Assessing the sustainability of Venus Bay's pipi fishery

Recreational Fishing Grants Program Research Report

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Non-technical summary

Venus Bay supports a diverse and vibrant recreational pipi fishery that is highly valued by the Victorian community. Pipis in the region have also been an important food source to traditional owners for many thousands of years (Godfrey 1989; Frankel 2017). The recreational and commercial harvest of individuals in any fishery necessarily has an impact on population biomass. However, fisheries can be successfully managed when information is available on the relative impact of harvest and environmental variation on population dynamics. This study is the fourth scientific investigation into the status of Venus Bay's pipi population and follows work by Early *et al (2013)*, Lewis *et al* (2013) and Parry (2014).

Venus Bay extends for approximately 24 kilometres from Point Smythe in the northwest to Arch Rock in the southeast. Harvester access is mostly confined to the northern part of the beach meaning that large areas receive limited fishing effort. Our results over the period 2015-2018 provide evidence that harvesting, especially in the peak summer period, locally reduces juvenile and adult pipi abundance within 3km of each of the five beach access points. This pattern is similar to that observed in many other recreational fisheries where harvest has localised impact at sites of fishing activity. The pipi harvest signal persisted even after we accounted for local and bay-wide environmental conditions.

Despite evidence of reduced abundances near beach access sites, fishing pressure across 2015-2018 only had impact on summer and autumn biomass. Adult biomass recovered in winter and spring, likely driven by the continual growth and recruitment of juveniles into larger size classes. Indeed, the observed reduced abundance of pipis does not appear to impact on local recruitment given that newly settled pipis were common along the beach at all times of the year. The southeast region of Venus Bay supports a large, and relatively unfished pipi population that could be playing a significant role in the production of local pipi recruits. This region appeared unaffected by recreational harvest. Further research is needed to understand the importance of small spatial and temporal scale recruitment on sustaining pipi populations.

Recruit and juvenile pipis were more abundant at the low water mark, whereas adults were more abundant higher on the beach. All life stages were also more abundant on steeper parts of the beach which are more common in the southeast region of Venus Bay. Pipi abundance across all life stages displayed complex relationships to tidal, wave, and weather conditions.

Our combined analyses across the three previous studies (Early *et al.* 2013; Lewis *et al.* 2013; Parry 2014) and the current one (2009-2017) indicate that there has been temporal variability in the summer biomass with values of around 0.1 kg/m^2 in 2009 and 2015-2017 and a high of 0.52 kg/m^2 in 2013. Our models did not detect any temporal variability in spring pipi biomass, with values between 0.07 and 0.14 kg/m^2 across studies. This variability in summer biomass and the relatively stable spring biomass indicates that fishing pressure across years is not having a discernible impact on pipi biomass, as we would expect a consistent decline in both seasons (especially in summer) over time if it was. The cause of the biomass variability,

therefore, could be driven by interannual differences in harvester effort, changed environmental conditions that affect pipi recruitment, growth and survival, or a statistical artefact arising from the comparison of different study designs.

Sexually mature female pipis were present at Venus Bay across all sampling trips which suggests that spawning is occurring year-round. Mature females were most abundant during the warmer months (November – March) which is likely when peak spawning occurs. The smallest mature female collected was 27 mm, and the average minimum size across all samples was 35 mm. The average size of all sexually mature females was 41 mm. These values, whilst not directly comparable with data from New South Wales and South Australia, suggest similarities in maturation pattens across pipi's geographic range. It is possible that harvesting over the summer months could impact on the number of offspring produced if many large females are removed at this time although the presence of recruits at all times of the year indicates the recruitment is nevertheless consistent in Venus Bay.

Adult pipis, despite actively moving up and down the shore with the tide cycle, do not generally move far along the beach. Only 3.7% of tagged pipis were recaptured within 12 months of release, the majority within 200m of the release point during the first four weeks of the study. One pipi recaptured after 11 weeks at liberty had only moved 125 m along the beach. In contrast, another pipi moved 2 km within just four weeks of release. 62% of movements greater than 200 m were towards the southeast part of Venus Bay. The relatively low pipi recapture rate could be reflective of low pipi detection probability, failed reporting of captures by harvesters, or animals moving outside the region of most intense harvester effort.

Overall, we conclude that recreational harvest has had a localised impact on Venus Bay pipis at beach access points but that this is to be expected for any recreational fishery. The localised harvester impact, however, does not appear to have had a major impact on longer-term (across years) trends in pipi biomass.

Replenishment of the pipi stock by recruitment is likely to occur across Venus Bay as evidenced by the presence of newly settled pipis along the beach throughout the year. The southeast region of Venus Bay supports a large pipi population which may be contributing to the production of local pipi recruits. Further research is needed to test this hypothesis. Populations may also be replenished by the movement of adult pipi to harvest areas, although this is less likely given available data on the distance and direction moved of tagged animals.

The minimum size of 35mm and the assignment of annual quota for the Victorian commercial fishery offers some protection to pipis as it affords the majority of individuals the chance to breed before they become vulnerable to capture. There is no minimum legal size for recreational anglers. Effective, and potentially active, management of the relatively high abundances of larger pipis away from beach access points will help buttress the production of new offspring. These new pipis could continue to recruit across the remainder of the beach and replenish more intensely harvested regions.

Introduction

Background and need

Australians have long valued and actively participated in recreational fishing (Clark 2017). A national survey in 2000-01 identified that recreational fishers are generally motivated to go fishing by the opportunity it affords to relax and unwind, provide enjoyable sport, and to spend time with friends and family in the outdoors (Henry & Lyle 2003). More recently, there has been an acknowledgment that the harvest of fish for personal consumption can be an important motivator for recreational fishers, especially among certain cultural groups (Arlinghaus *et al.* 2007; Cooke *et al.* 2018). The diversity of fisher motivators intersects with a more universal catch-dependent measure of fishing experience satisfaction, which in turn can pose challenges for fishery management (reviewed by Arlinghaus 2006).

Access to good data plays a fundamental role in sustainable fishery management. This data provides insight into the roles of environmental variation and harvest in driving population fluctuations (Morrongiello, Sweetman & Thresher 2019), estimates of key biological parameters such as age-at-maturity (Feiner *et al.* 2015), the ecosystem-wide consequences of fisheries activities (Lewin *et al.* 2019), and a means to test the effectiveness of different management actions (Mapstone *et al.* 2008). Indeed, effective fisheries management underpinned by good data has been instrumental in improving the status of fisheries around the world (Hilborn *et al.* 2020). Whilst relevant fishery and biological data is readily available for many commercially harvested species, it is often lacking for recreational fisheries (Venturelli, Hyder & Skov 2017; but see VFA's GoFishVic app https://vfa.vic.gov.au/recreational-fishing/gofishvic). A lack of fishery understanding challenges the future enjoyment of these resources by fishers, the long-term viability of target species, and the health of ecosystems they support (P. McPhee, Leadbitter & A. Skilleter 2002; Post *et al.* 2002; Cooke & Cowx 2004).

In Australia, the surf clam *Donax deltoides* (locally known as the 'pipi' or 'Goolwa cockle) has been harvested by indigenous communities for thousands of years (Godfrey 1989; Murray-Jones 1999), and more recently has supported a recreational fishery throughout its distribution (Ansell 1983; Murray-Jones & Steffe 2000; Lewis *et al.* 2013). Pipis form dense aggregations in the intertidal sediments of high energy sandy beaches, constituting up to 85% of the microbenthic infaunal biomass (Ansell 1983). Pipi populations display large natural fluctuations in abundance, due to variable levels of recruitment and mortality (King 1976; Ansell 1983; Murray-Jones 1999), and this high variability in abundance combined with a patchy distribution across beaches (Gray 2016) can contribute to localised depletion from overharvesting (McLachlan *et al.* 1996; Defeo 2003). There is a need for a greater understanding of local-scale pipi population demography and spatio-temporal patterns of abundance to inform sustainable catch rates for the recreational fishery.

Venus Bay supports one of only two large-scale recreationally fished pipi populations in Victoria (the other, Discovery Bay). Pipis are harvested recreationally from the intertidal zones of surf beaches for human consumption and bait. Pipis are also an important food resource for fishes and at Venus Bay likely help sustain the highly prized gummy shark and Australian salmon recreational fisheries (Kailola *et al.* 1993). In recent years there has been an increase in the number of recreational fishers harvesting pipis from Venus Bay. Before this, pipis were primarily harvested in small numbers for bait by local fishers. Active fisher participation reflects the valuable social amenity and family-friendly nature of pipi harvesting and should be encouraged. Previous studies have identified localised declines in the size and abundance of Venus Bay pipis at beach access sites over summer (Early *et al.* 2013; Lewis *et al.* 2013; Parry 2014). The viability of this socially inclusive fishery, based on the potential to collect enough of the preferred large pipis to satisfy individual catch limits (2L/day) (Victorian Fisheries Authority 2020), depends on sound, evidence-based fishery management decisions.

Pipi fisheries in Australia and at Venus Bay

Pipis have long been an important traditional food source to indigenous Australians, pre-dating European settlement as evidenced by the presence of extensive pipi shell middens in many coastal areas of Victoria, and in South Australia and New South Wales (Godfrey 1989; Frankel 2017). More recently, pipis have become an increasingly popular source of food and bait, and now support commercial and recreational fisheries throughout their range across southern Australia (Ferguson & Ward 2014). Commercial and recreational fisheries have long co-existed in New South Wales and South Australia (Murray-Jones & Steffe 2000; Ferguson & Mayfield 2006), but in Victoria the commercial fishery has remained relatively small compared to other states (Victorian Fisheries Authority 2018b).

