024b). Nonetheless, a sensitivity analysis was conducted between the 2020 and 2024 databases to identify the differences in the studies under the same key fish habitat name, and most of the studies appeared under the same key fish habitat name.

Fig. 5 presents a comparison of the ecosystem service valuations between the 2020 and 2024 ESVD. The ecosystem service valuations for

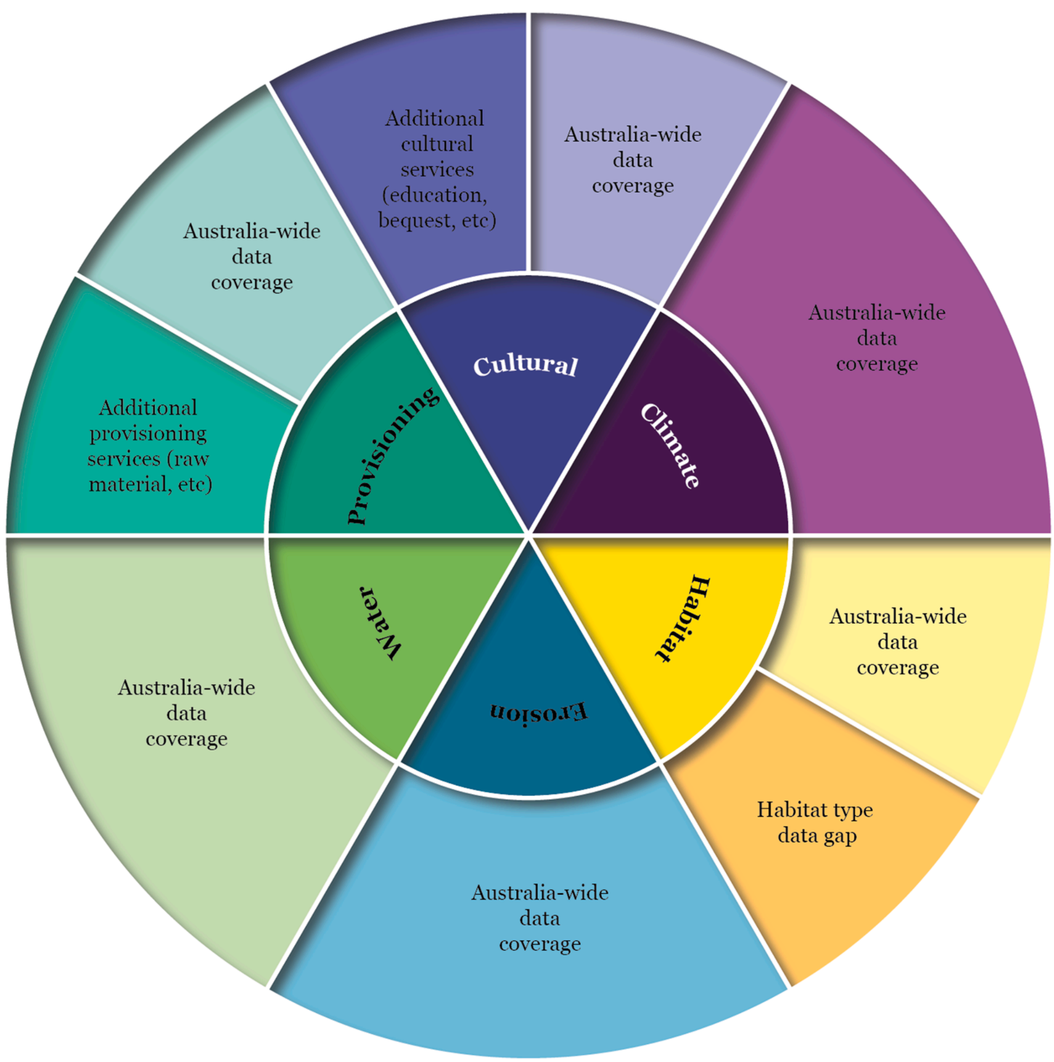

Fig. 4. Data gaps identified in the Australian ecosystem services literature.

