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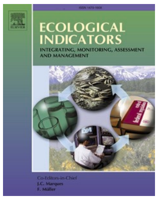

Seagrass valuation from fish abundance, biomass and recreational catch

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ABSTRACT

The value of critical habitats, such as seagrass, to act as a nursery varies spatially and temporally; however, such information is essential for the public and stakeholders to appropriately value and manage these habitats. We use an existing systematic long-term fisheries dataset in Port Phillip Bay to examine variability in nursery habitat value for an important commercial and recreational species, King George Whiting (*Sillaginodes punctatus*). Port Phillip Bay represents one of the most important marine assets in the southern hemisphere and is surrounded by the second-largest city in Australia, Melbourne, home to 4.5 million people. We modelled the abundance of King George whiting as a function of environmental variables, using Boosted Regression Trees (BRT). Fish densities ranged from 1,000 to 30,000 individuals $ha^{-1}y^{-1}$, equalling an adult biomass of 110–3,300 kg $ha^{-1}y^{-1}$. This production supports between 69 and 2,062 recreational fishing trips a year, with an estimated value of seagrass of AUD 687–20,625 $ha^{-1}y^{-1}$. Based on biomass production of King George Whiting and recreational fisheries data, the 6662 ha of seagrass in Port Phillip Bay are valued at around AUD 36 million annually.

1. Introduction

Marine fisheries play a key role in global food security, supporting coastal communities' socio-economic well-being through recreational and commercial fishing and associated industries. The ecosystems that support fisheries production are fundamental for maintaining these contributions to societal well-being (Jennings et al., 2016; Mcclanahan et al., 2015). While it is understood that coastal ecosystems such as seagrass are vital to fisheries through habitat provision and food supply, the global distribution of these productive ecosystems continues to decline (Orth et al., 2006). To better understand the value of seagrass ecosystems to society, it is essential to estimate how seagrass meadows link to fisheries values and spatial variability in seagrass habitats' contribution to fisheries production (Sheaves, 2017).

The analysis of the provision of ecosystem services from a spatially explicit perspective has been essential to further our knowledge about the relationships between ecosystem services and human use (Roces-díaz et al., 2015). Ecosystem services, like fisheries production, are underpinned by various ecological processes such as habitat and food provision that are scale-dependent. Knowing variation in ecosystem service production at scales of interest to resource managers can help allocate resources and aid management practices – from regional to global perspectives (Lindborg et al., 2017). Before this study, most of the research on fisheries valuations was done at much larger scales, resulting in overlooking scale-dependent processes, potentially hindering fine-scale conservation decisions (Cole and Moksnes, 2016).

There has been a long history of fisheries ecology on the spatial and temporal variability of fish in various ecosystems, often detected by applying simple sampling techniques (e.g. netting surveys) that capture the community composition of fishes associated with seagrass beds

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(Jenkins et al., 1997). These data can reveal differences in fish diversity and richness patterns between coastal ecosystems (Jenkins et al., 2000) and detect essential nursery areas for fish production (Nel et al., 2018). As a result, these studies show that aquatic habitats are highly variable in their importance to fish production. Many fish species use seagrass beds for better access to food (Horinouchi et al., 2012) and as a refuge from predation (Hindell et al., 2000). Fish abundance estimates can be used to establish a direct linkage between coastal ecosystems and fish production. They can be used to model fish biomass that in turn could be linked to catch or market values of economically important fish species (Jänes et al., 2020b).

King George Whiting (*Sillaginodes punctatus*, Cuvier 1829) is of high commercial and recreational importance in southern Australia (Kent et al., 2018). King George Whiting is a temperate, demersal fish with a complex life-cycle. Adults reside and spawn in coastal waters; after a long oceanic larval phase (80–100 days) small post-larval juveniles (approximately 20 mm standard length) appear in sheltered seagrass beds in bays and estuaries. These juveniles then reside here for 3–4 years before emigrating back to coastal waters, where they may live up to 18 years of age (Jenkins et al., 2000). Inter-annual variation of post-larval numbers in seagrass beds is high and is the primary influence on variation in fishery catches focused on 2–4-year-old sub-adults (Hindell and Jenkins, 2005). The obligatory dependence of this species on seagrass in the juvenile stages means it is vital to understand which seagrass areas are most resourceful so that the benefits of conservation and management efforts can be maximised.

This study analyses two systematic long-term fisheries datasets to provide useful insights about spatial variations of seagrass in relation to King George whiting production (Dodds et al., 2012). Over the past two decades, the Victorian Fisheries Authority (VFA) has monitored juvenile King George whiting abundance with standardized netting methodology resulting in a long-term dataset from eight locations within Port Phillip Bay, Victoria, Australia. The VFA has an extensive recreational fisheries survey dataset that provides data on recreational catch rates that can be applied to estimating seagrass's nursery value to this fishery. Using the iconic King George Whiting as the focal species in a case study, we aimed to value seagrass nursery properties to fish production by; **(a)** quantifying the variability in juvenile abundance on seagrass beds (ha^{-1} y^{-1}) and associated environmental drivers of this variability **(b)** modelling adult fish biomass from juvenile abundances (kg^{-1} ha^{-1} y^{-1}) **(c)** using recreational fishing data to estimate the value of this adult fish biomass in terms of recreational fishing value and **(d)** develop spatially explicit maps of these results across the entire Port Phillip Bay. Doing so may enable conservation and fishery decision-makers to improve this species' management through more targeted habitat protection and restoration of the most important seagrass beds (Magurran et al., 2010).