Victoria's recreational pipi fishery is managed using recreational fishing licences and equipment restrictions (i.e. no tools; hands and feet only). The Victorian Fisheries Authority consider the fishery to be sustainable as it is spatially limited (restricted to Beaches 1 to 5 and within 3km of access points), seasonally limited (generally occurring in the summer months) and is subject to a daily catch limit of 2 litres per shell per person (half a litre of shucked pipi meat), which is a reduced limit compared to other Victorian beaches. Compliance operations over the summer months show a high compliance rate with the catch limit amongst pipi fishers (VFA, pers. comm.).

Commercial pipi harvesting on a very small scale (a single licence holder) occurs in the relatively inaccessible south-eastern section of Venus Bay (Fisheries Victoria 2014). This is an area previously identified as sustaining a high abundance of large pipis that may help replenish the more exploited areas to the northwest (Lewis *et al.* 2013; Parry 2014).

Previous research on Venus Bay's pipi population has been funded by the Victorian Government through the Recreational Fishing Grants Program (Early *et al.* 2013; Lewis *et al.* 2013) and Friends of Venus Bay Inc (Parry 2014)

Study species and study location

Study species

Donax (Plebidonax) deltoides (common names: pipi, Goolwa cockle) are bivalve molluscs commonly found in the surf zone from Fraser Island in southern Queensland, through New South Wales, Victoria and Tasmania to the Eyre Peninsula in South Australia (King 1985; McLachlan *et al.* 1996). Pipis are found in maximum abundance from just below the high tide level to the end of the surf zone (King 1985; Murray-Jones 1999) on high wave energy beaches where diatom blooms (food source) regularly occur (King 1976; McLachlan & Hesp 1984).

Similar to other surf bivalves in the *Donax* genus, pipis are known to undertake tidal migrations over short spatial and temporal scales, by actively emerging from the sand during rising or falling tides to ride the waves shoreward or seaward (Ansell 1983; Ellers 1995; Murray-Jones 1999). Population dynamics of pipis appear to be characteristic of the infauna of high energy sandy beaches around the world, with variable recruitment, fast growth up to the size at which sexual maturity is reached, and a prolonged spawning period (Murray-Jones 1999).

Pipis reach sexual maturity at about 10-13 months. In South Australia, the size at maturity, where 50% of the population is mature, is 28 mm, while 95% of the population is mature at 32 mm (Ferguson 2013). In New South Wales, 50% of the population is mature at 36mm (Murray-Jones 1999). Spawning times appear to differ across pipi's distribution. In New South Wales, mature ovaries were found in pipis throughout the year indicative of 'dribble spawners'

(Murray-Jones 1999), while in South Australia mature oocytes were only present 6 months of the year with peak spawning occurring in September-October (King 1976; King 1985).

Pipi are broadcast spawners and release their eggs and sperm into the water column where fertilisation occurs. Pipi eggs develop into planktonic larvae and enter a larval dispersal phase lasting 6-8 weeks (King 1985), or 3-4 weeks as estimated in NSW populations (Murray-Jones 1999). Towards the end of the planktonic phase, pipi larvae develop a foot and rudimentary gills, at which point they locate suitable habitat and settle onto the substrate (Ferguson & Mayfield 2006). Once settled, larvae undergo metamorphosis and become benthic filter feeders.

Study location

Venus Bay is located approximately 170 km from Melbourne on the south-east coast of Victoria, Australia (Figure 1). Venus Bay is a large south-west facing bay exposed to high energy wave action with a wide intertidal margin that provides ideal habitat for pipis.

Public access is by foot only (no vehicle access) and is limited to the north-west corner of Venus Bay along public beaches 1-5, situated within the protected Cape Liptrap Coastal Park. These beaches include car park facilities, public toilets and are popular swimming locations. Beach 1 is the most frequented beach due to the presence of a surf lifesaving patrol.

Cape Liptrap Coastal Park

Cape Liptrap Coastal Park contributes to Victoria’s parks and reserves system, which aims to protect viable, representative samples of the State’s natural environments occurring on public land. The park provides opportunities for visitors to enjoy and appreciate natural and cultural values and makes an important contribution to tourism and the economy of local coastal settlements.

The park protects extensive heathland and coastal forest vegetation communities, including approximately 270 species of flowering plants; thirty threatened fauna species, including ten species listed as threatened under the Flora and Fauna Guarantee Act 1988 (Vic.), and 17 migratory bird species. The park also encompasses complex geological sequences, ranging from ancient Cambrian rocks to Recent sands, as well as spectacular coastal landforms. Of cultural value, Cape Liptrap Coastal Park includes numerous middens and other significant Aboriginal sites (Parks Victoria 2003).

Study objectives

This study had three objectives.

1) Extend existing records of the spatial and temporal dynamics of pipi recruitment and abundance at Venus Bay, and explore the role of fishery harvest and environmental variation in driving observed variation (component 1).

2) Estimate the size at maturity of female pipis and document temporal patterns in spawning activity (component 2).

3) Estimate levels of juvenile and adult pipi movement along the beach.

Component 1: Spatial and temporal dynamics of pipi recruitment and stock abundance

Methods

Sample collection

We conducted 18 sampling trips to Venus Bay (38.68° S, 145.80° E) from December 2015 to March 2018. Trips were spaced one to two months apart. On each trip, we sampled 18 transects that spanned 12 km of Venus Bay beach (Figure 1) and that directly corresponded to Parry's (2014) transects 1-18, Lewis *et al.'s* (2013) sites 1-4, and some of Early *et al.'s* (2013) transects 1-20. Note that Early and colleagues labelled their most south easterly transect number one, whereas we (following Parry) labelled our most north westerly transect number one. We sampled all 18 transects on a given trip in random order across three to five days, generally within two hours either side of low tide. Sampling did not occur when bad weather, tidal conditions, or excessive sand drifts prevented safe work or vehicular access to the beach.

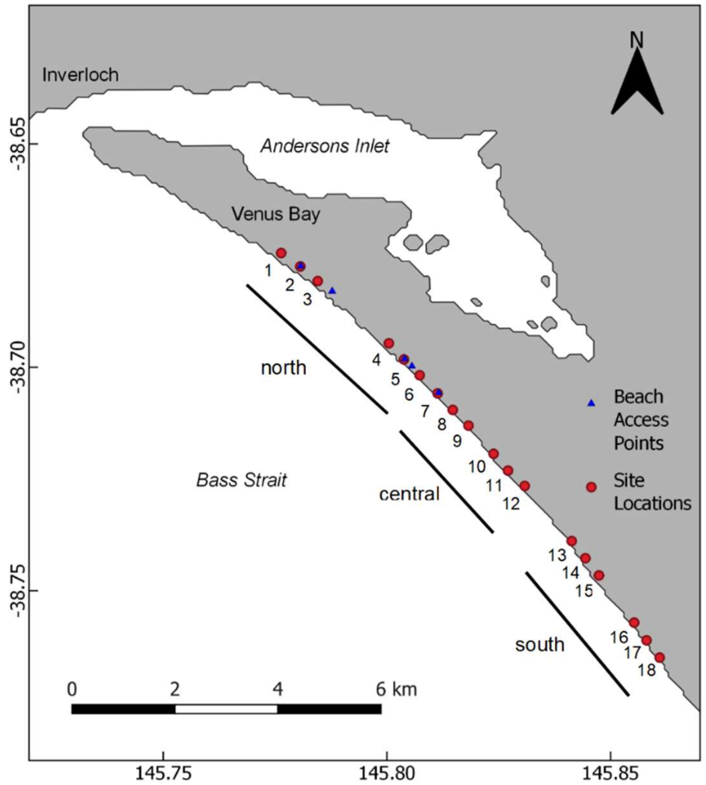

Figure 1: Map showing the location of the 18 sample transects (numbered) surveyed in this study, three beach regions (north, central, south) as per Parry (2014) and beach public access points.

Transects began two metres above the highest visible high-tide mark and extended down the beach to the water's edge at an angle perpendicular to the beach-sea edge interface. Three replicate sediment cores were taken using a spade corer (15.6cm diameter, 1L volume; Figure 2) every 10m down the beach until we reached the water. Transect lengths varied through space and time due to differences in beach profile and tide status. The longest transect was 180m. Each group of three cores at a given beach height were haphazardly taken within 1.5m either side of the transect line, and the resulting three litres of sand was sorted by hand and with a sieve.

Figure 2: Sampling using the spade corer

We measured the length of each pipi collected along its longest shell axis using callipers. Individual pipis were assigned to one of three life-stage groups for subsequent analyses (Figure 3):

- recruits (≤8mm, n=1004 pipis)
- juveniles (8.01-34.93mm, n=2423 pipis)
- adults only (≥35mm, n=1628 pipis)

We also pooled all pipis to explore patterns in total abundance (2.0-58.5mm, n=4494 pipis).

Figure 3: Example of adult and juvenile pipi.

