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RESEARCH ARTICLE

Restoring blue carbon ecosystems unlocks fisheries' potential

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Globally, blue carbon ecosystems, including salt marsh, mangroves, and seagrasses, and the associated ecosystem services they provide, have declined substantially. In response, ecosystem restoration has recently increased but the scale and urgency of these activities has been limited by the lack of economic drivers. Herein, a multidisciplinary approach is presented that links hydrologic restoration with ecologic outputs to highlight the economic potential for commercial fisheries that could arise from restoring a drained floodplain. Initially, stable isotope models are used to predict the return of Eastern school prawn (approximately 300 kg yr^{-1} ha^{-1}). Hydrologic models are then applied to determine the area of salt marshes and mangroves (over 2,000 ha) that could be potentially restored via tidal introduction. Together, these results indicate that ecological restoration in this region could contribute an annual benefit of approximately 230 tons of additional Eastern school prawn harvest, which could be valued at \$3.1 $\pm$ 1.3 million AUD to commercial fisheries. This would represent a growth of nearly 50% from current annual harvest in the state. Given that this assessment excludes other values that would be gained, such as other species of fisheries value, carbon sequestration, biodiversity, and flood control, it represents a conservative financial estimate. Overall, this analysis highlights the scale of fisheries co-benefits from tidal restoration projects, and how business cases for large-scale blue carbon ecosystem restoration projects could be developed using multidisciplinary approaches.

Key words: blue carbon, cost–benefit, fisheries, mangroves, rehabilitation, salt marsh, tidal introduction

Implications for Practice

- The method provided here allows practitioners to develop cost–benefit scenarios for restoration benefits in estuaries with commercial fisheries.
- Using this approach can also underline how much value has been lost historically and bring attention to the importance of blue carbon ecosystems for economies.

Introduction

Of all ecosystems on this planet, blue carbon ecosystems, including mangrove forests, tidal/salt marshes, and seagrass meadows are ranked second in the estimated dollar value of ecosystem services (approximately \$USD194,000 ha^{-1} yr^{-1}), with only coral reefs providing higher estimated values (Costanza et al. 2014). This is because blue carbon ecosystems are highly productive and provide critical nursery habitats to a broad range of organisms. They also support many ecosystem services, including high rates of carbon sequestration, recreation, flood attenuation, reduced erosion, nutrient reduction, fisheries enhancement, and coastal protection (Mulder et al. 2020; Costanza et al. 2021; Macreadie et al. 2021).

Unfortunately, blue carbon ecosystems have been lost at an alarming rate due to practices such as flood mitigation works, the draining of low-lying estuarine floodplains, and other land reclamation practices such as the creation of aquaculture facilities (Duarte et al. 2013). As an example of this problematic trend, it is estimated that approximately 50% of salt marshes, 52–78% of mangrove forests, and 20–26% of seagrass meadows have been lost in Australia since European settlement (Serrano et al. 2019). In many of these areas, excessive floodplain drainage has resulted in acid sulfate soil oxidation and the establishment of non-water tolerant vegetation in former wetland areas. This has increased the frequency and magnitude of poor water quality (e.g. acid and low dissolved oxygen blackwater) discharging into estuaries (Tulau 2011; Wong et al. 2011). Further, sea level rise is reducing the efficiency of gravitational drainage networks, resulting in diminishing economic return (Khojasteh et al. 2021; Waddington et al. 2022). Without urgent and

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widespread action, the outlook for blue carbon ecosystems is dire (Saintilan et al. 2022).

Due to the recognized services that blue carbon ecosystems provide, their restoration via tidal introduction has gained significant attention from researchers, policy makers, Non-Government Organisations, and the green finance sector (Vanderklift et al. 2019; Taylor et al. 2021; Waltham et al. 2021). Several case studies have now demonstrated that the introduction of tidal flows into previously disconnected areas can lead to the establishment of healthy blue carbon ecosystems (Abbott et al. 2020; Glamore et al. 2021; Sadat-Noori et al. 2021). Recently, several global initiatives and new environmental market frameworks have been introduced with the goal of scaling-up restoration of these ecosystems from a small number of pilot projects to globally significant aerial extents (Vanderklift et al. 2019). For instance, the United Nations (UN) General Assembly declared 2021–2030 the "UN Decade of Ecosystem Restoration" as well as "The Decade of Ocean Science for Sustainable Development", both of which strongly support large-scale restoration of coastal wetlands (Waltham et al. 2020). Further, projects that protect or restore blue carbon ecosystems are eligible to receive carbon credits through the globally applicable VERRA accreditation (Sapkota & White 2020), United Nations Framework Convention on Climate Chante market mechanisms (de Sépibus et al. 2013), as well as in Australia through its Emissions Reduction Fund (Kelleway et al. 2017).

Blue ecosystems can sequester carbon at up to 50 times the rate of other sites on an equal area comparison (Serrano et al. 2019). As such, the generation of blue carbon credits can significantly improve the financial viability of conservation and restoration projects. However, the carbon credit revenue stream alone may not always be sufficient to cover the often-significant expenses associated with the conservation or restoration of such large habitats (Vanderklift et al. 2019). More recently, analyses of some carbon offset schemes have questioned their integrity (Michaelowa et al. 2019; Hemming et al. 2022), causing some to question their use to justify investment. Similarly, existing land use (e.g. sugarcane, dairy, pasture grazing, rice production, macadamia farming, etc.) may provide sufficient economic return to dis-incentivize an on-ground change of practice. It is therefore essential to obtain accurate valuations of key ecosystem services other than carbon sequestration, commonly referred to as co-benefits, to achieve blue carbon ecosystem restoration at globally significant levels (Vanderklift et al. 2019; Waltham et al. 2021). In some systems where net additional carbon sequestration potential is low, co-benefits may provide the greatest potential return on investment. Valuation of co-benefits can thus be used to justify and/or attract investments into conservation and restoration projects that may not be financially viable via blue carbon credits alone.

One promising avenue for valuing blue carbon ecosystem co-benefits is the quantitative valuation of habitat–fishery linkages (Jänes et al. 2020). The idea behind habitat–fishery linkages is that the highly productive nature of blue carbon ecosystems (Twilley et al. 2017) can create additional habitats that will result in a quantifiable increase in fisheries productivity across the wider estuary (Taylor et al. 2018). Such increases in fisheries productivity can then be valued in monetary terms by analyzing the total economic output of commercial and recreational fisheries. To date, quantifying links between unique habitats and fisheries has relied on stable isotope ecology. In general, these studies identify that salt marshes and seagrass have the highest contribution (and therefore value) to the diets of commercially important species (Raoult et al. 2018, 2022; Baker et al. 2020; Hewitt et al. 2020). The degree of contribution can be strongly estuary dependent (Jänes et al. 2020), and, as a result, a closer examination of the per estuary contributions is necessary to explain the underlying causes of these differences in food web contributions. An explicit understanding of fishery–habitat linkages can value individual habitats according to their contribution to fishery productivity (Taylor et al. 2018), hence suggesting the potential restoration value of these habitats (Taylor & Creighton 2018). However, the potential increase in fisheries productivity that could be achieved in an estuary, based on an assessment of the area that could be restored, has not been conducted.

In this study, we address this gap by conducting a knowledge-based assessment of the restoration potential at a localized fishery, namely the Lake Wooloweyah Eastern school prawn (*Metapenaeus macleayi*) fishery in the Clarence River of New South Wales, on the east coast of Australia. To achieve this, we combined hydrodynamic and eco-hydrological modeling of tidal introduction options around the lake with ecological modeling of habitat–fishery linkages using the trophic subsidy method. We then modeled the potential economic value that could be added to the Lake Wooloweyah Eastern school prawn fishery. The principal objectives of this study were to:

(1) Determine the value of existing blue carbon ecosystems to fishery productivity using Eastern school prawn as a readily understood community indicator for fisheries productivity.
(2) Hydrologically quantify opportunities to convert drained low-lying coastal areas into blue carbon ecosystems via tidal introduction.
(3) Combine (1) and (2) to estimate and value future prawn fisheries commercial benefits as blue carbon ecosystems are developed.