2. Methods

2.1. Study site

Port Phillip Bay is a large, semi-enclosed marine embayment linked to the Southern Ocean (Bass Strait) by a narrow entrance (Fig. 1). Tides throughout Port Phillip Bay are semidiurnal with a range of around 1 m, with occasional winter storms and low-pressure systems increasing tidal range. An entrance region can characterise the hydrodynamics. In this sizeable flood-tidal delta, strong currents occur in the major channels and an 'inner' zone, where tidal currents are weak (Black et al., 1993). Seagrass in Port Phillip Bay generally consists of narrow bands and patches of the subtidal seagrass *Zostera nigracaulis*. Seagrass beds become more widespread towards Corio and Grand Scenic, due to protection from the predominant south-westerly winds experienced in the region (Fig. 1). This pattern reflects the distribution of sediment grain size that becomes progressively finer around the Bellarine Peninsula and west and north of the Bay.

2.2. Fish sampling

Juvenile King George Whiting (approximately 20–30 mm in length) were sampled annually (2003–2014) on seagrass beds at 8 locations by VFA once a month in two consecutive months (Oct – Nov). The total number of fishes caught throughout the study period was 12,011. Fish were sampled by hauling a 10 m seine net by hand (2 mm mesh size, 2 m drop) for a distance of 10 m across the seagrass bed in a depth 0.5–1.0 m.

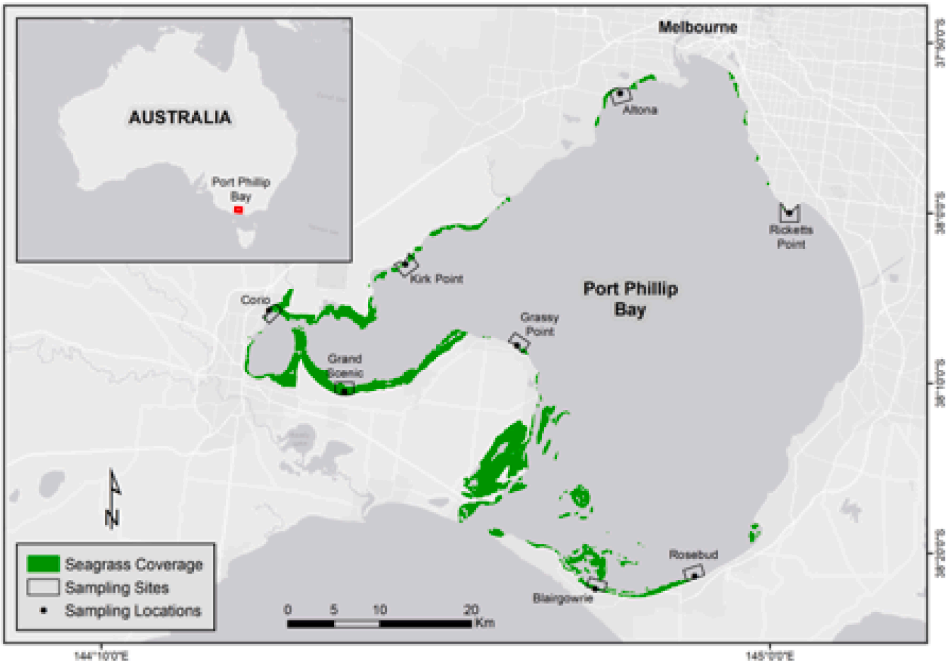


Fig. 1. The eight sampling locations, together with seagrass coverage in Port Phillip Bay with a 1 km buffer surrounding each site. The buffer was added to better capture the potential effect of the extent of seagrass to fish densities at each sampling location. The buffer has been clipped to the shoreline, so the area varies but is 1 km in each direction where there is water. Seagrass data layer for Port Phillip Bay was downloaded from seamapaustralia.org (Lucieer et al., 2019).

Four replicate hauls were made on each sampling event at each site with an estimated sampling efficiency of the net around 20–83% (Jenkins and Sutherland, 1997; Rozas and Minello, 1997). The total estimated area per individual haul is approximately 75 m^2 because, when hauling, the net gradually closes together.

Juvenile fish abundances were standardized to represent average abundances (ha^{-1}) at each sampling location each year with the following calculation:

$$a_{hal} = \left(\frac{a_l}{75m^2perhaul*4replcations*2months}\right)*10,000 \tag{1}$$

Equation 1: Where $a_{ha\,l}$ is the average per hectare fish abundance at each sampling station each year and a_l is the sum of King George Whiting from 4 individual hauls at each location l each year.

2.3. Environmental variables and modelling juvenile King George Whiting abundance

Over the past three decades, several environmental variables have been identified to affect juvenile King George Whiting dispersal and local abundance in Port Phillip Bay. Studies have recognised the importance of sea surface temperature affecting larval growth while dispersing in coastal waters (Jenkins and King, 2006); wave action causing physical disturbance and structuring fish assemblages (Moran et al., 2003); current velocity and winds (Jenkins et al., 2000) and the presence/location of seagrass beds (Ford et al., 2010). These various influences are thought to contribute to variation in larval transport; and ultimately settlement rates into the Bay's seagrass beds (Jenkins et al., 1996). Despite the significant contribution of these studies to our understanding of the environmental and ecological interactions influencing the dynamics of King George whiting, they are limited to short study periods (typically < 2 years) and have not been analysed under a unified modelling framework. In addition to these environmental variables, it is reasonable to assume that other biological and anthropogenic factors, in combination with those mentioned above, could affect fish densities on seagrass beds (see Fig. 2 for conceptual illustration). However, we were unable to assess in this modelling exercise due to data constraints.

Given other research on the role of vegetated coastal ecosystems and fisheries, we also aimed to include seagrass extent as a possible explanatory variable in the modelling. Seagrass extent at each location was estimated within a 1 km buffer zone/box surrounding the sampling station. This spatial resolution was chosen as it provides a relevant and easily relatable measure for ecologists and resource managers. Average October-November values of sea surface temperature were sourced from the Integrated Marine Observing System over the period of surveys (IMOS, 2017). Hydrodynamic parameters, including current speeds and wave orbital velocity for each month when fish sampling took place, were extracted from a coupled hydrodynamic and spectral wave model downscaled for the region (Ierodiaconou et al., 2018). All variables used to predict fish abundances were selected based on their known importance to affect larval transport and data accessibility. All environmental variables are listed in Table 1, and Fig. 2 provides a conceptual overview of other potential factors contributing to larval transport not addressed in this manuscript.