Environmental variables

It is likely that the number of pipis present at a given location at the time of sampling is related to both short- and long-term environmental conditions, that vary over the small and large spatial scale. We therefore developed a series of static (constant through time) and dynamic (changing through time) environmental variables at the core, transect, and whole-bay level (Table 1). These variables explored how changes to the local (core and transect) and bay-wide habitat, weather, tidal cycle and harvesting regime affected pipi abundance. During each field trip we measured beach height at three to five points from high to low water (depending on transect length of the beach) using a theodolite. These points were used to generate beach profiles and estimate the beach slope of each three-core group. The distance of each transect from the nearest public beach access point was used as a proxy for fishing pressure, with greater harvest likely to occur closer to these parts of the beach (VFA fisheries officers, personal communication).

Weather and oceanographic data were sourced from the Bureau of Meteorology, WillyWeather and NOAA (Table 1) for the period December 2015 to April 2018. Pipis likely have limited capacity to move large distances once settled on the beach and so previous environmental conditions are likely to play an important role in determining how many individuals are at a given location on a given day. We chose to explore the relative importance of environmental conditions over four biologically relevant time scales: the previous day, previous week (preceding 5 days), previous month (preceding 30 days) and previous two months (preceding 60 days). Hourly or daily environmental data were aggregated over these time periods from the date of each transects' sampling.

Table 1: Description of environmental variables used in pipi abundance models. See Supplementary Table 1 in the appendix for further details on variable development

Variable name	Code	Description	Source
Core scale predictors			
Distance	$dist$	The distance in metres from the high tide mark to where the core was taken	Collected during sampling
Slope	$slope$	The slope of the beach along the where the core was taken	Calculated from the beach slope data collected during sampling
Previous slope	$Pslope$	The slope of the beach towards the high water mark from where the core was taken	
Transect scale predictors			
Fishing pressure	$fish$	The distance in metres from the nearest access point to a given transect	Google Maps used to measure the distance from the closest access point (5 in total) to the top of each transect
Tide height	$tideH$	The absolute tide height [positive if incoming] [negative if outgoing]	High and low tides and their times for each day, adjusted by -6min for low tide and +6min for high tide from Waratah Bay. Sourced from WillyWeather https://tides.willyweather.com.au/vic/gippsland/venus-bay.html
Tide cycle	$tideC$	The relative position of the tide height in the tide cycle [0 and 100 = high tide] [50 = low tide] Therefore 0-50 is an outgoing tide and 50-100 is an incoming tide	
Bay scale predictors			
All bay scale predictors were averaged for the day before [.d], the week before [.w], the month before [.pm] and the two months before [.p2m] the core was taken			
Average temperature	Tav	The average daily temperature	from the Bureau of Meteorology:

Variable name	**Code**	**Description**	**Source**
max temperature	$Tmax$ and $TmaX$	The maximum daily temperature as an average of the daily maximums (Tmax) and the absolute highest daily maximum (TmaX)	using the Pound Creek Station Data (http://www.bom.gov.au/climate/ data/stations/); Daily 3 hourly measurements aggregated to daily (averages or maximums)
Sea Surface Temperature	SST	The average daily sea surface temperature	NOAA High-resolution Blended Analysis of Daily SST for Venus Bay bounded by transect coordinates https://www.esrl.noaa.gov/psd/data/gridded/ data.noaa.oisst.v2.highres.html
Wave Height	$waveH$	The average daily wave height	WaveWatchIII hindcast data 2015-2018, from the Bureau of Meteorology: Daily 3 hourly measurements aggregated to daily averages from 145.7E 38.8S

Statistical analyses

Spatio-temporal patterns in abundance

We used a generalized additive mixed model (GAMM) fit with a Poisson distribution to model the spatial patterns of recruit, juvenile, adult and total pipi abundance as a function latitude, longitude, height on the shore and season (summer [December-February], autumn [March-May], winter [June-August], spring [September-November]). Response data were the number of pipis per three-core grouping. We included a random intercept for each transect to account for the repeated measures nature of our data. The GAMM allowed us to describe and then interpolate complex and non-linear spatio-temporal patterns in abundance along the beach. Specifically, our full model was:

$$d_{ijk} \sim Poisson(\mu_{ijk})$$

$$\mu_{ijk} = \beta_0 + \beta_1 + f\left(x_{1,ij}, y_{1,ik}\right) + f\left(x_{2,ij}, y_{1,ik}\right) + f\left(x_{1,ij}, x_{2,ij}, y_{1,ik}\right) + f\left(x_{3,i}, y_{1,ik}\right) + \alpha_j + \varepsilon_{ijk}$$

$$\alpha_j \sim N(0, \sigma_\alpha^2),\ \varepsilon_{ijk} \sim N(0, \sigma_\alpha^2)$$

where μ_{ij} is the event indicator for the ith core from the jth transect sampled in the kth season. The term β_0 is the baseline pipi abundance and $\beta_1$is a fixed effect for season. We allowed for potential seasonal differences (y_1) in the abundance of pipis along the beach by fitting smoother terms (f) for latitude ($x_{1,ij}$), longitude $x_{2,ij}$ and their interaction. We also allowed for seasonal differences in pipi abundance up and down the beach (distance from the high-water mark; $x_{3,ij}$). α_i is the random intercept for each transect ($i = 1 \ldots .18$) and ε_{ijk} is the error term.

We fit 13 GAMM models with different combinations of spatial and temporal variables using the statistical software R and the *gamm4* package. Model selection was performed using Akaike's Information Criterion corrected for small sample sizes (ΔAIC_c) (Burnham & Anderson 2002).

The best model (one with lowest AIC_c value) was used to predict pipi abundance for each of the four seasons (summer, autumn, winter and spring) across 83 evenly spaced points along Venus Bay beach. These predictions, informed by our observed abundance data from 18 locations through time, allowed us to draw inference on parts of the beach where we did not survey. GAMM predictions were imported into QGIS version 3.2.3-Bonn and a heatmap of predicted abundance produced for each life stage and season combination.

Impacts of fishing pressure and environmental variation on pipi abundance

We explored the impact of fishing pressure and environmental factors on the abundance of potentially harvestable pipis (juvenile and adult) using a generalized linear mixed model (GLMM) fitted with a Poisson distribution and a random intercept for transect. We initially tested for just the potential impact of harvest on abundance by including linear and quadratic terms for '*distance from nearest access point m*'. We assumed that harvest pressure is linearly related to distance and thus will be greatest closest to access points.

We then assessed the importance of different combinations of core, transect and bay-wide environmental variables, in conjunction with fishing pressure (Table 1), in explaining spatio-temporal variation in the abundance of all pipi life stages. We ran separate suites of models for environmental data aggregated at four biologically relevant time scales (previous day, previous week, previous month and previous two months). Curvi-linear patterns were accommodated by allowing environmental variables to have a quadratic shape. Each competing environmental model could only include one of the four measures of temperature (average daily temperature, average maximum daily temperature, absolute maximum daily temperature and sea surface temperature), one of the two measures of tide (tide height and tide cycle), and one of the two measures of beach slope (beach slope and previous beach slope) (Table 1). Fishing and environmental models did not include latitude, longitude, or season as spatio-temporal variation is explicitly accounted for by varying environmental data. We did not use a GAMM model due to computational limitations and our desire to produce relatively easy-to-interpret abundance predictions as a function of environmental variables. Competing models were compared using ΔAIC_c from the *dredge* package, and GLMMs were run using the statistical software R and the *lme4* package.

Comparison to previous studies

We compared spatio-temporal patterns in our pipi data to that collected in previous studies at Venus Bay. Each previous study sampled slightly different sets of transects at different times of the year, which precluded a direct comparison of fine-scale spatial patterns. We therefore adopted the approach of Parry (2014) and allocated individual transects to one of three regions (north, central, south; Figure 1) and one of four collection seasons for subsequent analysis. All three previous studies (Early *et al.* 2013; Lewis *et al.* 2013; Parry 2014) reported the biomass of pipis (with shell on) along each transect in kg/m^2. They also only sampled from the mean high-water mark down 60m of the beach. We therefore truncated our data to cores from within this beach height range (six sets of three cores; total area per transect of 0.342m^2) and estimated pipi weight per transect using the length-weight relationship presented in Parry (2014):

$$\log_{10} weight(g) = -4.183 + 3.248 * \log_{10} length(mm)$$

We extracted transect-level pipi biomass data from graphs presented in each study's report (Early *et al.* 2013: Figure 6; Lewis *et al.* 2013: Figure 4; Parry 2014: Figure 9). Comparative analyses were limited to spring (September- November) and summer (December-February) as these were the only seasons surveyed in other studies. Spring seasonal data was available from our study (2016 and 2017), Lewis' study (2009) and Early's study (2011). Summer seasonal data was available from our study (2015/16, 2016/17 and 2017/18), Lewis' study (2009/10), and Parry's study (2013/14). No southern region data was available for spring 2016. We therefore included southern data that was collected in August so we could test for yearly differences in regional biomass.

Seasonal estimates of regional biomass were compared among studies using a linear mixed effects model:

$$y_{ijk} = \beta_0 + \beta_1 x_j + \beta_2 x_k + \beta_3 x_{jk} + \alpha_j + \varepsilon_{ijk}$$

$$\alpha_j \sim N(0, \sigma^2),\ \varepsilon_{ijk} \sim N(0, \sigma^2)$$

Where y_{ijk} is the spring or summer biomass in kilograms at transect i, from region j, in year k. β_1, β_2, and β_3 are the main effects and interaction for region and year. α_j is a random intercept for transect and accounts for the repeated measures of biomass at a given location through time. Biomass included zero values so was 4th root transformed to meet model assumptions of homogeneity of variance. Models were fit using the *lme4* package in R and compared using ΔAIC_c. We performed post hoc contrasts with Tukey-adjusted p values among levels of regions and years as appropriate.