Methods

Study Area

This study focuses on the Lake Wooloweyah segment of the Clarence River estuary, in eastern Australia (Fig. 1). Three tidal channels (Palmers, Oyster, and Micalo) connect Lake Wooloweyah to the Clarence River, with the easternmost channel, Oyster Channel, providing the largest hydraulic conveyance. Lake Wooloweyah is a shallow lagoon (around 1.3 m on average; (Foley & White 2007) of high ecological value and is listed on the "Directory of Important Wetlands in Australia", supporting extensive areas of seagrasses, mangrove forests, and salt marshes (see macrophytes in Fig. 1; Directory of Important Wetlands in Australia 2001, https://www.dcceew.gov.au/water/wetlands/australian-wetlands-database/directory-important-wetlands). The lake has a local catchment of 174 km^2 with an average annual rainfall of

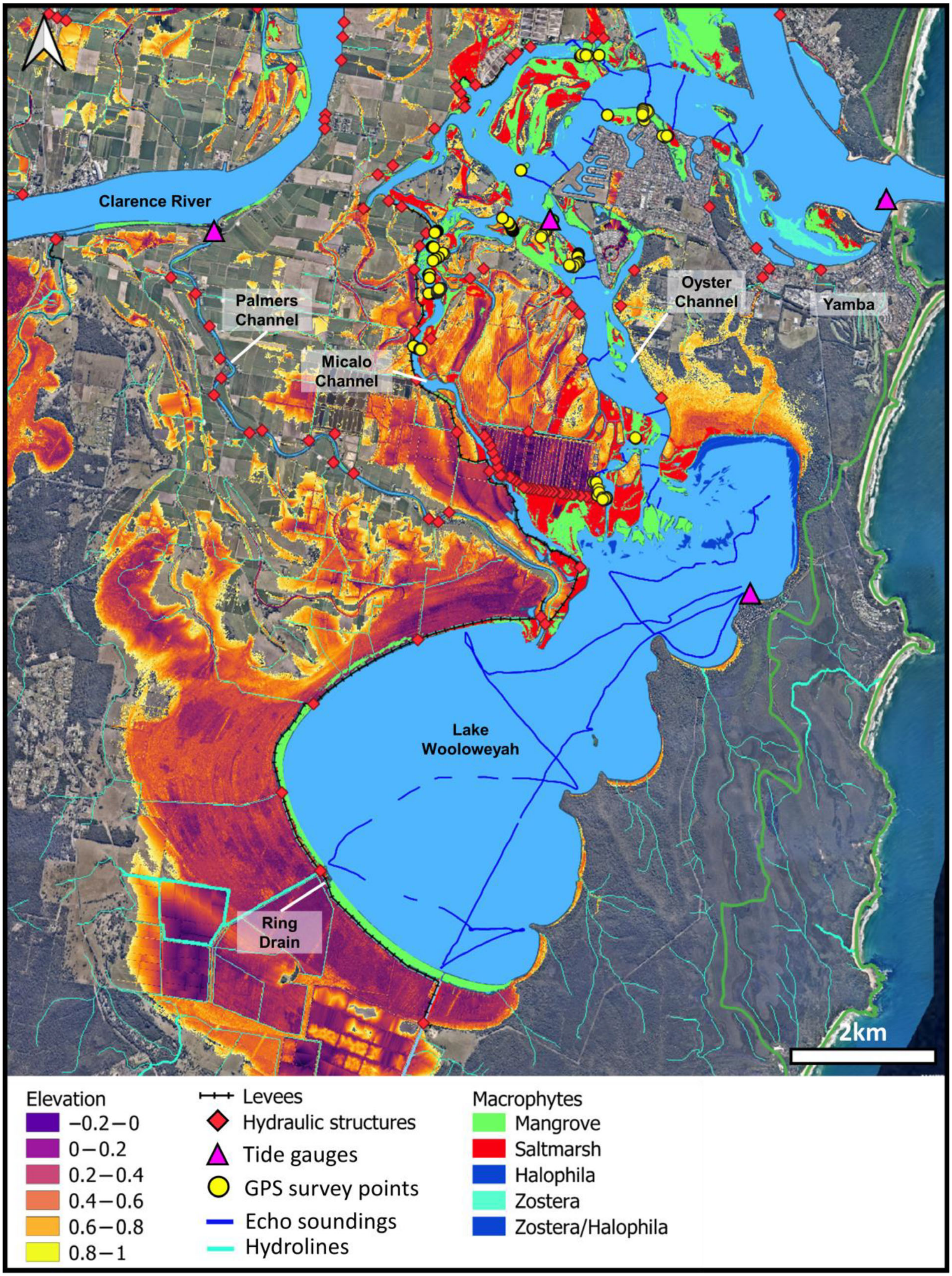

Figure 1. Satellite imagery of Lake Wooloweyah overlaid with digital elevation model showing the elevation around the lake, and the infrastructure used to control tidal ranges around it. Note the significant area only slightly above sea level.

1,457 mm, a high level of interannual variability and a pronounced summer and autumn rainy season (Foley & White 2007).

An extensive network of gravity drains and floodgates have been constructed to facilitate agricultural practices in the low-lying areas around the lake (Fig. 1). This extensive drainage system consists of greater than 20 km of major drains, including a large ring drain around the south western shoreline of Lake Wooloweyah, 10.2 km of levees, as well as numerous one-way floodgates that prevent tidal/saltwater intruding into the drainage system (Foley & White 2007). Here, we analyzed the suitability of these drained floodplain areas to create blue carbon ecosystems via tidal introduction based on hydrodynamic modeling simulations. Although it is documented that large parts of these drained floodplain areas were historically freshwater dominated backswamps and floodplains (Foley & White 2007), the combination of sea level rise and land-subsidence has substantially increased the potential for the establishment of intertidal vegetation (already present throughout Lake Wooloweyah).

Stable Isotope Analysis

A total of 14 sites were sampled (Fig. 2) using a sled net (0.75 × 0.4 m mouth, 4 m length 26-mm diamond mesh body, and 6-mm octagonal mesh cod end). A total of six trawls of approximately 100 m were conducted for each site and Global Positioning System (GFS) locations for the beginning and end of each trawl were recorded. Prawns were bagged and labeled with their site location for processing. To capture the size ranges that are directly captured by fisheries, we also obtained 44 prawn samples sourced directly from fishery catches. A random size selection was then subsampled for muscle tissue.

In parallel, leaves from independent plants of primary producers were collected from these same sites (if present), including: *Sporobolus virginicus*, *Zostera mulleri*, *Avicennia marina*, *Sarcocornia quinqueflora*, *Sueda australis*, and local sugar cane (*Saccharum* sp.). Particulate organic matter (POM) was collected by filtering approximately 1 L of water collected from the water column onto a 0.2 μm pre-combusted glass-fiber filter. Fine benthic organic matter (FBOM) was collected by gently removing the top centimeter of sediment into a plastic tube as per Hewitt et al. (2020).

Samples of muscle tissue and plant matter were placed in a drying oven at 60°C for at least 24 hours. Dried tissues were then ground into powder using a ball mill (Retsch Mixer Mill MM 200) before being sent to Griffith University's Stable Isotope Laboratory in Queensland, Australia for processing.