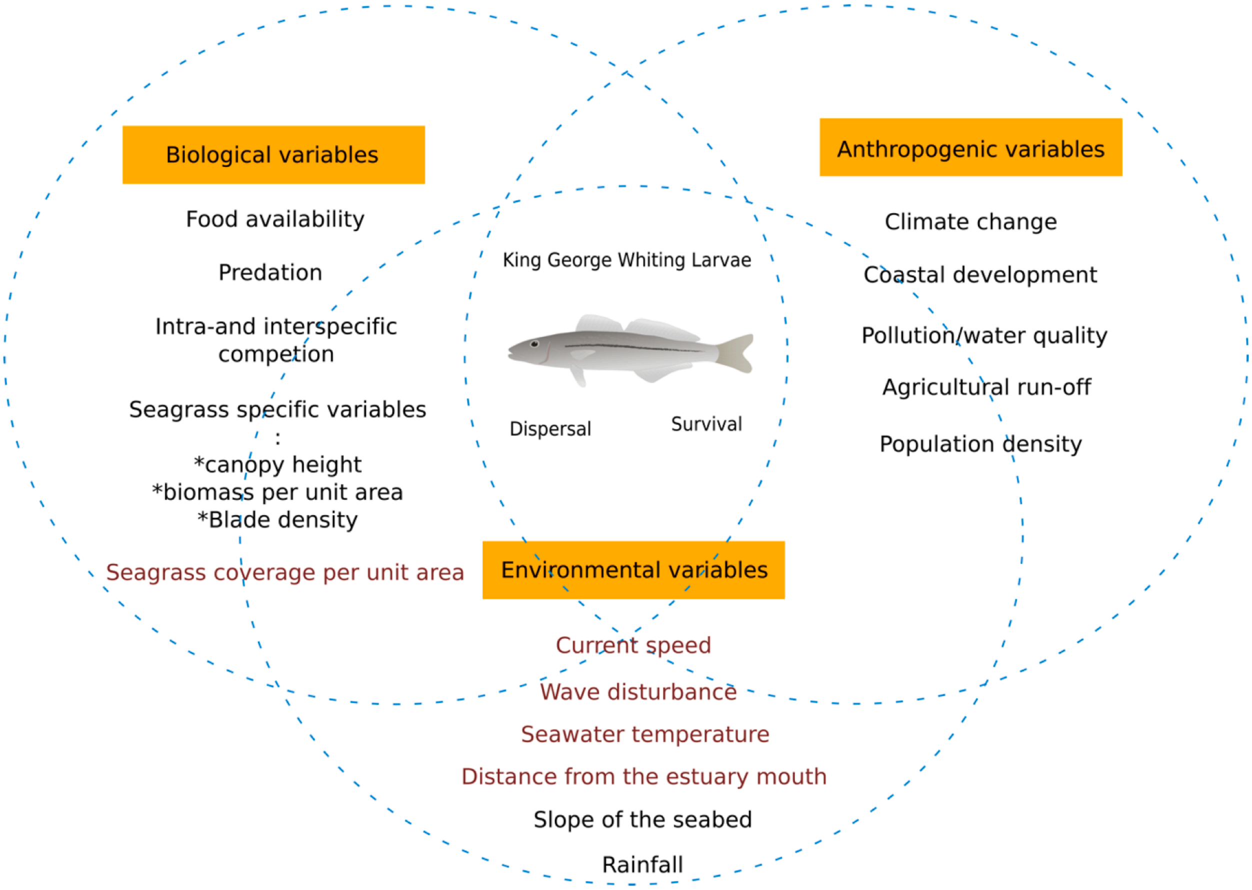


Fig. 2. Conceptual illustration of key biological, anthropogenic and environmental variables likely to affect fish densities on seagrass beds. Variables marked in red were used to explain differences in King George Whiting abundances on seagrass beds in 8 sampling stations in Port Phillip Bay and predict fish abundances across the whole seagrass cover within the Bay. Three dotted circles represent biological, environmental and anthropogenic variables that overlap and interact with one another.

Table 1
Environmental variables used to explain differences in fish abundances on seagrass beds in Port Phillip Bay.

Predictor	Justification for inclusion	Measurement	References
Sea surface temperature	Influences growth rate	Average temperature during the sampling period	(Jenkins and King, 2006)
Wave orbital velocity	An indicator for disturbance	Average wave velocity	(Moran et al., 2003)
Current velocity	Indicator for dispersal potential	Average current speed	(Jenkins et al., 2000)
Distance from the estuary mouth	Habitat variability	Sampling location distance from the estuary mouth	(Jenkins et al., 1996)
Seagrass cover per unit area	An indicator of habitat availability	Total seagrass area within 1 km^2 buffer zone	(Ford et al., 2010)

2.4. *Boosted Regression trees*

The associations between environmental variables and King George Whiting abundance at 8 locations in Port Phillip Bay were explored using Boosted Regression Trees (BRT), which combine machine learning with statistical modelling approaches. BRT models with properly tuned parameters can handle different types of independent variables, and the predictive performance of the model is superior compared to traditional statistical methods and even to deep learning (Elith et al., 2008). BRT iteratively develops a large ensemble of small regression trees constructed from random subsets of the data. Each successive tree predicts the residuals from the previous tree, thus gradually boosting the overall model's predictive performance (Elith et al., 2008).