Results and discussion

Spatio-temporal patterns in abundance

The best models explaining variation in the abundance of each life stage and total abundance all included latitude and longitude interacting with season (Table 2). The best models also included distance from the high water mark interacting with season, except for recruit abundance (Table 2). The four best models were then used to predict recruit, juvenile, adult and total abundance along and up the beach for each season.

All pipi life stages were present at Venus Bay year-round (Figure 4). Recruits (≤8mm) were found in greatest abundance during spring and summer, initially in the northern and southern parts of the beach then all over. Recruit abundance declined, particularly in the south, during autumn to their lowest levels in winter. Juvenile pipis (8.01-34.93mm) were present across the whole beach in each season, albeit often in low numbers. Juveniles were particularly rare in the central parts of the beach and during winter.

Adults (≥35mm) were most abundant across all seasons at the southern end of Venus Bay (Figure 4). Large juvenile pipis in winter and spring likely grow and become adults in summer, resulting in adults found (albeit low abundance) across the whole beach. By autumn there were no adults found across the centre of Venus Bay (after the summer intensive harvest). Overall pipi abundance was greatest during summer, autumn and spring. Pipis were most common in the southern parts of the beach with a peak in abundances in the north during autumn related to an increase in recruits.

Taken together, our model indicates that whilst pipi recruitment occurs all year and across the whole beach, something happens to these pipis as they grow that makes their distribution more patchy and variable across seasons. Of note is the low abundance then disappearance of larger pipis in the central and northern parts of Venus Bay by autumn, and the high abundance of all life stages in the south-east part of the beach.

Table 2: Model selection results for the competing spatio-temporal models comparing the effects of latitude and longitude, distance and season on recruit, juvenile, adult and total P. australis abundance. All tested models are included in the table ranked by degrees of freedom. Each line is a separate model and the formula is shown under the heading predictors. Degrees of freedom (df), AICc, ΔAICc and the Log likelihood for each model are shown, with the top ranked model (ΔAICc = 0) highlighted in boldface.

	predictors	**df**	**AICc**	**delta**	**logLik**
recruit	t2(s.lat,s.long) * season + s(s.distance) * season + season	37	1942.917	2.284	-933.390
	t2(s.lat,s.long) * season + s(s.distance) + season	**31**	**1940.633**	**0.000**	**-938.566**
	t2(s.lat,s.long) * season + season	29	2255.201	314.568	-1097.943
	t2(s.lat,s.long) + s(s.distance) * season + season	19	1967.563	26.930	-964.497
	t2(s.lat,s.long) + s(s.distance) + season	13	1966.515	25.883	-970.122
	s(s.distance) * season + season	13	1959.309	18.676	-966.519
	t2(s.lat,s.long) + season	11	2268.522	327.889	-1123.163
	t2(s.lat,s.long) + s(s.distance)	10	2052.486	111.854	-1016.161
	t2(s.lat,s.long)	8	2403.585	462.952	-1193.739
	s(s.distance) + season	7	1958.815	18.182	-972.366
	season	5	2257.742	317.109	-1123.849
	s(s.distance)	4	2045.734	105.101	-1018.852
	Intercept only	2	2393.500	452.867	-1194.746
juvenile	**t2(s.lat,s.long) * season + s(s.distance) * season + season**	**37**	**8874.381**	**0.000**	**-4399.122**
	t2(s.lat,s.long) * season + s(s.distance) + season	31	9376.521	502.140	-4656.510
	t2(s.lat,s.long) * season + season	29	9634.670	760.290	-4787.678
	t2(s.lat,s.long) + s(s.distance) * season + season	19	9130.133	255.752	-4545.782
	s(s.distance) * season + season	13	9128.110	253.730	-4550.919
	t2(s.lat,s.long) + s(s.distance) + season	13	9677.579	803.199	-4825.654
	t2(s.lat,s.long) + season	11	9932.321	1057.941	-4955.062
	t2(s.lat,s.long) + s(s.distance)	10	9763.548	889.167	-4871.692
	t2(s.lat,s.long)	8	9992.300	1117.919	-4988.096
	s(s.distance) + season	7	9673.843	799.463	-4829.880
	season	5	9929.210	1054.830	-4959.583
	s(s.distance)	4	9759.860	885.480	-4875.915
	Intercept only	2	9989.117	1114.736	-4992.554
adult	**t2(s.lat,s.long) * season + s(s.distance) * season + season**	**37**	**3168.402**	**0.000**	**-1546.133**
	t2(s.lat,s.long) * season + s(s.distance) + season	31	3189.494	21.092	-1562.997
	t2(s.lat,s.long) * season + season	29	3583.561	415.159	-1762.123
	t2(s.lat,s.long) + s(s.distance) * season + season	19	3221.345	52.943	-1591.388

	predictors	df	AICc	delta	logLik
	s(s.distance) * season + season	13	3240.764	72.362	-1607.246
	t2(s.lat,s.long) + s(s.distance) + season	13	3243.687	75.285	-1608.708
	t2(s.lat,s.long) + season	11	3641.049	472.646	-1809.426
	t2(s.lat,s.long) + s(s.distance)	10	3274.627	106.225	-1627.231
	t2(s.lat,s.long)	8	3714.250	545.848	-1849.072
	s(s.distance) + season	7	3262.533	94.131	-1624.225
	season	5	3660.332	491.930	-1825.144
	s(s.distance)	4	3295.688	127.286	-1643.829
	Intercept only	2	3734.540	566.138	-1865.266
total	**t2(s.lat,s.long) * season + s(s.distance) * season + season**	**37**	**6812.512**	**0.000**	**-3368.188**
	t2(s.lat,s.long) * season + s(s.distance) + season	31	7196.998	384.485	-3566.748
	t2(s.lat,s.long) * season + season	29	7523.473	710.960	-3732.079
	t2(s.lat,s.long) + s(s.distance) * season + season	19	6928.456	115.944	-3444.943
	s(s.distance) * season + season	13	6933.666	121.154	-3453.697
	t2(s.lat,s.long) + s(s.distance) + season	13	7342.014	529.502	-3657.871
	t2(s.lat,s.long) + season	11	7669.289	856.777	-3823.546
	t2(s.lat,s.long) + s(s.distance)	10	7380.287	567.774	-3680.061
	t2(s.lat,s.long)	8	7694.952	882.439	-3839.422
	s(s.distance) + season	7	7345.706	533.194	-3665.812
	season	5	7674.174	861.662	-3832.065
	s(s.distance)	4	7384.394	571.881	-3688.182
	intercept only	2	7700.037	887.524	-3848.014