mangroves, saltmarshes, seagrasses, and open waterways key fish habitats were found to be within the same order of magnitude in both databases, generally exhibiting less than a 30 % difference in valuation estimates. The most remarkable discrepancies were observed in freshwater, which decreased by 81 %. These differences may be attributed to a substantial increase in the number of additional studies in provisioning and water treatment services that derived lower estimates in the ecosystem services. For instance, the 2020 ESVD recorded only 1 and 16 estimates for water treatment and provisioning services for freshwater, whereas the 2024 ESVD included 50 and 84 estimates, respectively. Additional data enhances the ability to detect global patterns, thereby minimising the impact of outliers in the valuation estimates. This finding underscores the relevance of expanding the analysis of ecosystem service valuations in Australia, where the number of estimates remains limited.

4.3. Application of ecosystem service valuation estimates in Australia

Key fish habitats provide a wide array of benefits to the community, as indicated in the preceding sections. Nonetheless, anthropogenic development and activities have caused significant pressure on these ecosystems, resulting in depletion and degradation in those aquatic ecosystems (Culhane et al., 2019, Häder et al., 2020, Junk et al., 2012, Wernberg et al., 2024). To manage the environmental damage, a global mitigation hierarchy has been adopted in countries such as United States and Australia (McKenney and Kiesecker, 2010, Lapeyre et al., 2015), with avoiding or preventing impacts as the primary step. When avoidance is not feasible, efforts should be focused on minimising the impacts, with offsetting or compensation of the residual impacts as the final recourse (McKenney and Kiesecker, 2010, Lapeyre et al., 2015).

In Australia, biodiversity offsets are considered under the *Environmental Protection and Biodiversity Conservation Act 1999* (Commonwealth), and individual offset policies have been developed for each state jurisdiction. In NSW, activities that impact on fish or key fish habitat may trigger approval requirements under Part 7 of the *Fisheries Management Act 1994*. This may involve a requirement to offset impacts by undertaking environmental compensation works to ensure 'no net loss' of key fish habitat, as outlined in the NSW Biodiversity Offsets Policy for Major Projects and the NSW Fisheries Policies and Guidelines (NSW Department of Primary Industries, 2013, NSW Department of Primary Industries, 2014). The preferred approach occurs when a proponent is able to propose, deliver and manage a 2:1 (offset: impact) offset as environmental compensation, to the satisfaction of the relevant agency. This may not be achievable in some circumstances. When a