In this study, BRT modelling was applied to assess the importance of environmental variables (Table 1) for explaining differences in fish abundance from 2003 to 2014 across the eight sampling locations. A random 70% of the data were assigned for training the model, 15% for testing and 15% for validating the model. BRT modelling was done in R using the gbm package (Elith et al., 2008). When fitting a BRT, the learning rate was set at 0.01 and tree complexity at 5. The learning rate determines each successive tree's contribution to the final model as it proceeds through the iterations. The tree complexity fixes whether only main effects (tree complexity = 1) or interactions are also included (tree complexity greater than 1). The learning rate and tree complexity combined determine the total number of trees in the final model. To avoid commonly occurring problems with overfitting the model, early stopping, a cross-validation technique was applied to determine the optimal number of trees (80) resulting in the best performing model. Mean square error (MSE) – a commonly used statistic to assess BRT model performance was preferred over root mean square error (RMSE) as it can better handle larger deviations in the dependent variable (i.e. fish abundances). The resulting best model was then used to predict fish densities across the region where seagrass beds occur based on the associations between fish density and the environmental variables. Site-specific fish abundances and environmental variables can be found in the supplementary materials (Figures S1 and S2).

2.5. *Biomass modelling*

Total average annual King George Whiting biomass production (kg ha^{-1} y^{-1}) supported by the seagrass ecosystems at each sampling station and across Port Phillip Bay was determined by the following methodology developed by Peterson et al. (2003) and revised by Zu Ermgassen et al. (2016). The methodology estimates the total potential average annual biomass production of fish, i.e. the increased biomass of all fish added to the environment by seagrass ecosystems. We consider species-specific natural mortalities and the age of the first harvest. The following equation calculates the proportion of individuals in age class 0.5 surviving to age class *i*.

$$y = e^{-Mi} \tag{2}$$

Equation 2: Where *y* is the proportion of fish population surviving to age class *i* and *M* is the species-specific natural mortality, thus, for each age class, the biomass enhancement (kg ha^{-1}) was calculated by:

$$B_i = B_{0.5} \times e^{(-M\times(i-0.5))} \tag{3}$$

Equation 3: Where Bi is the biomass enhancement for age class i, and B0.5 is equal to the juvenile fish abundances. For each age class, the average fish's length was calculated using Lorenzen (2000) growth equation and the average weight was estimated using length-weight relationships. The total average annual biomass enhancement (kg ha^{-1}) of species was calculated by summing the incremental increase in weight for an average fish in each year class by the number/density (ha^{-1}) of fish (B_i) in each age class. All biomass predictions represent theoretical stock production after the first age of harvest (r $> =$ 3), meaning individuals older than three years. Overall, we estimate the total potential annual biomass production of all adult fish added to the system through the existing seagrass habitat without making assumptions about the fishing community's response. Table 2 provides an overview of the parameters used for biomass modelling.

Here, we assigned all biomass predictions based on enhancement contribution which does not account for fish movement patterns or residency time between seagrass locations. By doing so, we are likely undervaluing seagrass contribution to King George Whiting production and should therefore view the results as conservative.

2.6. *Economic valuation*

Biomass production (kg ha^{-1} y^{-1}) of King George Whiting supported by seagrass ecosystems in Port Phillip Bay was valued using a combination of long-term recreational fisheries survey data and the estimated value of each recreational fishing trip. To convert the biomass production estimated from the biomass modelling described above into the recreational fishery value, we: 1) calculate the average number of King George Whiting harvested per fishing trip and the biomass of these fish; 2) utilise estimates of the value of a recreational fishing trip; 3) combine these to calculate the number of recreational fishing trips per annum that each seagrass area can support based on the produced adult fish biomass and the resulting recreational value.

The recreational fisheries survey data were collected from 1998 to 2016 (n = 31,451) by Victorian Fisheries Authority. This dataset indicates that on average, 14.5% of recreational fishers target King George Whiting during their fishing trips in Port Phillip Bay with an average catch per unit effort of 6.44 (SD = 10) King George Whitlings per trip, which is well below the legal bag limit of 20 fish per person per trip (VFA, 2021). Based on length-weight relationships, minimum harvestable biomass of legal size (27 cm) King George Whiting can be estimated to be around 250 g (Smallwood, Tate and Ryan, 2018). Thus, on average, 1.61 kg of King George Whiting could be caught per average

Table 2
King George Whiting life-history parameters used for biomass modelling were derived from www.fishbase.org.

Species	*Sillaginodes punctatus*
Common name	*King George Whiting*
Max age	*15*
M (Natural mortality)	*0.74*
L ∞ (asymptotic max. length)	*53.2*
K (Brody growth coefficient)	*0.47*
t0 (age at 0 length)	*−0.3*
a	0.00296
b	3.2
r (age of first harvest)	3

fishing trip, assuming all fish are kept. Catch and release is a common practice by recreational fishers; however, it is reasonable to assume that no one releases legal-size King George Whiting due to their high eating qualities.

Utilising a choice-modelling approach, Huang et al. (2020) valued the seagrass contribution to boat-based recreational fishing across Port Phillip Bay and Western Port Bay. Huang et al. (2020) analysed the degree to which seagrass extent increases recreational fishing catch and then linked this recreational catch model with a choice model to quantify the welfare gains of the current extent of seagrass to the cost (their time in travelling and petrol costs to travel there). In this sense, it is not the direct cost of fishing, but more an estimate of how much people must value a location to spend their time to travel there. The average boat-based recreational fishing trip in Port Phillip Bay was valued at AUD 10, excluding boat purchase.

By knowing how much harvestable fish biomass a hectare of seagrass can produce, the average catch of King George Whiting (1.61 kg) per fishing trip and how much an average adult spends per fishing trip (AUD 10), we can estimate a theoretical seagrass value based on the total number of King George Whiting fishing trips a hectare of seagrass can support. This provides an estimated value for the seagrass ecosystems based on the additional biomass of fish theoretically available to the fishery per unit area of the coastal ecosystem and not what is caught. All calculated market values reflect 2019 standards. We used recreational fishing data to value seagrass in Port Phillip Bay due to the closure of commercial net fishing (the primary commercial target method) in the Bay, which was a strategic governmental plan to manage fish stocks and further promote recreational fishing opportunities.