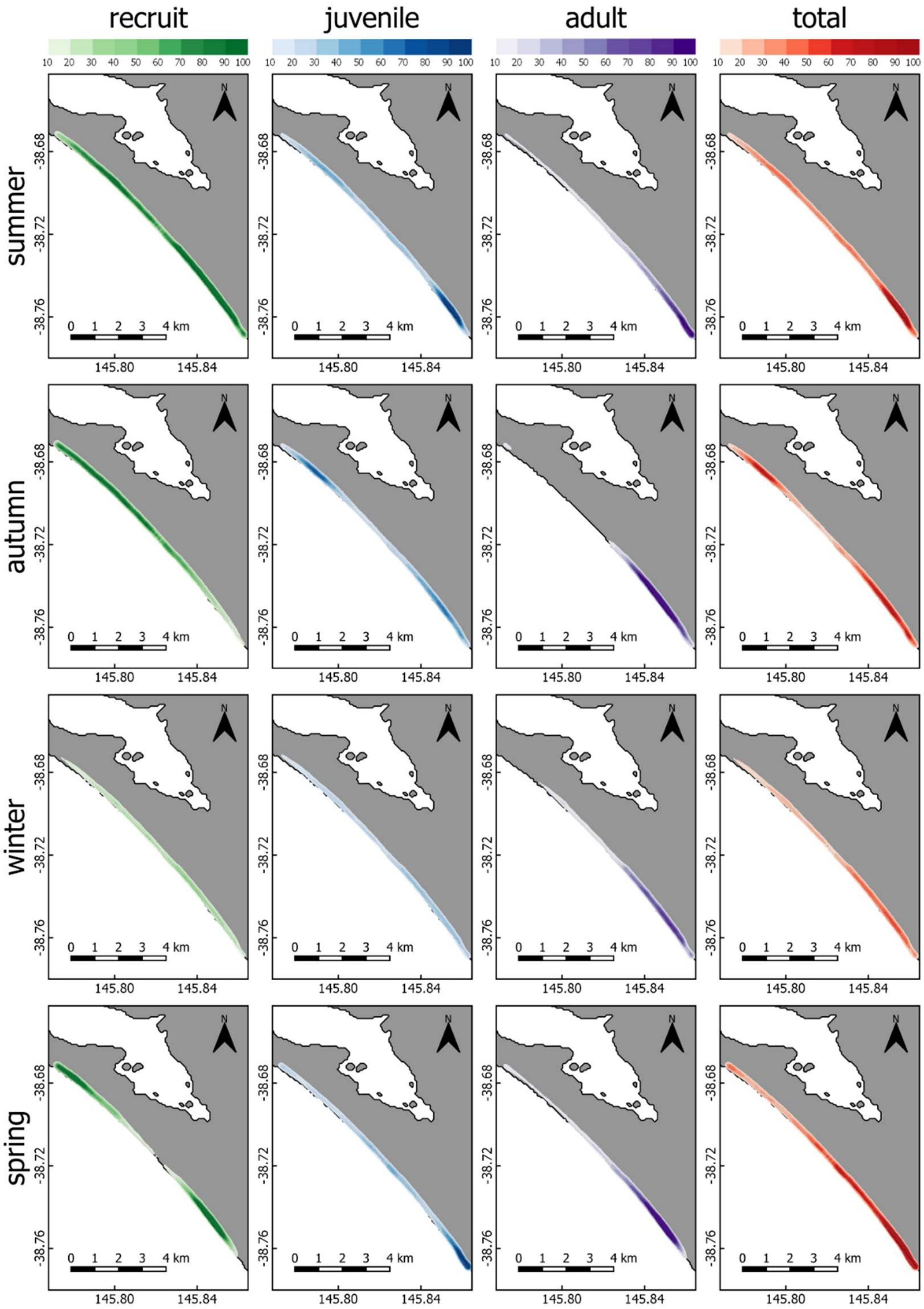

Figure 4: Spatio-temporal maps of recruit (green), juvenile (blue), adult (purple) and total (red) pipi abundance across Venus Bay. Predicted abundances were rescaled to be a proportion (0-100 %) of the maximum predicted abundance for each data set (recruit = 0.46, juvenile = 14.47, adult = 2.07, total = 6.68). This rescaling was done to aid visual interpretation.

Impacts of fishing pressure and environmental variation on pipi abundance

Fishing pressure

The effect of fishing pressure varied across seasons for juvenile and adult pipis (Table 3). In summer, juvenile and adult abundance increased exponentially the further away from a beach access point samples were (Figure 5, Figure 6). In autumn and winter, juvenile and adult abundance increased as fishing pressure decreased up to about 4000-5000m from an access point, whereafter it plateaued or began to decline (Figure 5, Figure 6). Spring juvenile abundance peaked at about 3500 metres from the nearest access point, and then declined thereafter. There was no clear effect of fishing pressure on the spring abundance of adult pipis.

Our results provide evidence that harvesting, especially in the peak summer period, locally reduces pipi abundance near beach access points. Harvesters may be unwilling to walk greater distances to collect pipis and thus areas further away are afforded some protection via isolation. Juvenile and adult pipi abundance showed similar responses to our measure of fishing pressure, which indicates that both smaller and larger pipis are harvested. Patterns of pipi abundance in autumn and winter also reflected a potential effect of harvest. However, for these seasons it is apparent that other environmental factors are likely to play an important role in shaping abundance patterns.

It is important to note that we assume fishing pressure declines at a constant rate as we move further from beach access points. It is also plausible that fishing pressure displays a non-linear style pattern, whereby harvesters will readily travel 1-2km, but not much further. Whilst additional work could formally parameterise the spatial extent of fishing pressure, we believe our results and conclusions drawn are robust.

Table 3: Model selection table for the five best fishing pressure models for juvenile and adult pipi abundance through time (season – summer, autumn, winter and spring). Parameter estimates, model degrees of freedom, AICc, delta AICc and log likelihood values are shown. Fishing pressure estimates can be either linear or curvi-linear (^2 denotes a quadratic term). (+) are added to highlight where the categorial season or its interaction with fish appears in the model. Bold text highlighted the best juvenile and adult model.

	intercept	Fishing pressure	fish^2	season	fish * season	fish^2 * season	df	AICc	delta	logLik
juvenile	**1.15**	**0.222**	**-0.142**	**+**		**+**	**10**	**9872.455**	**0**	**-4926.146**
	1.121	0.181	-0.109	+	+	+	13	9874.22	1.765	-4923.974
	1.026	0.12		+	+		9	9896.999	24.544	-4939.433
	1.049	0.135	-0.025	+	+		10	9898.971	26.516	-4939.403
	1.022	0.227		+			6	9922.636	50.181	-4955.287
adult	**-0.375**	**2.43**	**-1.414**	**+**	**+**	**+**	**13**	**3558.992**	**0**	**-1766.36**
	-0.264	1.184	-0.675	+		+	10	3614.065	55.073	-1796.951
	-0.612	1.404	-0.45	+	+		10	3627.93	68.938	-1803.883
	-0.483	1.213	-0.457	+			7	3629.342	70.349	-1807.629
	-1.014	1.121		+	+		9	3633.846	74.854	-1807.856

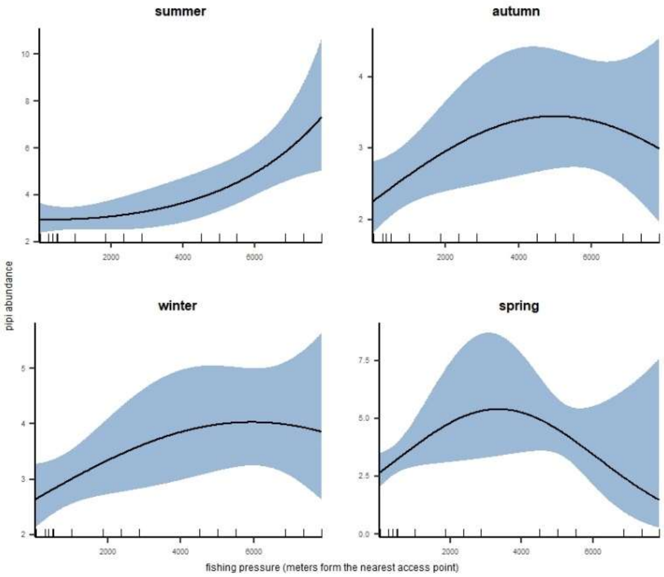

Figure 5: The predicted effects of fishing pressure on juvenile pipi abundance across seasons (summer, autumn, winter and spring). Black lines represent the best fit and blue shaded areas the 95% confidence intervals.

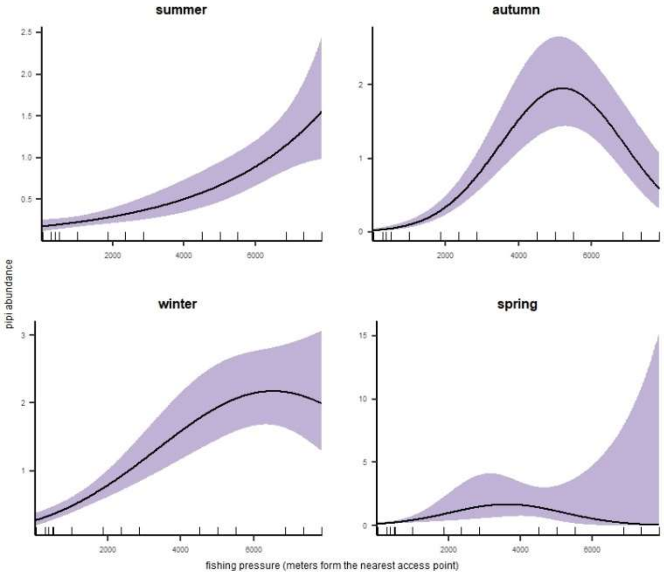

Figure 6: The predicted effects of fishing pressure on adult pipi abundance across seasons (summer, autumn, winter and spring). Black lines represent the best fit and blue shaded areas the 95% confidence intervals.

Fishing pressure and environmental variation

Here, we explored the relative importance of fishing pressure and variables describing environmental variation at the scale of the core, the transect and the beach, calculated over one-day, five-day, 30-day or 60-day time periods.

The best models predicting the abundance of recruit, juvenile and adult pipi all included the same predictor variables, albeit calculated over different time periods (recruit: previous day; juvenile: previous month; adult: previous two months). All models included distance from the high water mark, beach slope, distance from beach access points, maximum temperature and wave height (Table 4).

Recruit and juvenile pipis were more abundant closer to the low water mark (Figure 7; Figure 8), whereas adults were more abundant higher on the beach (Figure 9). All life stages were also more abundant on steeper parts of the beach which are more common in the southeast region of Venus Bay (Figure 7; Figure 8; Figure 9). The tidal conditions at the time of sampling had variable impact on each life stage: recruits were found in higher abundance at low or high tides (Figure 7), whereas adult were more abundant in between tides (Figure 9). Recruits were more abundant when the previous day had big waves (Figure 7), whereas juvenile and adult abundance was lower after prolonged periods of high wave conditions (Figure 8; Figure 9). Likewise, recruits were more abundant following hotter days whereas juvenile and adults were most abundant following cooler periods.

Despite the evidence that environmental conditions at the core, transect and bay scale affect pipi abundance (Table 4), we still detected a clear signal of fishing impact on juvenile and adult pipis (Figure 8; Figure 9). Our analyses indicate that harvest is locally reducing pipi abundance with higher numbers of larger pipis persisting in areas that are less accessible to harvesters. It is important to note that this is not an indication of the sustainability of the pipi resource in Venus Bay. It shows that fishing has a localised impact at beach access points which is to be expected as all forms of recreational fishing have an impact on wild populations. For example, line fishing can reduce the abundance and size of target species (Malcolm *et al.* 2018), while the size and abundance of fishes often diminishes the closer you get to fisher access points such as jettys or boat ramps (Holles *et al.* 2013).