Approximately 9 mg of tissue was used to determine stable isotope delta values of carbon, nitrogen, and sulfur. Delta values were determined with a Europa EA GSL Elemental analyzer (Europa Scientific Inc., Cincinatti, OH, U.S.A.) coupled with a Hydra 20-22 automated isoprime isotope ratio mass spectrometer (Sercon Ltd., www.serconlimited.com). Ten internal standards comprised of bovine liver, glycine NBS127, GylcineLSU 1Delta, and a low and high mix (calibrated to International atomic energy agency international standards of Pee Dee belemnite for $\delta^{13}C$, atmospheric nitrogen for $\delta^{15}N$, and Vienna-Canyon diablo troilite for $\delta^{34}S$) were run with each tray

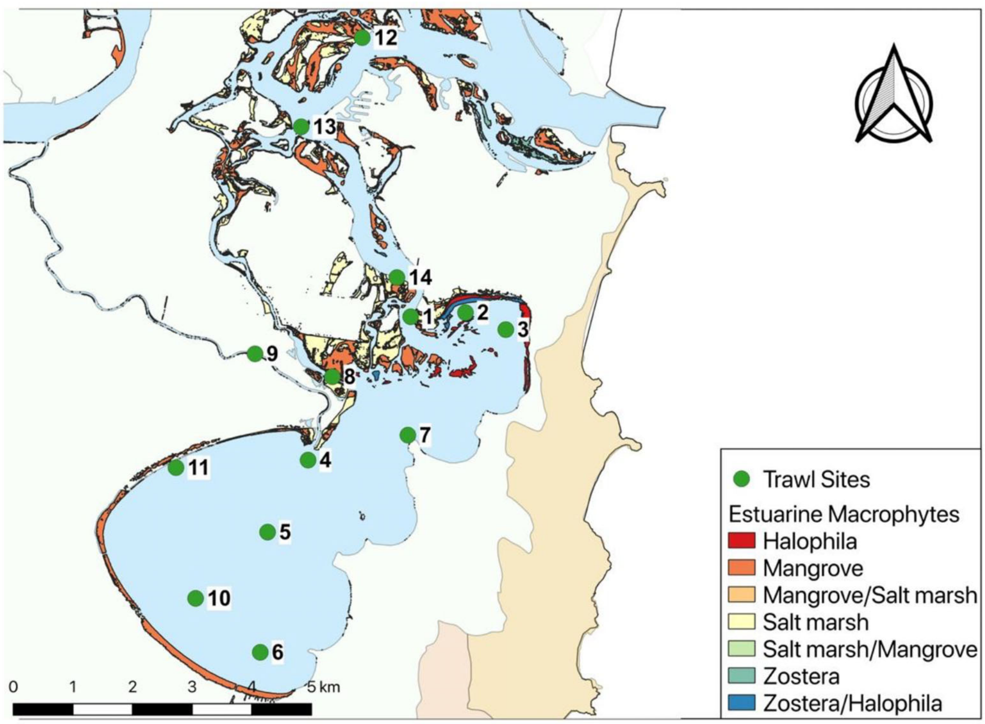

Figure 2. Location of prawn and habitat sampling sites within Lake Wooloweyah and Clarence River. *Source*: Habitat data sourced from Fisheries Spatial Data Portal (2020, https://webmap.industry.nsw.gov.au/Html5Viewer/index.html?viewer=Fisheries_Data_Portal).

of approximately 60 samples to verify the precision of the results. The mean difference of these measurements relative to repeat measurements of the standards was 0.3‰ for δ^{15}N, 0.1‰ for δ^{13}C, and 0.4‰ for δ^{34}S, respectively.

The mixing model approach used here to assess the contribution of estuarine habitats to the diets of prawn broadly follows that used in Raoult et al. (2018, 2022), and Hewitt et al. (2020), but with slight improvements. Stable isotope values of sources were first examined for a priori grouping, as sources that overlap in the iso-space are indistinguishable in the model (Parnell et al. 2010). Any sources that had means and standard deviations (SD) that overlapped across all axes were grouped. This resulted in just one grouped source that included mangroves, *S. australis* and *S. quinqueflora*, and all other sources were independent. Contributions of these sources to the diets of Eastern school prawn were determined using Bayesian stable isotope mixing models using MixSIAR (Stock et al. 2018) in R V. 4.2.1 (R Core Team 2021).

Eastern school prawn stable isotope values were adjusted to account for trophic enrichment relative to primary producers, with Δ^{13}C of -0.1 ± 1.33, Δ^{15}N of 3.6 ± 0.92, and Δ^{34}S 0 ± 1. Recent meta-analyses and targeted studies have identified that diet type and content have a greater impact on discrimination factor than species relatedness (Canseco et al. 2021; Stephens et al. 2022), and we chose a discrimination factor that was obtained from controlled experiments on prawns given an omnivorous diet from Viozzi et al. (2021). Models were set to long run times (chain length of 300,000; burn of 200,000; thin of 100, three chains) with a multiplicative setting to account for within-population variability. Diagnostic criteria (Geweke and Gelman) were checked to ensure models converged. As there is no reliable stomach content data for these prawns, no priors were used.

Hydrodynamic Modeling

Field investigations were undertaken in June 2020 and included a bathymetry survey covering Lake Wooloweyah and the connecting channels. High precision Real time kinematic global positioning system elevation surveys of intertidal vegetation communities in and around the lake were also undertaken (Fig. 1). The bathymetric data collected during the fieldwork were used to build a combined one- and two-dimensional hydrodynamic model for the entire Clarence River estuary (Fig. 3). The resolution of the model mesh is variable throughout the domain, with higher levels of detail applied in sections with complex geometries and flow patterns, such as constricted tidal channels and geomorphological features such as flood and ebb tide shoals.

The hydrodynamic model includes the main channels and embayments of the estuary but excludes the drained non-tidal floodplains. The model was built using the RMA2 modeling software package that solves the depth-integrated shallow water equations in multiple dimensions. Inflows from all major upstream estuary catchments and the nearest oceanic tide gage were included in the boundary condition. The model was calibrated against long-term local tidal gage data and flux data from multiple boat mounted Acoustid Doppler Current Profiler deployments (Glamore et al. 2009). Furthermore, the model was validated against long-term water level data at multiple locations in the Oyster Channel and within Lake Wooloweyah using data collected and verified by the NSW State Government (https://mhl.nsw.gov.au/Station-204485). Additional water level sensors were deployed in Micalo channel (Fig. 3) to assist in validating head loss factors.

Mapping Blue Carbon Ecosystem Creation Potential

For this assessment, the hydrologic feasibility was considered the primary factor for identifying areas suitable for habitat rehabilitation. This captured the upper range of fisheries benefits that can be achieved for this system. To facilitate the prioritization of potential rehabilitation efforts in practice, the hydrologically feasible area for tidal rehabilitation was divided into four eco-hydrologically distinct segments.

The hydrologic feasibility for tidal habitat creation was assessed using a Geographic Information Systems-based modeling approach. In this approach, calculated tidal planes from the nearest location in the estuary were extrapolated across the adjacent low-lying lands. This approach was deemed valid as the channel network linking the estuary to the floodplain are extensive and water velocities across the area would be slow (<0.6 m/second). Therefore, as head loss is a function of velocity, limited head loss (if any) would be anticipated in the tidally restored floodplain areas. Previous tidal introduction works have validated this approach, as long as accurate tidal boundary conditions can be obtained in the estuary (e.g. Rayner et al. 2021; Sadat-Noori et al. 2021).