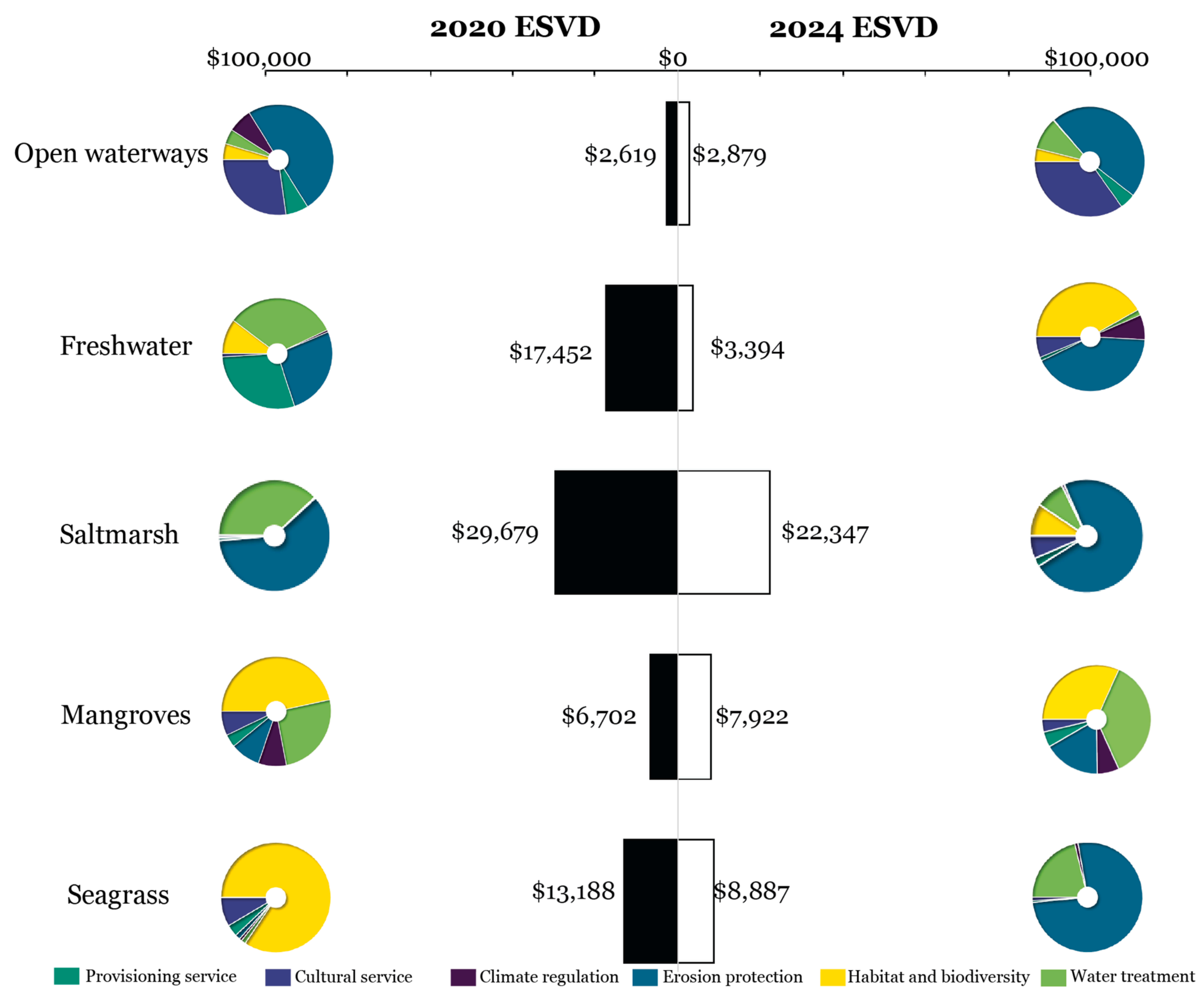

Fig. 5. Comparison 2020 Ecosystem Services Valuation Database (ESVD) and 2024 ESVD.

proponent can demonstrate they have thoroughly investigated several offset site proposals and yet an offset outcome is not achievable, funds currently at the rate of $56.75 / m^2 of the offset area can be provide by the proponent into a Trust for agreed supplementary measures (NSW Department of Primary Industries, 2014). In coastal and estuarine environments in NSW, it appears that a monetary rate of $56.75/m^2 for offsetting of key fish habitat is insufficient, and the need to investigate more robust valuations initiated this project (DPI – Fisheries, 2020). The current monetary offset value in NSW was estimated based on the valuation provided by Costanza et al., (1997). However, updated information reveals that the values presented by Costanza et al., (1997) undervalued many ecosystems worldwide (Costanza et al., 2014). When a compensatory rate is undervalued and lower than the cost of effective rehabilitation, proponents may be incentivised to prioritise paying for compensation rather than agreeing to undertake the on-ground offset (DPI – Fisheries, 2020). Finally, the current offset policy is applied to developments with large impacts and there is a growing concern that many small-scale projects are not effectively offset. If the impact of these numerous small projects is not addressed, a cumulative 'death by a thousand cuts' can lead to substantial piecemeal degradation of key fish habitat and potentially exceed the impact of large-scale projects. Therefore, there is a need to regularly update the current valuation of key fish habitat offset values to ensure the protection of the aquatic ecosystem.