Further, the observed local reduction of juvenile and adult pipis does not appear to be impacting on local recruitment given that pipi recruits are common right across Venus Bay at all times of the year (Figure 4). In addition, there is a large, and valuable pipi population in the southeast region of Venus Bay that could be playing a significant role in the production of pipi recruits. Previous genetic studies have identified relatively large-scale mixing of pipi populations along Australia's east coast (Miller *et al.* 2013), suggesting that local recruitment (i.e. pipis on a given beach were spawned there) is less important for pipis. Further research is needed to understand how important small spatial and temporal scale recruitment is on sustaining pipi populations.

Table 4: Model selection table for the five best environmental models explaining each of, recruit, juvenile, adult and total Pipi abundance. The intercepts, environmental predictor variables – linear term (quadratic term), degrees of freedom, AICc, delta AICc and log likelihood values are shown. Only environmental variables included in at least one of the five best models from any age class are included in the table. Bold lines show the best model for each age class, used in all further analysis. See Table 1 for variable descriptions.

	intercept	distance	fish	Pslope	tideH	tideC	waveH.pd	waveH.pm	waveH.p2m	Tmax.pd	Tmax.pm	Tmax.p2m	Tav.p2m	**df**	**AICc**	**delta**	**logLik**
recruit	**-0.886**	**1.626 (-0.745)**	**0.222 (-0.263)**	**-0.591 (-0.111)**	**0.056 (0.404)**		**0.274 (0.428)**			**0.703 (-0.214)**				**14**	**1720.687**	**0**	**-846.186**
	-1.021	1.507 (-0.737)	0.208 (-0.247)	-0.393	0.042 (0.415)		0.291 (0.414)			0.715 (-0.222)				13	1722.413	1.726	-848.071
	-1.163	1.583 (-0.738)		-0.547 (-0.094)	0.050 (0.397)		0.271 (0.420)			0.695 (-0.207)				12	1723.248	2.562	-849.508
	-1.26	1.486 (-0.733)		-0.383	0.039 (0.407)		0.286 (0.408)			0.707 (-0.214)				11	1723.913	3.226	-850.858
	-1.164	1.576 (-0.732)	0.068	-0.538 (-0.096)	0.057 (0.397)		0.277 (0.422)			0.694 (-0.205)				13	1724.483	3.796	-849.106
juvenile	**1.348**	**0.193 (-0.092)**	**0.211**	**-0.374 (-0.087)**	**0.004 (0.035)**			**-0.354 (0.081)**			**-0.164 (-0.039)**			**13**	**9614.363**	**0**	**-4794.046**
	1.348	0.183 (-0.095)	0.203	-0.374 (-0.087)				-0.347 (0.077)			-0.153			10	9614.939	0.576	-4797.388
	1.374	0.182 (-0.093)	0.205	-0.370 (-0.086)				-0.352 (0.078)			-0.165 (-0.029)			11	9615.014	0.651	-4796.409
	1.349	0.185 (-0.095)	0.201	-0.376 (-0.087)		-0.021		-0.345 (0.077)			-0.156			11	9615.089	0.726	-4796.446
	1.374	0.184 (-0.093)	0.203	-0.372 (-0.086)		-0.021		-0.349 (0.078)			-0.168 (-0.028)			12	9615.276	0.913	-4795.522
adult	**-0.452**	**-0.330 (-0.183)**	**1.040 (-0.400)**	**-0.571 (-0.161)**	**0.106 (-0.119)**				**-0.924 (-0.205)**			**-0.702 (0.260)**		**14**	**3061.756**	**0**	**-1516.721**
	-0.492	-0.341 (-0.189)	1.048 (-0.403)	-0.580 (-0.162)	0.123 (-0.125)				-0.680 (-0.209)				-0.473 (0.319)	14	3062.046	0.29	-1516.866
	-0.81	-0.327 (-0.184)	0.787	-0.571 (-0.159)	0.104 (-0.124)				-0.932 (-0.204)			-0.709 (0.261)		13	3066.39	4.634	-1520.059
	-0.853	-0.339 (-0.190)	0.792	-0.580 (-0.159)	0.121 (-0.131)				-0.687 (-0.208)				-0.479 (0.319)	13	3066.722	4.966	-1520.225
	-0.8	-0.296 (-0.195)	1.111 (-0.441)	-0.609 (-0.167)		-0.055 (0.209)			-0.649 (-0.201)				-0.453 (0.326)	14	3068.407	6.651	-1520.046

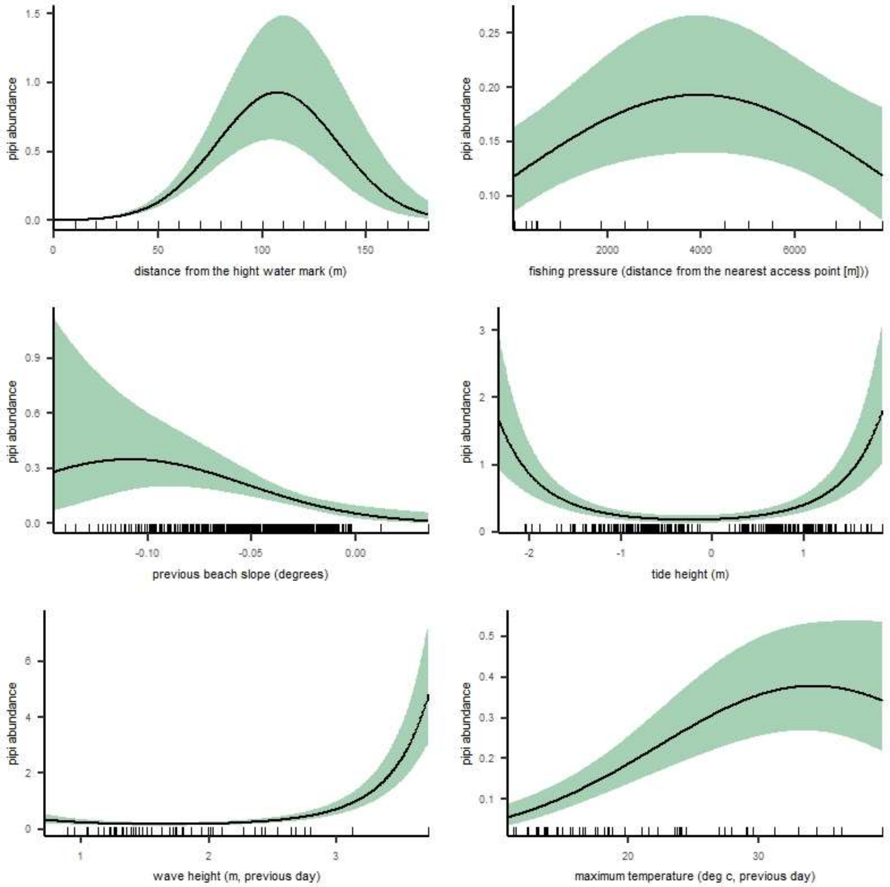

Figure 7: Predicted effects of environmental variables on pipi recruit abundance. Only the environmental variables included in the best model are shown. Values have been transformed back to their original scales. Black lines represent the best fit and green shaded areas the 95% confidence intervals.

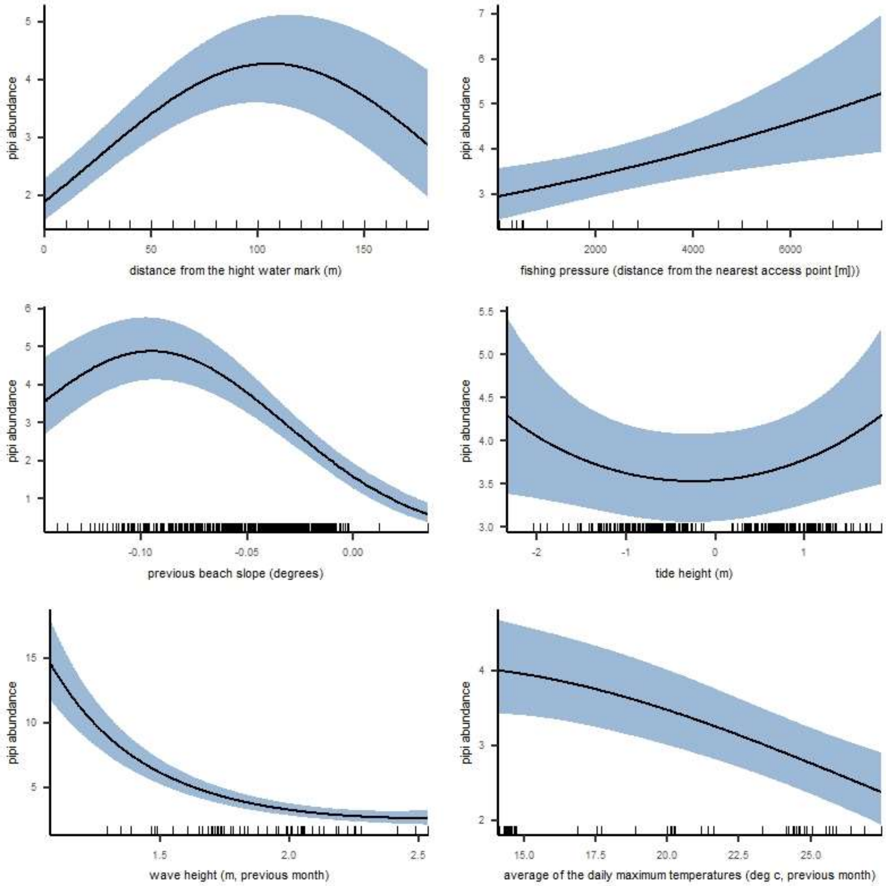

Figure 8: Predicted effects of each environmental variable on juvenile pipi abundance. Only the environmental variables included in the best model are shown. Values have been transformed back to their original scales. Black lines represent the best fit and blue shaded areas the 95% confidence intervals.