The digital elevation model (DEM) used for this analysis was the "BARE POINT 2010-04-28 2 km × 2 km 1 m Resolution Digital Elevation Model" from the NSW Government Spatial Services obtainable via the ELVIS data platform (https://elevation.fsdf.org.au/). In densely vegetated areas such as salt marshes, Light Detection and Ranging (LiDAR)-derived DEMs can suffer from minor vertical inaccuracies. To ground-truth the DEM, Realtek measurements were collected across the existing Lake Wooloweyah fringing wetland area (Fig. 1). LiDAR data were in strong agreement with bare Earth measurements and no adjustment was made to the DEM (vertical resolution ± 0.01 m).

Co-Benefits of Potential Habitat Rehabilitation

The approach used herein reflected that used in Taylor et al. (2018) and refined in Raoult et al. (2022). Briefly, the approach uses stable isotope mixing model outputs (contributions of each habitat to the diets of Eastern school prawn in Lake Wooloweyah collected above) to attribute value of fisheries landings to estuarine habitats. This first required regrouping of primary producer sources contributing to the diets of prawns that were included in the stable isotope model to account for which habitat they belonged to, with the assumption that each source in a group contributes equally (i.e. the two salt marsh succulents contribute 2/3 of the "mangrove and others" group contribution). Because POM and FBOM have no distinct habitat, and do not consist of a habitat that could be attributed a value, they were not included in the valuation process (i.e. their contribution to the value was not accounted).

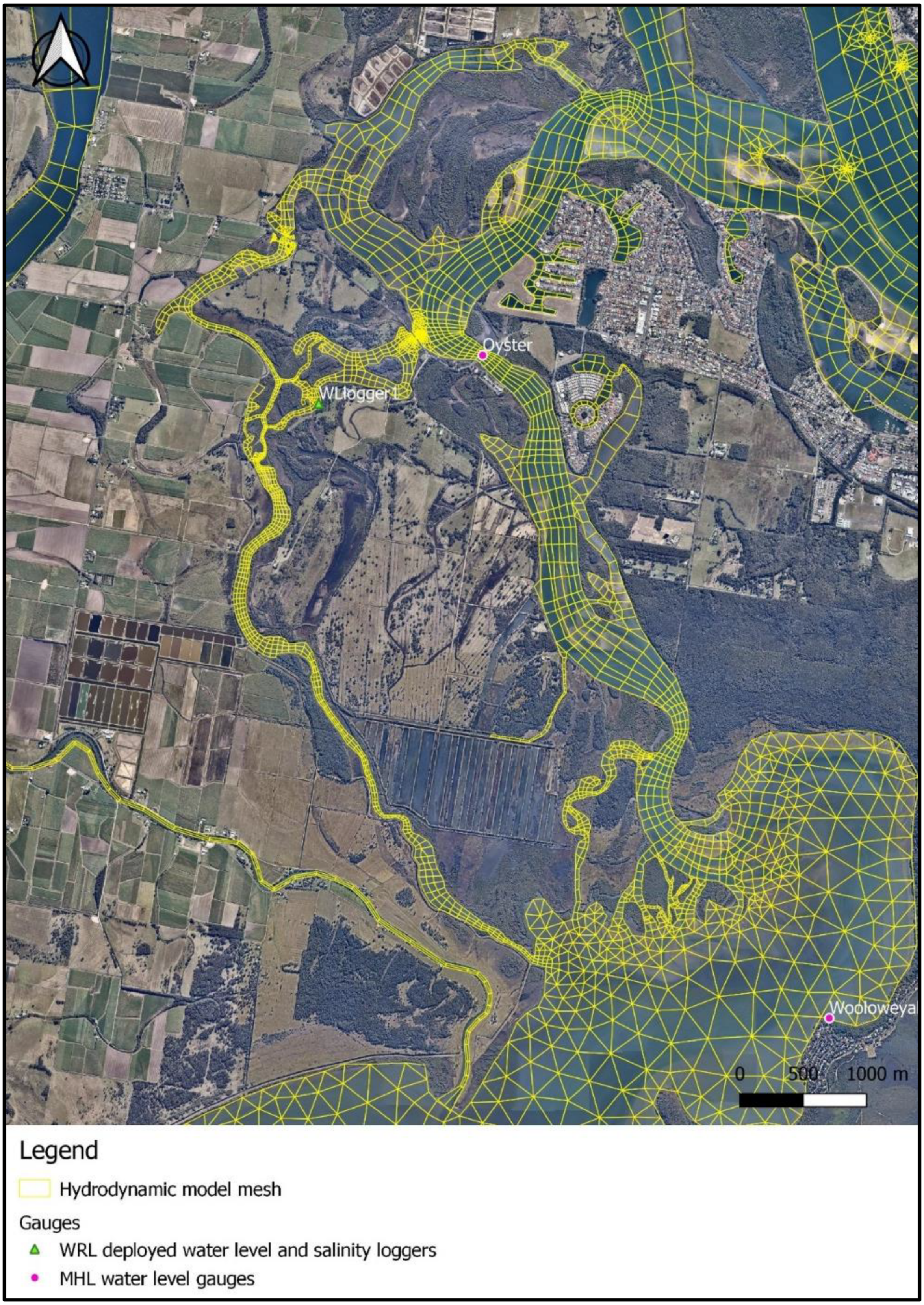

Figure 3. A subset of the hydrodynamic model numerical mesh with water level logger positioning in Lake Wooloweyah.

Using a Monte Carlo Markov chain approach with the inter-annual variability in the landings of prawns, the value per kilogram of prawn product, and the uncertainty in the contributions of the habitats, the direct market value of the Eastern school prawn product arising from the habitats was estimated with 5,000 simulations. This approach accounts for uncertainty within the model outputs rather than solely using mean or other summary statistic (here assumed to be a normal distribution using the SD around the means). In addition, catch data collected through fisher logbook reporting by NSW DPI Fisheries, and market price at first point of sale, were used to determine the value of the fishery and included all Eastern school prawn-specific landing data within the Clarence River estuary (as there is uncertainty about location data in logbook records) from 1978 to 2009, after which data were only available for 2019 and 2020. Logbook records prior to 1978 were available, however, they did not differentiate between prawn species and could also include species that do not draw their nutrition from within the estuary itself, and as a result those data could not be used reliably. To attribute a value that accounts for the rarity of the habitats, the posterior estimates of habitat values for the Lake Wooloweyah Eastern school prawn fishery were then divided by the areal extent (in hectares) of each habitat to obtain a value per hectare per year estimate. Value calculated was total value product (referred to as total economic output in Taylor et al. 2018), which accounts for not just the landed value of prawns for the fishery, but the broader value of these hypothetical landings for the broader economy.

The potential scenario explored was one where the habitat rehabilitation adds value to the fishery based on current per hectare value determined above and adds value to the estuary-wide valuation based on the possible area of each habitat that may be repaired using the hydrological model. Multiple scenarios were explored via the hydrologic model to estimate intertidal vegetation (mangrove/salt marsh/seagrass rehabilitation) outcomes based on inundation regimes. Seagrass habitats were not included in the valuations as the potentially available land for restoration was not sufficiently low enough to promote seagrass habitat if tidal flows were permitted onsite.

Results

Vegetation Linkages

The vegetation elevation modeling, results were grouped into four clusters (Fig. 4). The vertical layering of vegetation follows the attenuating trend of the tidal regime from the mouth of the Clarence River estuary into Lake Wooloweyah. The vertical habitable range decreases dramatically as the tidal range decrease within the lake, especially for mangroves. It is also evident that there is a substantial degree of vertical overlap across the different surveyed vegetation groups, even though points were measured in proximity for the four clusters.

Based on the vertical distribution of surveyed GPS points within each vegetation group per cluster, the vertical habitable ranges for mangroves and salt marsh were inferred. Tidal flats existed below the habitable range of mangroves, and coastal upland forest above the salt marsh range.