2.7. Statistical analysis

Data cleaning and merging of databases for the fish abundance and economic value analysis were carried out with tidyverse package in R (Wickham, 2017), whereas fish biomass was modelled in C++. BRT modelling was done with the gbm package in R (Greenwell et al., 2020). All R and C++ code used to carry out the analysis is available on request.

3. Results

3.1. Abundance and biomass per sampling location

Throughout the study period, fish abundances and biomass on seagrass beds varied notably among sampling locations. The highest median values originated from Rosebud (4,050 individuals = 432 kg^{-1} ha^{-1} y^{-1}) and lowest in Ricketts Point (450 individuals ha^{-1} y^{-1} = 51 kg^{-1} ha^{-1} y^{-1}) (Fig. 3).

3.2. Environmental variables

Juvenile fish abundances from individual sampling locations were combined with environmental variables and analysed with Boosted Regression Trees (BRT) modelling as fish abundances underpin biomass and dollar value estimates. BRT output shows that the three most important variables with a combined relative contribution explaining around 80% of model variability were average current speed (32%), wave orbital velocity (26.4%) and monthly average sea surface temperature at the time of sampling (21.5%) (Fig. 4). Seagrass extent within the sampling station explained 16% and distance to estuary mouth 5% (Fig. 3). Distance to the estuary mouth and sampling month had both marginal (<5%) effects on the model's explanatory output (Fig. 4). Partial dependence plots, which represent the relationship between the variables and the fitted function from the BRT, are displayed in Fig. 5. Partial dependence plots give an indication of how fish abundances change when the predictor variable values increase. Cross-validation suggested 80 to be an optimal number of trees for early-stopping to avoid overfitting of the model.

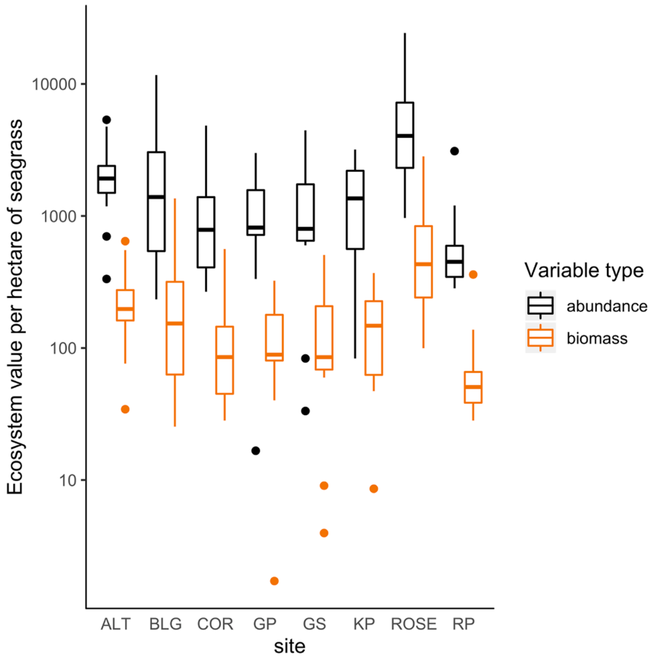


Fig. 3. Annual per hectare abundance and biomass (kg) values of seagrass ecosystems to King George Whiting production in 8 individual sampling locations in Port Phillip Bay (2003–2014). Altona – ALT; Blairgowrie – BLG; Corio – COR; Grassy Point – GP; Grand Scenic – GS; Kirk Point – KP; Rosebud – ROSE; Rickets Point - RP. The solid line in the middle of the box represents the median, and the box itself represents the interquartile range (IQR) which shows where 50% of the data is distributed. The lower and upper boundaries of the box represent the 25th and 75th percentile.

The environmental predictors from the BRT model output show how to carry out a small-scale prediction of fish densities and prediction to areas sampled in the empirical studies (Fig. 6).

These data show 80.6% (5,370 ha) of the total seagrass area (6662 ha) within Port Phillip Bay on average supports 1,000 – 10,000 fish per hectare per year (ha^{-1} y^{-1}), but with some areas supporting over 30,000 fish ha^{-1} y^{-1}. Seagrass meadows as nursery grounds result in an additional biomass of 110 – 1,080 kg^{-1} ha^{-1} y^{-1}, or over 3,300 kg^{-1} ha^{-1} y^{-1} in the high-density locations. At least 7.2% of the total seagrass area in the Bay can produce more than 3,300 kg^{-1} ha^{-1} y^{-1}.

On average, hectare of seagrass supports 69 – 865 fishing trips per year, resulting in a recreational value of seagrass of AUD 887 – 6,750 ha^{-1} y^{-1} (Fig. 6). Based on biomass production and recreational fisheries data, the 6662 ha of seagrass have an estimated recreational fishing value of AUD 36.782 million annually.

4. Discussion

In this study, we utilized an existing systematic long-term fisheries-seagrass dataset to model the spatial variation of seagrass value within Port Phillip Bay originating from King George Whiting production – a key fisheries species in a region with almost 1 million recreational fishers (VFA and BBV, 2020). We used fish abundances and biomass patterns in seagrass contributions from machine learning to estimate fisheries production and used these data to provide the basis for fine-scale estimates of the economic value of seagrass ecosystems. The majority of seagrass in the Bay (80.6% = 5369 ha^{-1}) yielded 110 – 1,080 kg harvestable biomass of King George Whiting per hectare per year with a recreational value of AUD 678 – 6,750. Based on fish biomass production and recreational values, overall, 6662 ha of seagrass across the Bay here is estimated to be worth $36.782 million annually.