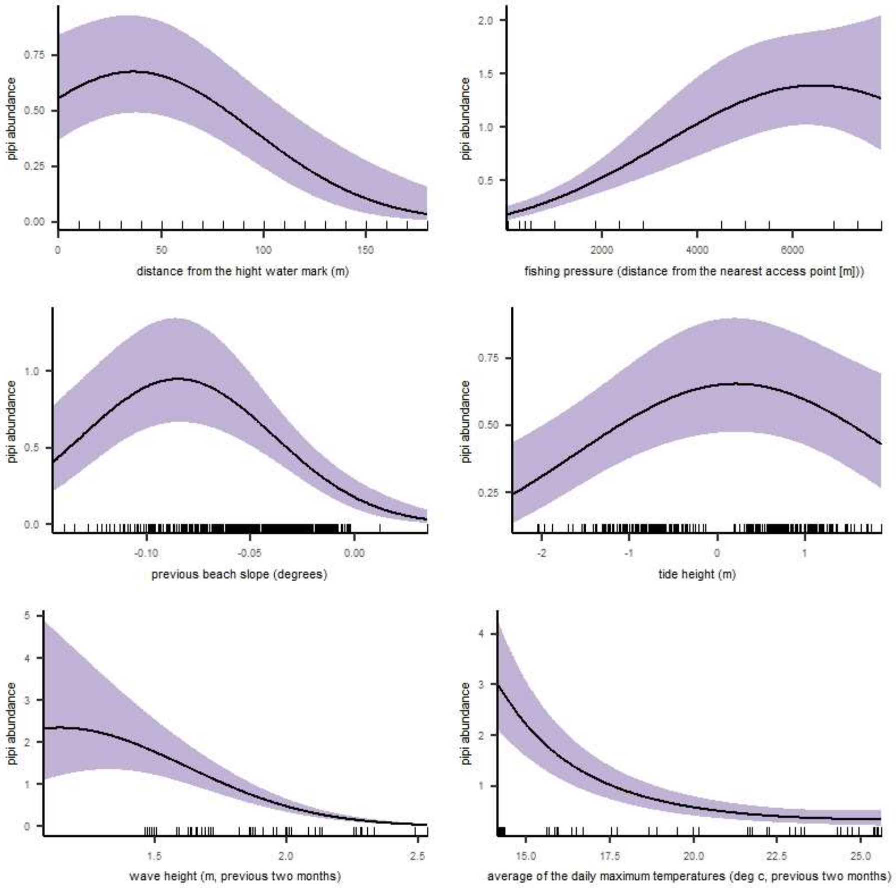

Figure 9: Predicted effects of each environmental variable on adult Pipi abundance. Only the environmental variables included in the best model are shown. Values have been transformed back to their original scales. Black lines represent the best fit and purple shaded areas the 95% confidence intervals.

Biomass comparisons with previous studies

There was considerable spatial, seasonal and inter-annual variation in pipi biomass at Venus Bay (Figure 10). The maximum observed biomass for each season was: spring 0.5 kg/m^2 (2016), summer 3kg/m^2 (2013), autumn 1.2kg/m^2 (2017) and winter 1.8kg/m^2 (2017). Data was available across multiple studies for spring and summer. In Spring, biomass was relatively constant, ranging from 0.11kg/m^2 in 2009and 0.12kg/m^2 in 2011 to 0.07-0.14kg/m^2 in 2016-17. In summer, biomass was more variable, ranging from 0.14kg/m^2 in 2009 to 0.52kg/m^2 in 2013 and then back down to 0.09-0.12 kg/m^2 in 2015-2017.

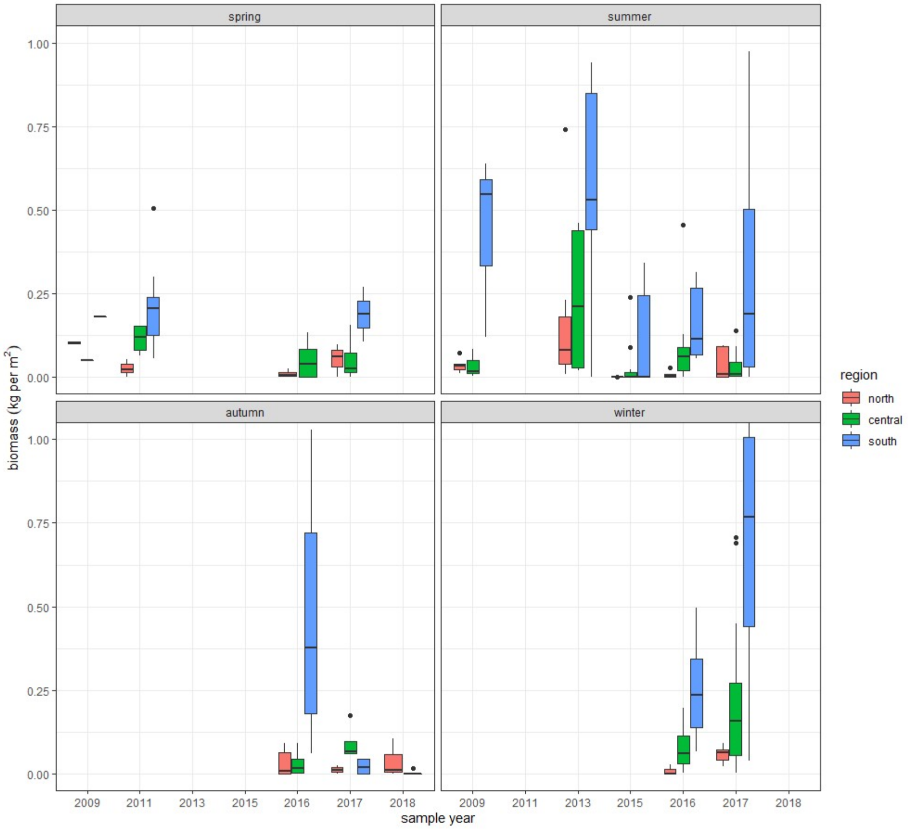

Figure 10: Boxplots of pipi biomass (kg/m^2) per transect, grouped by season and beach region across seven years of observation. For each boxplot, the horizontal black line shows the median observation (i.e. 50th percentile value). The vertical span of each box represents the interquartile range (25th to 75th percentile of observation). The wider the interquartile range, the more different transects within that grouping are to each other. 2009 data comes from Lewis et al (Lewis *et al.*), 2011 data from Early et al. (2013), 2015 data from Parry (2014) and 2015-2018 data from this study.

We formerly analysed seasonal, regional and inter-annual differences in biomass for spring and summer. Despite apparent temporal differences in spring biomass (Figure 10), the best model explaining spring biomass across the Lewis, Early and our study included just region (ΔAICc to next best mode that included region + year = 5.2). Using Tukey HSD tests, we found that South biomass was substantially higher than that in the North (p<0.001) and Central (p=0.004) regions (Figure 11). We found no observable difference between North and Central biomass (p=0.431).