The habitable ranges were inferred from the survey point groups as follows:

(1) The mangrove habitable envelope is from the two-fifth percentile of the mangrove downslope points to the median of the mangrove/salt marsh interface.
(2) The habitable range extends as low as the bottom whisker of the mangrove downslope limit, which represents the fifth percentile.
(3) The salt marsh habitable envelope is from the median of the mangrove/salt marsh interface to the median of the salt marsh/coastal upland forest interface. It further extends to the upslope limit (top whisker) of either the salt marsh or the salt marsh/coastal upland forest interface points, whichever is higher.
(4) In the Lake Wooloweyah flood tide delta group, we were not able to survey any salt marsh/upland vegetation interface points. Based on an examination of the DEM and mapped salt marsh areas, and taking into consideration the upslope limit for salt marsh, the upper limit was set as 0.45 m Australian Height Datum.

Modeling indicated that large areas of possibly up to 2,000 ha of currently drained lands around Lake Wooloweyah were hydrologically suitable for creating intertidal salt marsh and mangrove habitats (Table 1).

Fishery–Habitat Linkages From Stable Isotopes

A total of 93 Eastern school prawns were collected from research tows and commercial fisheries and processed for stable isotope values. Stable isotope values of sources of primary production were generally well distributed within the iso-space across the three isotopic tracers (Fig. 5). The exception was for mangroves and salt marsh succulents, which had to be grouped for subsequent analyses to improve model outputs. Sugar cane and FBOM were ^{34}S depleted and distinct from the rest of the primary producers. The δ^{15}N values for Eastern school prawn were very broad suggesting variability in diet choice within the population, however size did not account for this pattern for prawns with size data available (linear model $F_{[1,43]} = 2.29$, $p = 0.13$) and no further corrections were made as a result.

Salt marsh grass *Sporobolus virginicus* had the highest contribution to the diets of Eastern school prawn (52.5 ± 7.9%), followed by POM (21.6 ± 9.7%). The posterior distributions from these two sources were generally broad, indicative of high variability within the Eastern school prawn population. The other sources in the system had generally low contributions (<10%; Fig. 6).

The per hectare gross value product of salt marsh was highest relative to other habitat types (\$2.48 ± 1.03 thousand AUD yr^{-1} ha^{-1}), while mangroves had the lowest value (\$0.29 ± 0.26 thousand AUD yr^{-1} ha^{-1}). The distribution of salt marsh and seagrass values was broad, however, with 75% values close to or above \$4,000 AUD yr^{-1} ha^{-1}. Based on this

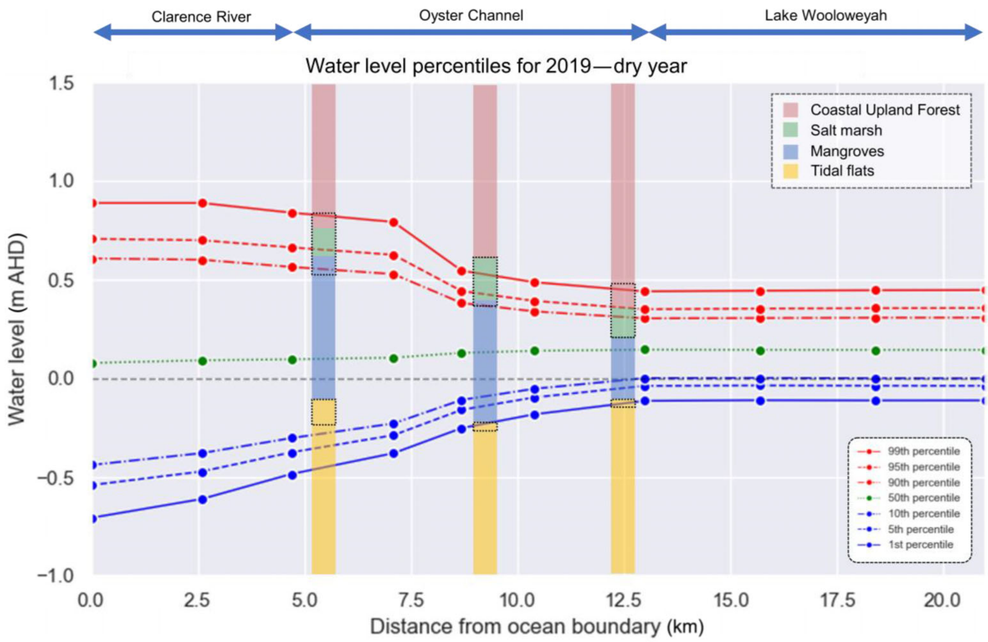

Figure 4. Water level statistics versus intertidal vegetation extent from the Clarence River estuary to upstream locations in Lake Wooloweyah.

analysis, salt marshes are expected to produce approximately 200 kg of Eastern school prawn per hectare per year, approximately twice that of seagrasses (Fig. 7).

Potential Return on Investment

Given the area of estuarine habitat that could be rehabilitated through modifications of hydrological infrastructure, and assuming the mean per hectare value of estuarine habitat remains constant, the projected range of wider benefits to the Eastern school prawn fishery within Lake Wooloweyah is \$3.1 ± 1.3 million AUD/year (Fig. 8).

Discussion

There are substantial fisheries flow-on benefits that could potentially arise from rehabilitating large areas of coastal wetlands. However, as our assessment exclusively examined flow-on benefits to fisheries for one species, it overlooked additional benefits that may arise for other species that occur in the system (e.g. Eastern King Prawn), recreational fisheries, and other intrinsic values. Thus, while the potential benefits of rehabilitation identified within this system are high, they are conservative. The framework provided here allows for practitioners to complete cost–benefit analysis of rehabilitation projects in estuaries where commercial fishing occurs.

Table 1. Summary of low, intermediate, and high range of the modeled estuarine habitat rehabilitation potential in hectares, separated into different hydrological zones within Lake Wooloweyah.

	Rehabilitation option	*Mudflats*	*Mangrove*	*Salt marsh*
Low-end range	Ringdrain west	0	13.1	80.8
	Ringdrain southwest	1.9	51.8	429.1
	Prawnfarm	0	38.9	33.3
	Micalo west	0	7.2	31.9
	Sum	2	111	575.1
Intermediate range	Ringdrain west	0	35	164
	Ringdrain southwest	1.9	141.7	911.7
	Prawnfarm	0	51	31.8
	Micalo west	0	15.8	100.8
	Sum	2	243.6	1208.3
High-end range	Ringdrain west	0	128.6	182.8
	Ringdrain southwest	5.7	672.4	908.5
	Prawnfarm	2.3	75.4	10.6
	Micalo west	0.2	61.2	115.5
	Sum	8.2	937.7	1217.4