The three most important predictor variables explaining 80% of the BRT output of the spatial patterns of fish abundances on seagrass beds

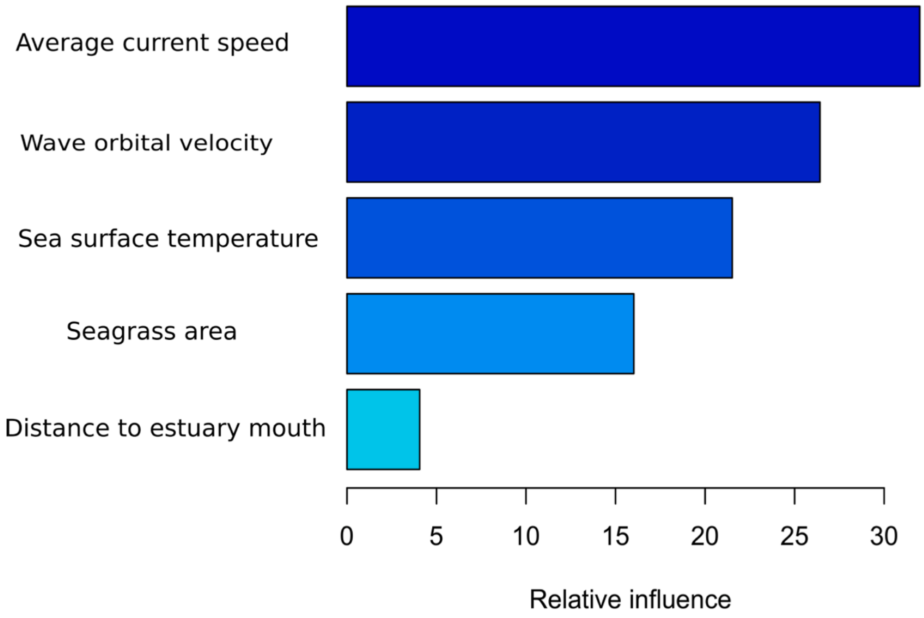


Fig. 4. Relative contribution of independent variables to BRT model variability in relation to fish abundances ha^{-1} with a model Mean square error (MSE) = 1074. MSE is a measure of uncertainty to assess the model's performance. MSE measures the average of the squares of the errors — that is, the average squared difference between the estimated values and what is estimated. MSE is a risk function corresponding to the expected value of the squared error loss.

were average current speeds, wave orbital velocity and sea surface temperature. Long-shore wind-driven surface gravity waves create turbulent mixing on the coastline and provide mechanisms by which larvae can be transported both on– and offshore (Blanchette et al., 2008; Lechner et al., 2018). However, the influence of current speeds and water velocity in determining diel timing of spawning of 11 reef species on the east coast of Australia varied among species; some avoided spawning during low current speeds while the majority showed no clear response (Sancho et al., 2000). Species-specific preferences to current speeds and water velocities are likely to vary, but it is important to bear in mind the possible effect of current speeds and water velocities to fish abundances when considering differences in spatial patterns of fish distribution.

Sea surface temperature explained 21.5% of BRT output, and it indicates that colder sea surface temperatures cause lower abundances of King George Whiting. Sea surface temperature has been identified as an important variable affecting fish larvae abundances globally (Kono et al., 2016; Lemus et al., 2020). However, when observing the relationship between juvenile fish numbers and sea surface temperature, no distinct trend or pattern is observed. Fish numbers seem to be very low at 15 and 17 degrees and similar around 14, 16 and 18 + degrees. This could be related to inner-annual variation in temperature more broadly, possibly capturing spawning or environmental conditions around Kangaroo Island, where it is believed that King George Whiting larvae start their journey towards Port Phillip Bay. Another variable that affects the dispersal potential of larvae is the distance from the estuary mouth. It is an important predictor for some fish as it might indicate dispersal potential (i.e., it is harder for larvae to reach habitat this is further away from their travel trajectory) (Ford et al., 2010). However, in our case, the distance of seagrass from the estuary mouth had a minor effect on model explanatory performance (5%).

The lower importance of seagrass area as a predictor variable (16.05% of BRT output) could be a result of the fish sampling methods, where all sampling was conducted on seagrass beds. This could hinder the importance of seagrass in the model output as there is no comparison to unvegetated areas or other types of substrate. The importance of seagrass to King George Whiting is well understood and enhancement to bare sediment areas previously established (Blandon and Ermgassen, 2014a; Jänes et al., 2020b). If there had been a comparison to unvegetated areas, then the value of seagrass from the perspective of fish abundance, biomass and dollar figures would have been reduced; simply because unvegetated areas do harbour some juvenile fish. To complement previous knowledge in the field, our goal was to explore the variability in fish production originating from seagrass beds, which has not received as much attention as enhancement comparisons to unvegetated areas.

To account for the potential effects of seagrass per unit area, we applied a 1 km^2 buffer zone across sampling stations and estimated the extent of seagrass within that region. The results suggest that if the extent of seagrass is over 150 ha within 1 km^2, then fish abundance levelled off. This has important implications for seagrass conservation and management when it is needed to determine the optimal area to conserve or restore to maximise fish production.

However, seagrass condition or temporal change in seagrass area was not tracked over time which could have further implications on the importance of seagrass to King George Whiting.

Nevertheless, a recent *meta*-analysis shows that seagrass presence increases the survival of several juvenile fish species all around the world (Lefcheck et al., 2019).