Considering the precautionary principle, it is recommended that new offset values are selected by assessing the larger value between the present value of the ecosystem service valuation and the restoration cost per each key fish habitat. This methodology ensures that the offset value accounts for the ecosystem service as a minimum and reduces the oversight of temporal lags required in the restoration of natural ecosystems. In the absence of ecosystem data or estimates of restoration costs for some key fish habitat types, the median global values of available ecosystems can be used to determine the offset value. When multiple ecosystem service valuations were identified, the adopted ecosystem service value can be determined considering the value that is more representative for the key fish habitats in the specific location (i.e. valuations captured in the same region or with similar environmental and socio-economic conditions). Caution should be considered for ecosystem services that may be underrepresented by monetary valuation methods, such as cultural services (Hirons et al., 2016), and further research should explore alternatives to ensure the representation of intangible services for offsetting purposes (Cheng et al., 2019; Hirons et al., 2016). While it is acknowledged that localised ecosystem service valuation estimates may not be feasible at every location, if the services are significantly more or less highly valued in specific locations, further scrutiny may be warranted.

5. Conclusions

Australian aquatic ecosystems provide valuable benefits to human wellbeing, including provisioning, cultural and regulating services. The economic valuation of these ecosystems provides a quantitative estimation, facilitating the promotion of policies and management for ecosystem protection. While all aquatic ecosystems provide ecosystem services, the investigation of the economic valuation of these ecosystems in Australia has been unevenly distributed. Kelp, mangroves, saltmarsh and seagrass have the highest number of economic estimates in Australia, whereas shellfish habitats had only two estimates. Some other important fish habitats such as snags and gravel beds have not yet had an economic valuation of their ecosystem service values and were not able to be considered in this review. Additionally, although several studies have quantitatively assessed the ecosystem services of key fish habitats in Australia, the majority were conducted in NSW and VIC, limiting a continent-wide picture of the ecosystem services and their values across Australia. Despite provisioning and cultural services being the most common researched ecosystem services in Australia, no available valuation of typical provisioning and cultural services identified worldwide were found, including aquatic ecosystems used for construction, tools, timber, fuel, cognitive development and bequest values. The assessment of the economic valuation per ecosystem revealed that Australian economic values were typically below the global median for provisioning, cultural and climate regulation services. This discrepancy may be linked to the limited information on certain ecosystem services, lack of Australian-wide data and spatial specific conditions such as population and resource demands. Overall, significant variation of Australian valuation estimates was identified depending on the location and region, even between estuaries within the same region, highlighting a risk of using valuation from one state to another. More research is needed to ensure the economic valuation of aquatic ecosystem services in Australia is well represented continent-wide, and to ensure that additional ecosystem services, such as raw materials and cognitive development, are not overlooked. These additional valuations can strengthen the evidence-base for policies promoting ecosystem protection and rehabilitation. They also underscore the importance of taking significant measures to avoid development impacts, limiting offsetting to an option of last resort for only the most unavoidable impacts.

CRediT authorship contribution statement

Laura Montano: Writing – original draft, Visualization, Validation, Investigation, Formal analysis, Conceptualization. **Alice Harrison:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Brad Henderson:** Writing – review & editing, Validation, Investigation, Conceptualization. **Melinda A. Coleman:** Writing – review & editing, Validation. **Vincent Raoult:** Writing – review & editing, Validation. **Matthew D. Taylor:** Writing – review & editing, Validation. **Troy Gaston:** Writing – review & editing, Validation. **Patrick G. Dwyer:** Writing – review & editing, Validation, Conceptualization. **Robert Costanza:** Writing – review & editing, Validation. **Andrew Dansie:** Writing – review & editing, Supervision, Conceptualization. **William Glamore:** Writing – review & editing, Supervision.

Declaration of competing interest

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If there are other authors, they 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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Data availability

Data will be made available on request.

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