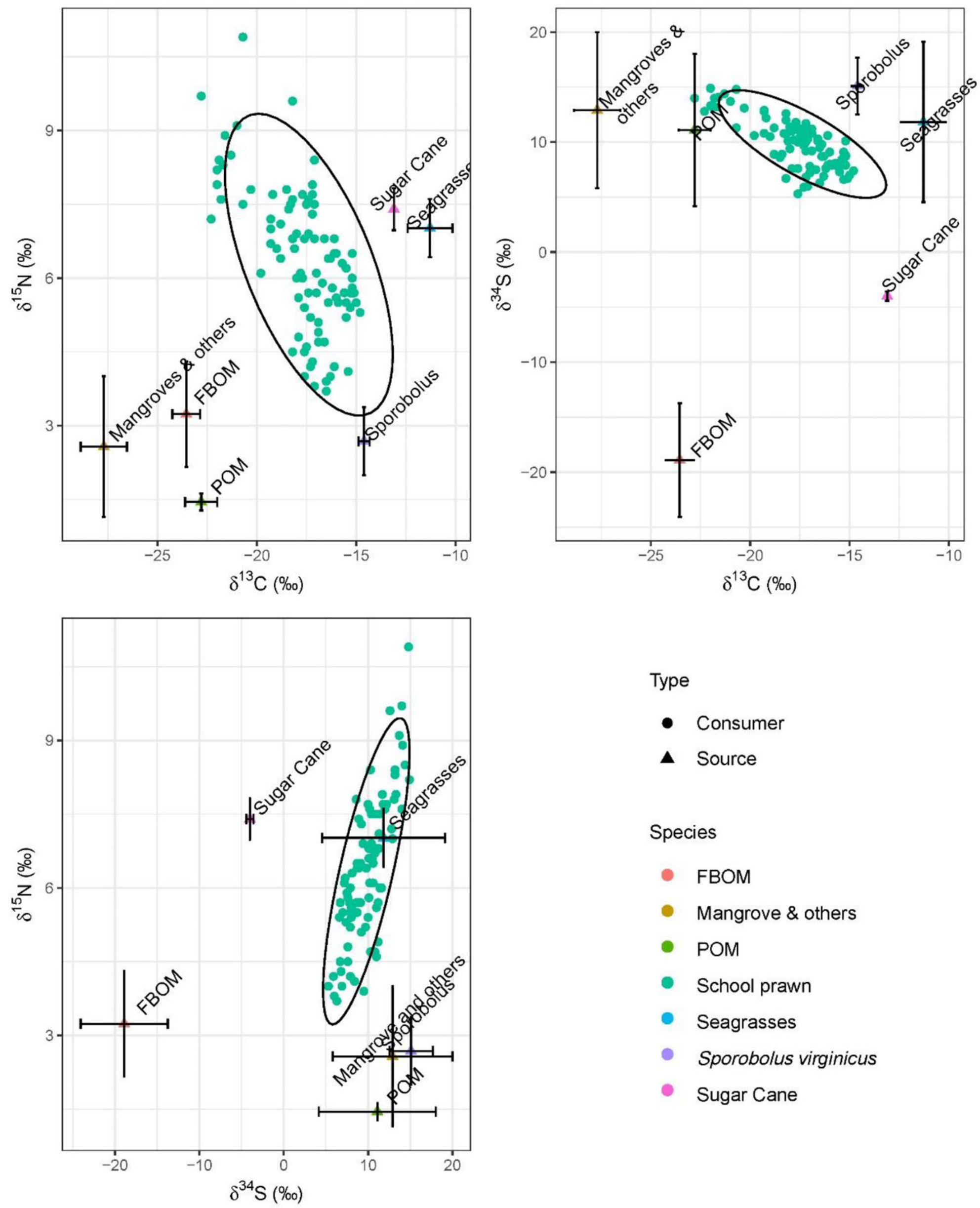

Figure 5. Stable isotope biplots of Eastern school prawn consumers in relation to sources available in Lake Wooloweyah (mean ± SD). Consumer values are not corrected for trophic enrichment, and the 95% ellipse is present to highlight the distribution of the prawn values.

The multidisciplinary approach present herein offers support for potential blue carbon rehabilitation projects (zu Ermgassen et al. 2021), given the likely flow-on benefits that could be recouped. Conversely, this also denotes the scale of the loss occurred from the drainage of these sites via levees and floodgates globally. On the east coast of Australia alone, hundreds of thousands of hectares of coastal land have been reclaimed behind levees and floodgates (Rogers et al. 2022) and instating tidal flushing may result in major economic benefits (Taylor et al. 2018).

The values presented herein exclude many potential sources of additional value that estuarine habitat provide. For example, this valuation excluded other species that are captured in the estuary that would also benefit from additional estuarine habitats (Raoult et al. 2018, 2022), thereby under-estimating the "true" value of the habitats for fisheries. In many ecosystems, recreational fishery benefits are similar in scale to commercial fisheries (Pouso et al. 2020). Further, there is direct value associated with carbon sequestration in tidal wetland habitats which may also be high (Lockwood & Drakeford 2021). However, while these broader social estimates are conservative, there is currently no existing mechanism to link potential economic value of these co-benefits with an economic return for private landholders who would need to forego current land use returns from dairy

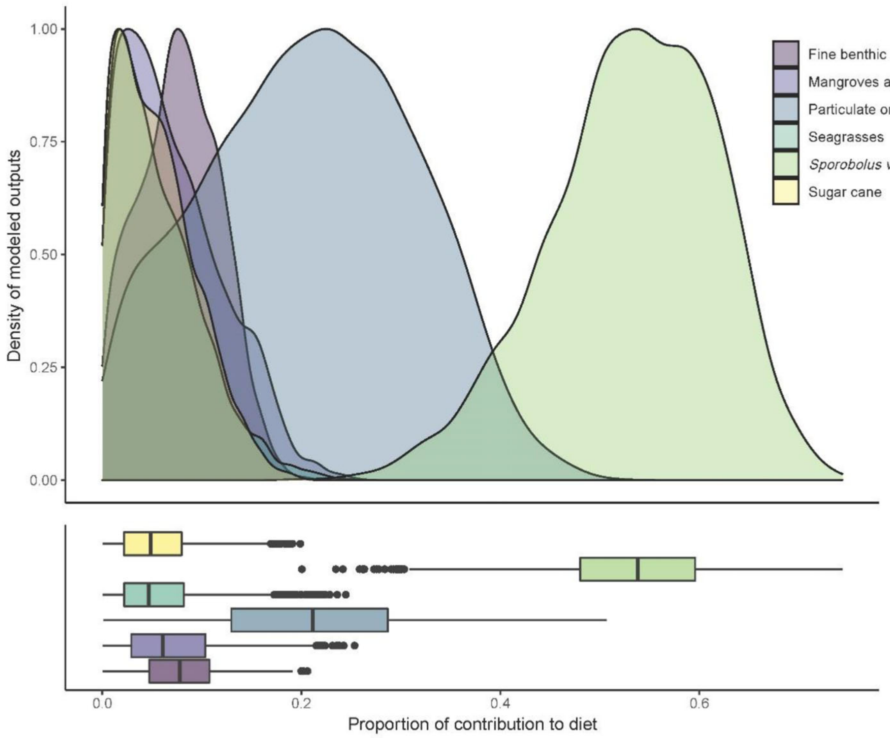

Figure 6. Scaled density distributions of the proportion of contribution of estuarine sources to diets of Eastern school prawn, as estimated from Bayesian stable isotope mixing models. Boxplot below of same distributions for ease of interpretation.

or sugarcane. Given the growing interest on the value of co-benefits in blue carbon ecosystems, mechanisms like Australian Carbon Credit Units for carbon in Australia that would allow land-holders to be recompensed for forgoing land rights should be developed to account for these other restoration values.

The dynamic link between fisheries valuation and hydrodynamic modeling undertaken in this study provides a novel means to integrate physical dynamics with ecological processing. This approach was particularly important as the tidal wave was substantially dampened as it propagated from the river entrance into Lake Wooloweyah. These changes strongly influenced the vegetation, reducing the vertical extent of mangroves by approximately 50%. The use of an integrated isotopic/hydrodynamic approach ensured that the extents of intertidal vegetation and hence, blue carbon restoration trajectories, were accurately modeled. This approach is a substantial improvement on existing geospatial approaches that apply a bucket model (i.e. without hydraulic losses) throughout the estuary (e.g. Cole Ekberg et al. 2017). However, it is worth noting that further research is required to develop causative relationships (vs. correlations) linking tidal dynamics with intertidal vegetation establishment and growth. This would ensure that future predictions of salt marsh and mangroves are accurately predicted in restoration projects or under climate change pressures.