Abundance, biomass and dollar values of coastal ecosystems estimated from fisheries production often vary and are affected by the scale and the location of the study. For example, Blandon and Ermgassen (2014b) estimated the fisheries enhancement value of seagrass from multiple sites across southern Australia at $ AUD 31,650 ha^{-1} y^{-1} from which only $ AUD 397 ha^{-1} y^{-1} originated from King George Whiting production (24.5 kg ha^{-1} y^{-1}). Such estimates fall in the lower range of our predictions in Port Phillip Bay, possibly indicating notable importance of seagrass in Port Phillip Bay to King George Whiting production compared to average nation-wide estimates. However, it is common in *meta*-analyses (e.g. Blandon and Ermgassen, 2014a) that cover wide spatial context to average input data making their values applicable across wider spatial context. As a result, fish production in some parts of the coastline are overestimated and in some underestimated. A coordinated national fishery monitoring approach that considers the scale of monitoring enables accountancy for ecological processes between fish and ecosystems to make more informed comparisons across and within regions. Considering scale - both spatial and temporal - when allocating resources and prioritizing management actions.

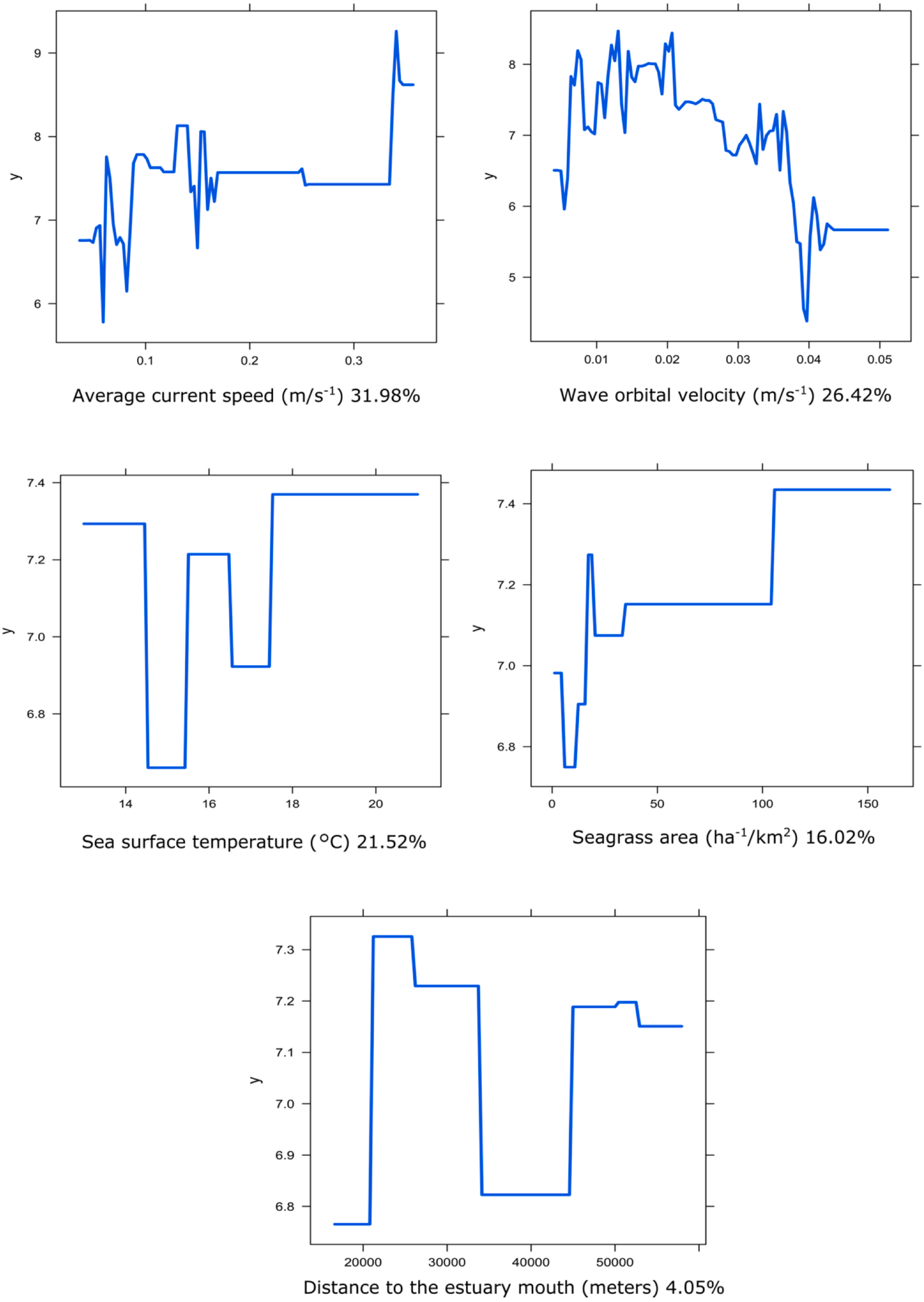
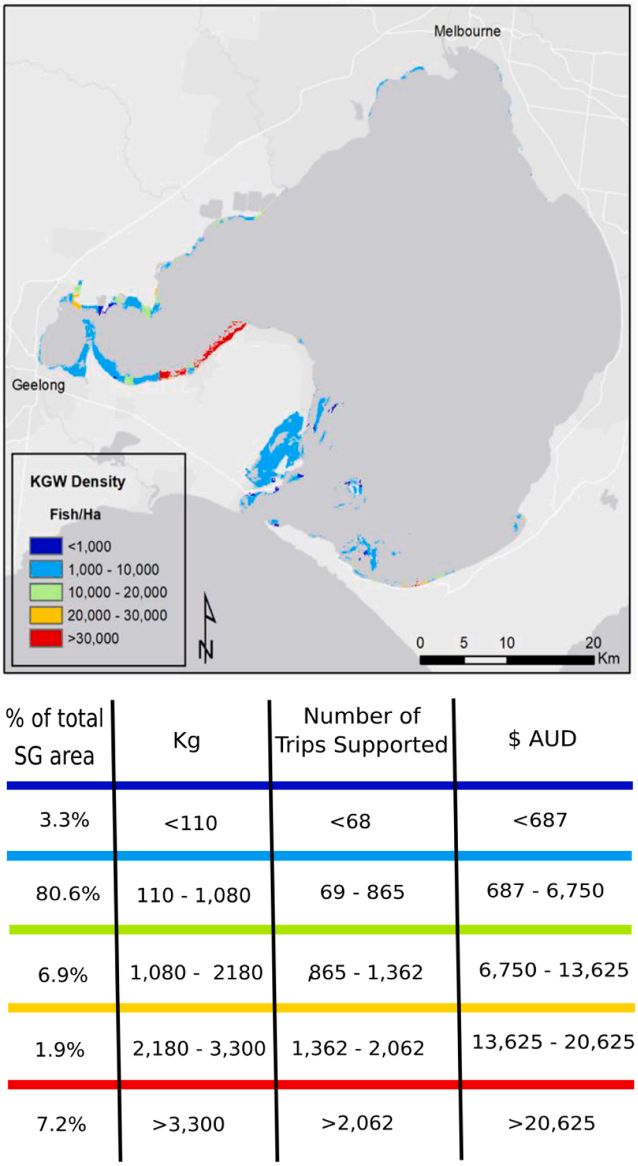