Considerations for Interpretation

It is important to note that the approach taken to valuation here deals strictly with potential benefits derived from provisioning services, essentially assuming a linear increase in Eastern school prawn productivity (and economic impact) alongside an increase in habitat. In reality, diverse and interacting factors may moderate the magnitude of benefits that arise from the habitat repair scenarios evaluated and it is important to consider these alongside the estimates provided here. Species-specific population processes will have a key influence on how the exploitable components of the Eastern school prawn population respond to these enhanced provisioning services. Eastern school prawn populations are inextricably linked with freshwater inflow to estuaries, which influences spawning, recruitment, growth, and broader estuarine health and productivity (Ruello 1977; Glaister 1978). This also influences harvest patterns and harvest distribution between estuarine and inshore components of the fishery (Ives et al. 2013). Thus, the rainfall and freshwater inflow regime is likely to moderate both the population level, and the level of recruits that are available to utilize the enhanced provisioning derived from the habitat repair (as is spawning stock levels; discussed below). Realization of any productivity benefit for Eastern school prawn will also depend on unquantified processes including density dependence, predator–prey dynamics, and concomitant increases in productivity of primary consumer intermediates (such as grazers on salt marsh halophytes), which provide physical trophic linkages between salt marsh and exploitable prawns on which monetary benefits depend. Finally, other extrinsic factors may impact the realization of benefits associated with repair. As an example, at the time this manuscript was being prepared, a biosecurity control order was in place following detection of white spot virus in

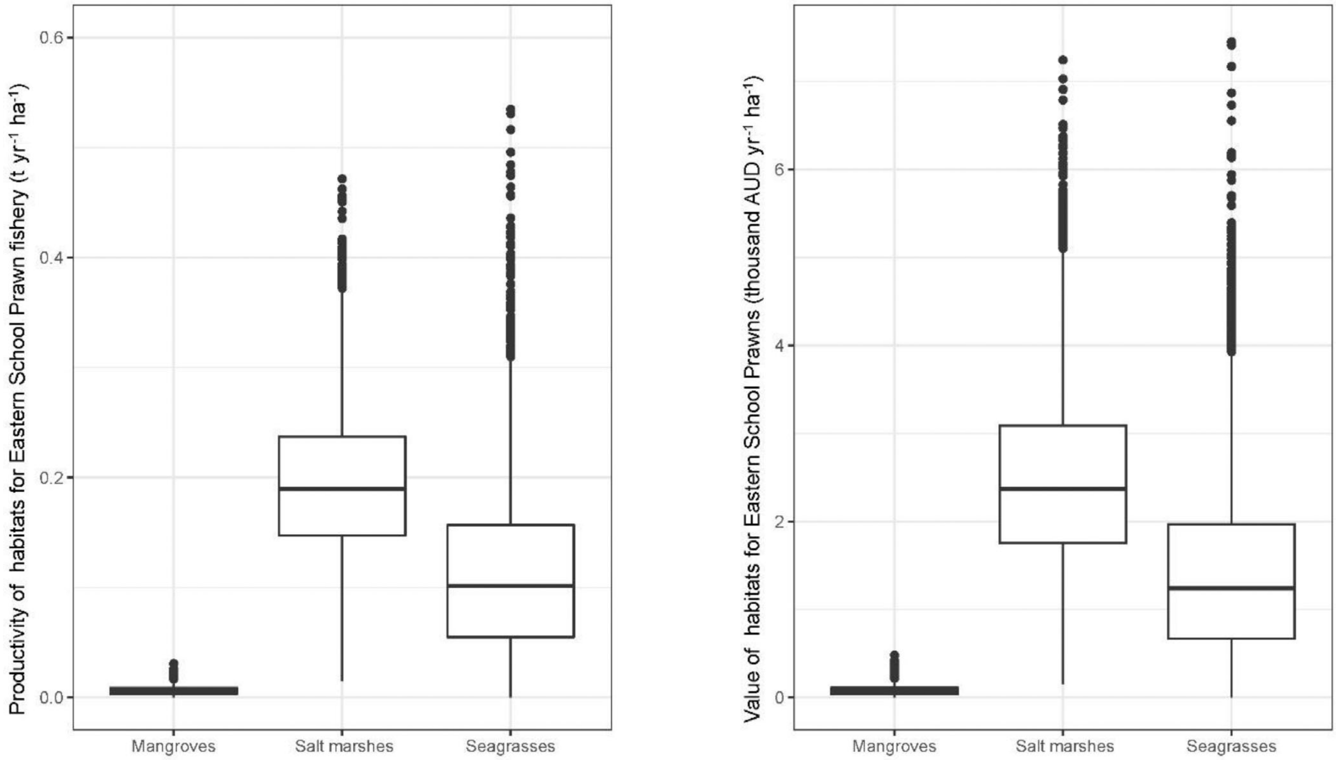

Figure 7. Boxplots of per area gross value product (value of prawns landed by the fishery) of estuarine habitats for the Eastern school prawn fishery (left), and approximate production of Eastern school prawn per area for each habitat type, as inferred from Bayesian stable isotope mixing models and simulations within a Monte-Carlo Markov chain framework. Horizontal bars represent 25, 50, and 75% quantiles for data distribution.

prawn farms adjacent to the Clarence River. This led to restrictions of the movement of uncooked prawns away from the estuary. While cooked prawns can still be shipped for sale, this control order prevents access to the bait market (which requires uncooked prawns), and thus reduces the diversity of market outlets available to on-sell product. Stochastic events such as this will always pose a threat to fully realizing the economic benefits of any habitat repair endeavor, and these uncertainties should be discussed before making decisions to restore a habitat for these purposes.

Recent stock assessments for Eastern school prawn in NSW indicate that the stock is in comparatively good shape, with estimated stock biomass approximating 7,500 t, and a depletion ratio of approximately 0.8 (Taylor 2020). While this suggests that the species has ample spawning stock, it also highlights that there is unrealized scope for increased harvest of the species within the current (pre-restoration) productivity regime. This implies that there are likely to be other fishery or market forces at play that may be constraining fishing effort and harvest rates. Current standardized catch rates (approximately 80 kg_{std}/day) reported in Taylor (2020) for estuary fishing are likely profitable, but anecdotes from fishers indicate that prawns are smaller and slower growing (than they have historically been) in key estuaries, including the Clarence River (Taylor et al. 2019), which may be indicative of other productivity bottlenecks. Diffuse-source agricultural contaminants and catchment-derived stressors have been shown to impact productivity of Eastern school prawn (Taylor & Loneragan 2019), in particular the lethal and sublethal effects of acid sulfate soil by-products (McLuckie et al. 2019, 2021; Russell et al. 2019) and imidacloprid pesticides (McLuckie et al. 2020). In addition, imports of similar product can reduce market opportunities and put chronic downward pressure on prices, negatively impacted profitability. Adding additional product into a crowded market may further exacerbate this; however, expansion of sustainably caught Eastern school prawn into niche domestic export markets may be possible.

As a final point, the estimates also assume complete replacement of most of the restored area with Salt couch (*Sporobolus virginicus*), which was the source with the greatest contribution to the diet of school prawn. In reality, the recolonized salt marsh assemblage could include a diversity of salt marsh halophytes (Rankin et al. 2022), some of which may not have a significant trophic link to Eastern school prawn, or the restored area may experience incomplete revegetation. This would also affect the magnitude of monetary benefits derived from habitat repair.

Notwithstanding the considerations outlined above, it is important to point out that the area of salt marsh that could be restored under this scenario is considerable when compared to the current overall areal coverage of salt marsh within NSW (approximately 6,552 ha), so benefits of the magnitude reported are certainly plausible. By way of a simplistic validation, take

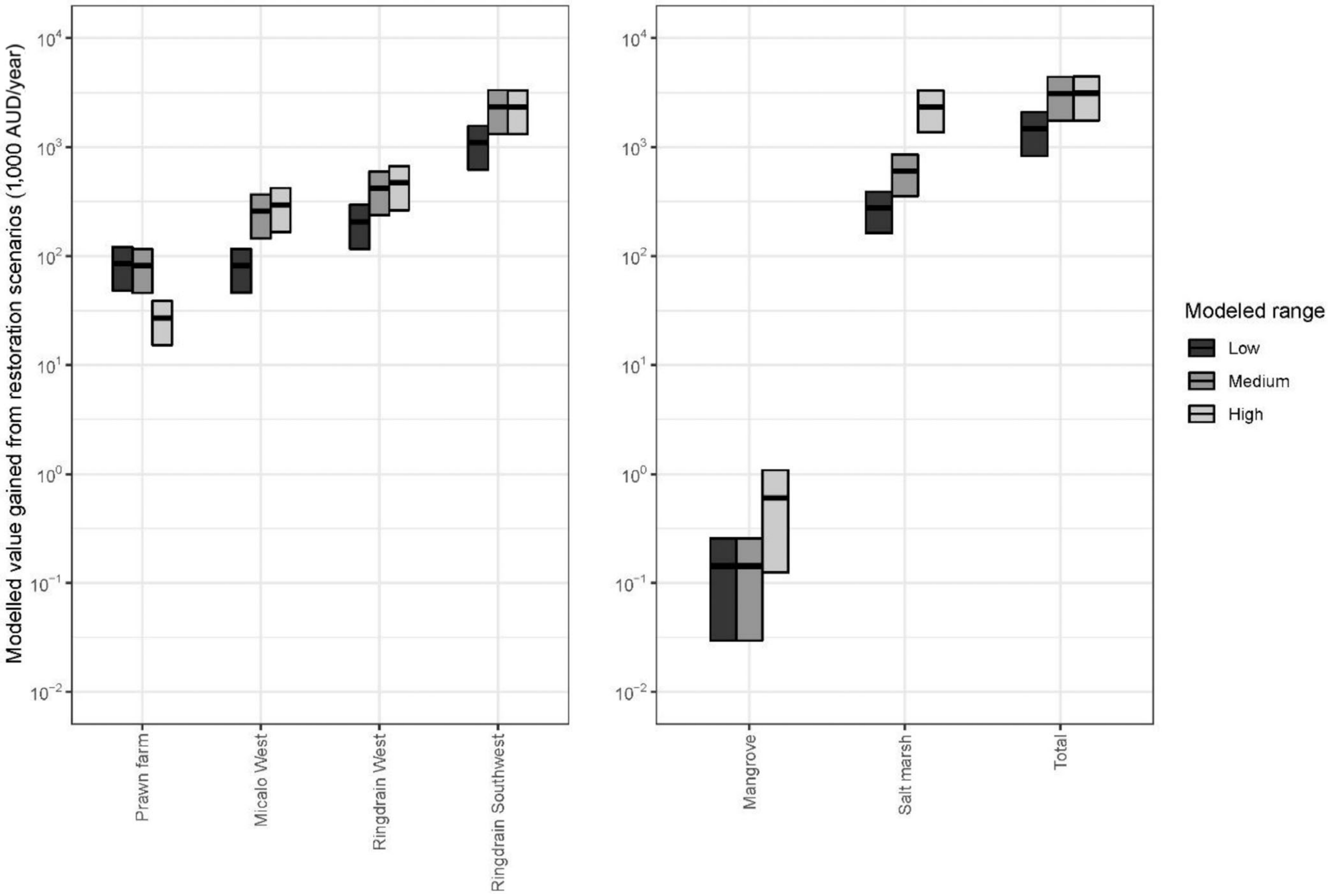

Figure 8. Potential flow-on value of landed Eastern school prawn (mean ± SD) that could arise from the restoration of blue carbon ecosystem designated areas in Lake Wooloweyah, separated by low, medium, and high range rehabilitation scenarios, and by habitat.

for example the recent (2015–2022) state-wide productivity of the Eastern school prawn stock within NSW (approximately 700 t/year) which is supported by the 6,552 ha of salt marsh—this equates to $10^{2.1}$ kg/year of prawns for each hectare of salt marsh. The benefits estimated here for Clarence River for the salt marsh gained following habitat repair—$10^{2.3}$ kg ha^{-1} yr^{-1}—at least roughly equates to this ratio of Eastern school prawn and salt marsh across NSW under current conditions.

Stable Isotope Methods

While stable isotopes have been used increasingly to value estuarine habitats using habitat-fishery approaches (Taylor et al. 2018; Jänes et al. 2022; Raoult et al. 2022), there are still uncertainties when using this method. The inclusion of sulfur isotopes in addition to carbon and nitrogen provides a greater level of certainty about model outputs (as discussed in Hewitt et al. 2020; Raoult et al. 2022), but some sources from different habitats still needed to be grouped. For example, salt marsh succulents and mangroves did not have stable isotope values that were distinguishable. This leads to uncertainty about which source is driving the contribution to diet, or whether the contributions of each source are even (as was assumed here). In this study, however, the contributions of those mixed sources were relatively low compared to the dominant sources (POM and *S. virginincus*) and this is unlikely to have had a significant effect on the valuation.

One consideration that could affect model outputs is the amount of detrital matter, which may be an aggregate of various primary producers, that is consumed by Eastern school prawns. Decomposition progressively changes the stable isotope values of detritus for δ^{15}N and δ^{13}C (Kelleway et al. 2022), and this species of prawn does present with relatively large (approximately 50%) amounts of detrital matter in their digestive system (Ruello 1973). However, decomposition effects are minor relative to the isoscape positions of the major sources in this system (approximately 2‰ compared to values of −28 and −14‰ for mangroves and seagrasses, respectively), and detrital matter is likely to be a mix of fresh and partially decayed plant matter. As stable isotope values reflect mass fractionation, a mix of fresh and decomposed plant matter would have intermediate stable isotope values that would reduce the effect of decomposition. Finally, reliance on gut contents alone may be deceptive because they do not reflect nutrients that animals actually absorb (Brush et al. 2012), and this species of prawn also consumes crustaceans, bivalves, and annelid worms (Ruello 1973) that are more likely to be absorbed. These patterns suggest that, while decomposition effects on detrital matter could have affected model outputs, they are unlikely to significantly change the conclusions of the trophic pathways.

Another source of uncertainty with a stable isotope approach is the diet-tissue differentiation factors used to correct for enrichment between consumer and source. Incorrect selection of this value can lead to bias (Swan et al. 2020). Typically, these factors are selected based on species relatedness, as they can only be assessed accurately through long-term captive experiments; however more recent studies and meta-analyses have identified that diet type is a more powerful determinant of appropriate tissue differentiation factors (Britton & Busst 2018; Canseco et al. 2021). As such, we used a value from freshwater shrimp fed an omnivorous diet likely to resemble natural diets (Viozzi et al. 2021) rather than a species-specific value using protein-rich diets (Hewitt et al. 2021). The fact that corrected consumer values were mostly within the bounds of the iso-scape suggests that it was appropriately selected (Smith et al. 2013). However, the range of $\delta^{15}N$ values for the prawn consumers was broad (approximately 6‰), suggesting that the sampled population fed on multiple trophic levels. This was not driven by prawn size (usually ontogenetic growth drives an increase in trophic level), and so could not be corrected within this framework. Future studies attempting to replicate this approach should take care when identifying trophic discrimination factors, or removing $\delta^{15}N$ values from analyses, as they are more prone to anthropogenic pollution and greater uncertainty within this discrimination factors in comparison to sulfur and carbon isotopes.

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