Fig. 5. Standardized functional form relationships (marginal effects) of boosted regression tree (BRT) analysis between environmental variables and fish abundances. The variables are ordered by their relative contribution in the BRT model.



% of total SG area	Kg	Number of Trips Supported	$ AUD
3.3%	<110	<68	<687
80.6%	110 - 1,080	69 - 865	687 - 6,750
6.9%	1,080 - 2180	865 - 1,362	6,750 - 13,625
1.9%	2,180 - 3,300	1,362 - 2,062	13,625 - 20,625
7.2%	>3,300	>2,062	>20,625

Fig. 6. Knowing the association between fish densities and environmental variables in each previously determined 1 km^2 box around sampling locations (800 ha in total) provides input data for the model. Total seagrass area (6662 ha^{-1}) in Port Phillip Bay was then valued from the perspective of King George Whiting abundances, biomass, number of recreational fishing trips supported and dollar value per hectare per year.

The recreational fisheries sector is particularly difficult to value as their catch is not sold. As a result, recreational fishers do not have net profit associated with catching the fish itself. Recreational fisheries value logic is opposite to commercial fisheries as fishers spend money to catch fish they later do not sell, or sometimes just for the enjoyment of the activity. Due to the complex nature of recreational fisheries, economic value estimates are often not available or cannot be easily compared with the gross value of production measures used for valuing the commercial sector. However, within this study, we attempted to bridge this gap by estimating the seagrass ecosystem value based on recreational catch data. Non-market valuation techniques, which capture angler's behaviour through survey questionaries, are often available to estimate recreational fisheries' value by estimating how much an average fisherman spends per fishing trip (Economic Study of Recreational Fishing in Victoria, 2015). Variables recorded often include travel distances, gear, accommodation and food costs, target species, hours spent on fishing etc. In Australia alone, recreational fisheries annual economic value was estimated to be $2.56 billion in 2013 based on fishers estimated direct attributable annual expenditure as a proxy and recognition of the sector's recreational service values beyond catch (FRDC, 2015).

The seagrass value estimates from recreational fisheries in our study might seem substantial, but we still believe them to be conservative. This is because here, we were able to thoroughly focus on the relationships between King George Whiting and seagrass beds, but many more species of commercial and recreational interest have close associations with seagrass in the region. For example, mullets, flatheads and snapper are commercially and recreationally sought-after species that are known to derive considerable dietary input from seagrass ecosystems, making them vital for sustaining these fisheries (Jänes et al., 2020a). Secondly, the sampling efficiency of seine nets could range from 20 to 83% depending on species (Jenkins and Sutherland, 1997) as well as within species (Rozas and Minello, 1997), and thus the number of fish sampled is always an underestimate of the actual number present. Thirdly, current economic estimates are derived from recreational data; however, commercial state-wide fisheries reports could be used to estimate commercial values of seagrass ecosystems. However, we applied recreational fishing data to value seagrass in Port Phillip Bay due to the closure of commercial fishing in the Bay, which was a strategic governmental plan to further promote recreational fishing opportunities (VFA and BBV, 2020). The logic and methods used in this study to value seagrass from the perspective of recreational fisheries could be applied to any other ecosystem anywhere in the world in case of suitable data availability.

We were able to estimate the nursery value of the seagrass ecosystem to King George Whiting production at a fine spatial scale by synthesizing existing fisheries data in conjunction with machine learning and economic analysis. With the continued degradation of coastal ecosystems globally, decision-makers are required to understand the benefits humans derive from the natural world to combat degradation and know associated costs if no action is taken. We highlighted fisheries benefits provided by seagrass ecosystems and presented our findings in conjunction with the principles of environmental-economic accounting to help decision-makers prioritize conservation and management scenarios in socio-economic context.

CRediT authorship contribution statement

Holger Jänes: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Data curation. **Paul Carnell:** Supervision, Writing - original draft, Project administration, Funding acquisition. **Mary Young:** Formal analysis, Data curation, Writing - original draft. **Daniel Ierodiaconou:** Supervision, Writing - original draft, Project administration, Funding acquisition. **Gregory P. Jenkins:** Conceptualization, Resources, Writing - original draft. **Paul Hamer:** Conceptualization, Resources, Writing - original draft. **Philine S.E. Zu Ermgassen:** Methodology, Software, Writing - original draft. **Jonathan R. Gair:** Methodology, Software. **Peter I. Macreadie:** Supervision, Writing - original draft, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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Data accessibility

All raw data used for this chapter is accessible through the online data storage website CloudStor: https://cloudstor.aarnet.edu.au/plus/s/bUAjm0NaTizmQJO.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108097.

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