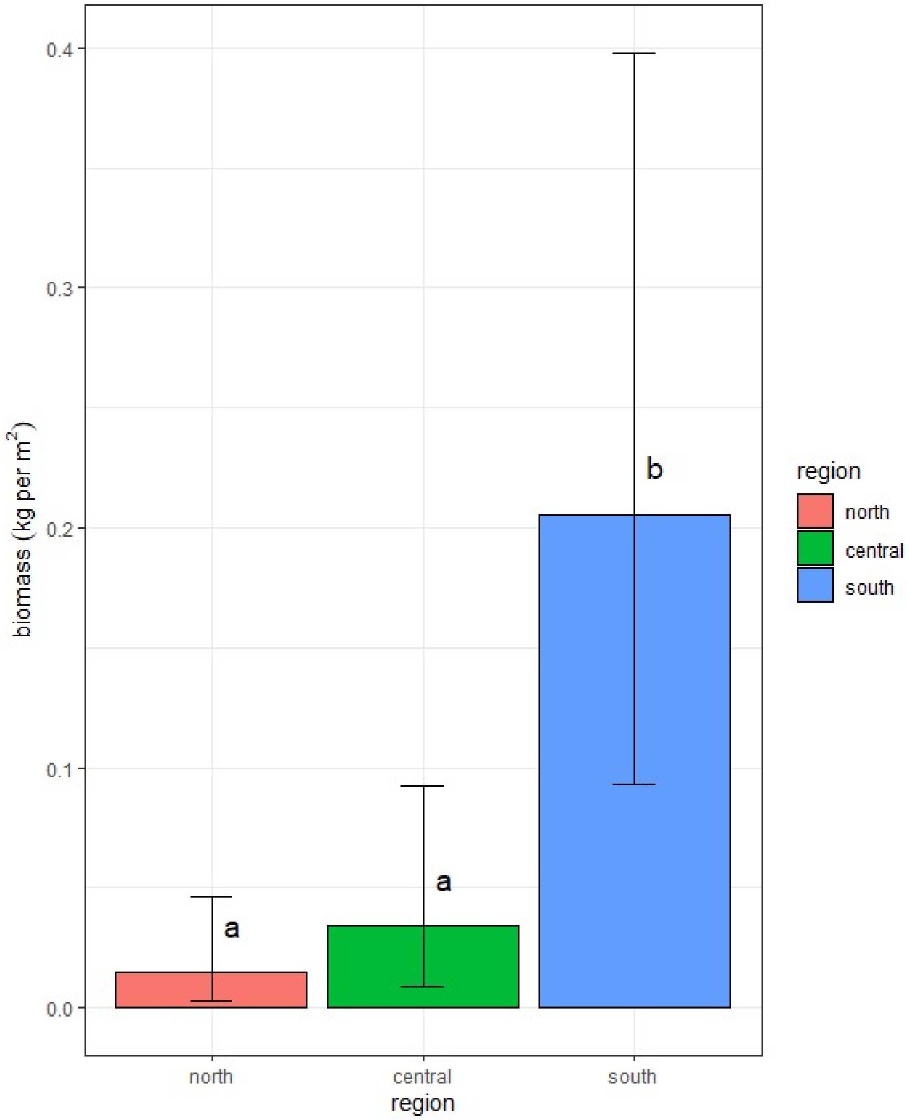

Figure 11: Predicted spring pipi biomass (+/- 95% confidence interval) for three regions at Venus Bay. Groups sharing the same letter are not significantly different from each other (alpha = 0.05, Tukey-adjusted).

The best model explaining summer biomass across the Lewis, Parry and our study included region and year (ΔAICc to next best mode that included just region = 8.4). Using Tukey HSD tests, we found that South biomass was substantially higher than that in the North (p=0.004) and Central (p=0.024) regions (

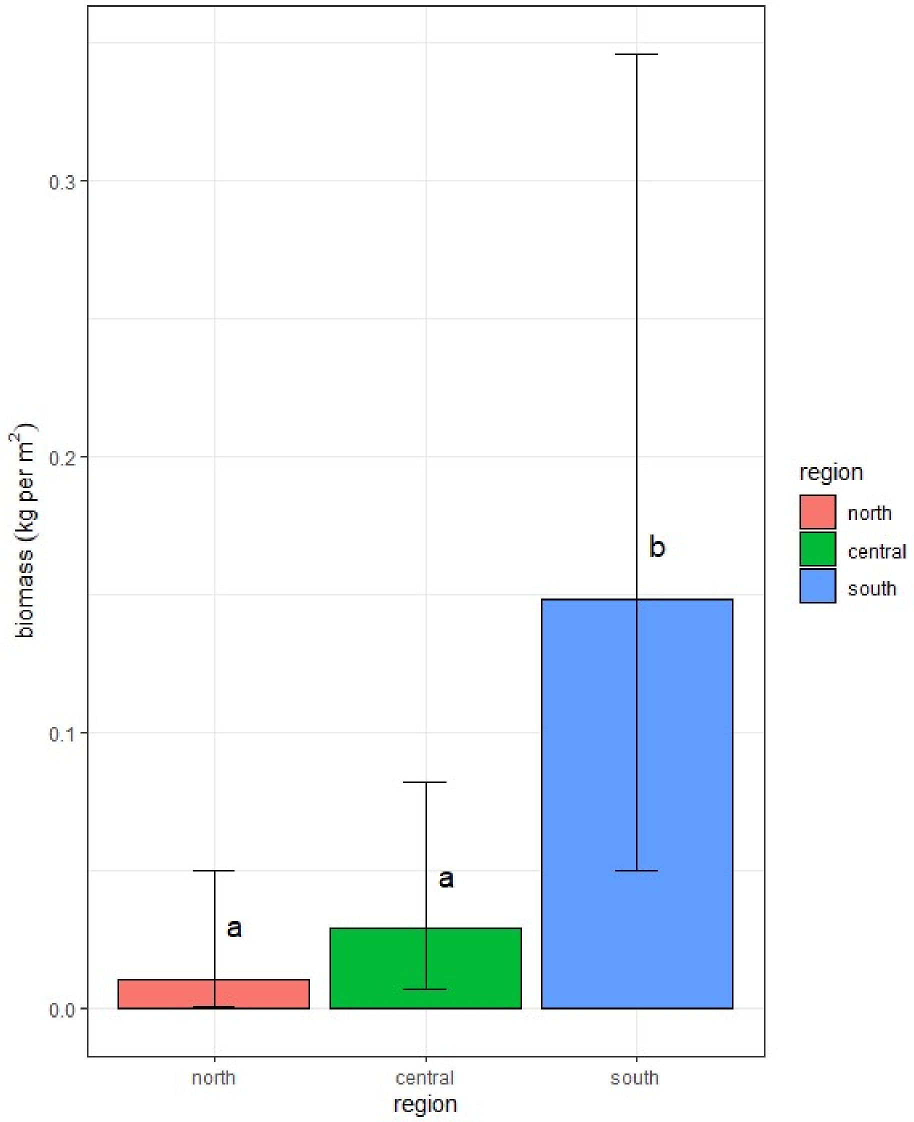

Figure 12). Again, we found no observable difference between North and Central biomass (p=0.454). Summer pipi biomass was significantly lower in 2015 compared to all other years while biomass was highest in 2013 (Figure 13). The lack of a clear temporal trend in pipi biomass across years suggests that harvesting is not having a long-term impact on the Venus Bay pipi population. Inter-annual variability in biomass is likely related to changes in environmental conditions that affect pipi recruitment, growth and survival.

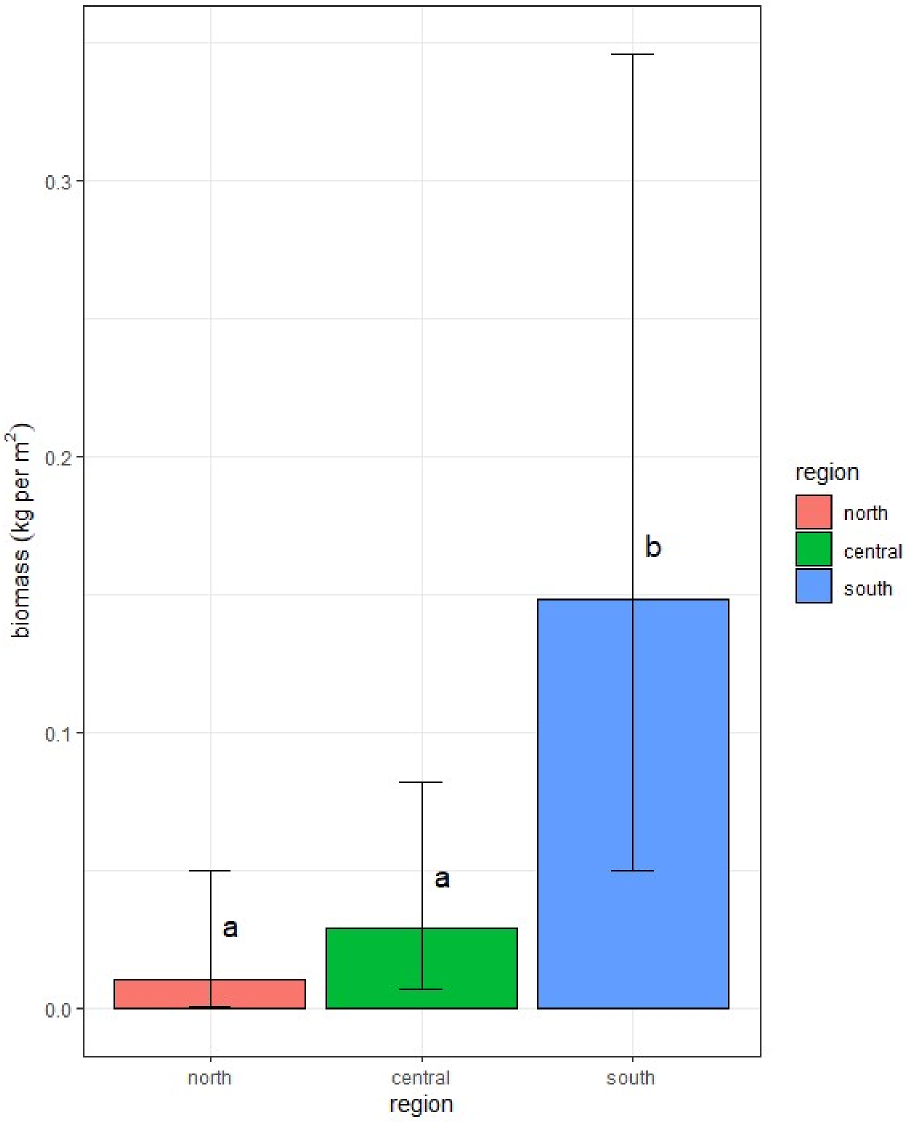

Figure 12: Predicted summer pipi biomass (+/- 95% confidence interval) for three regions at Venus Bay. Groups sharing the same letter are not significantly different from each other (alpha = 0.05, Tukey-adjusted).

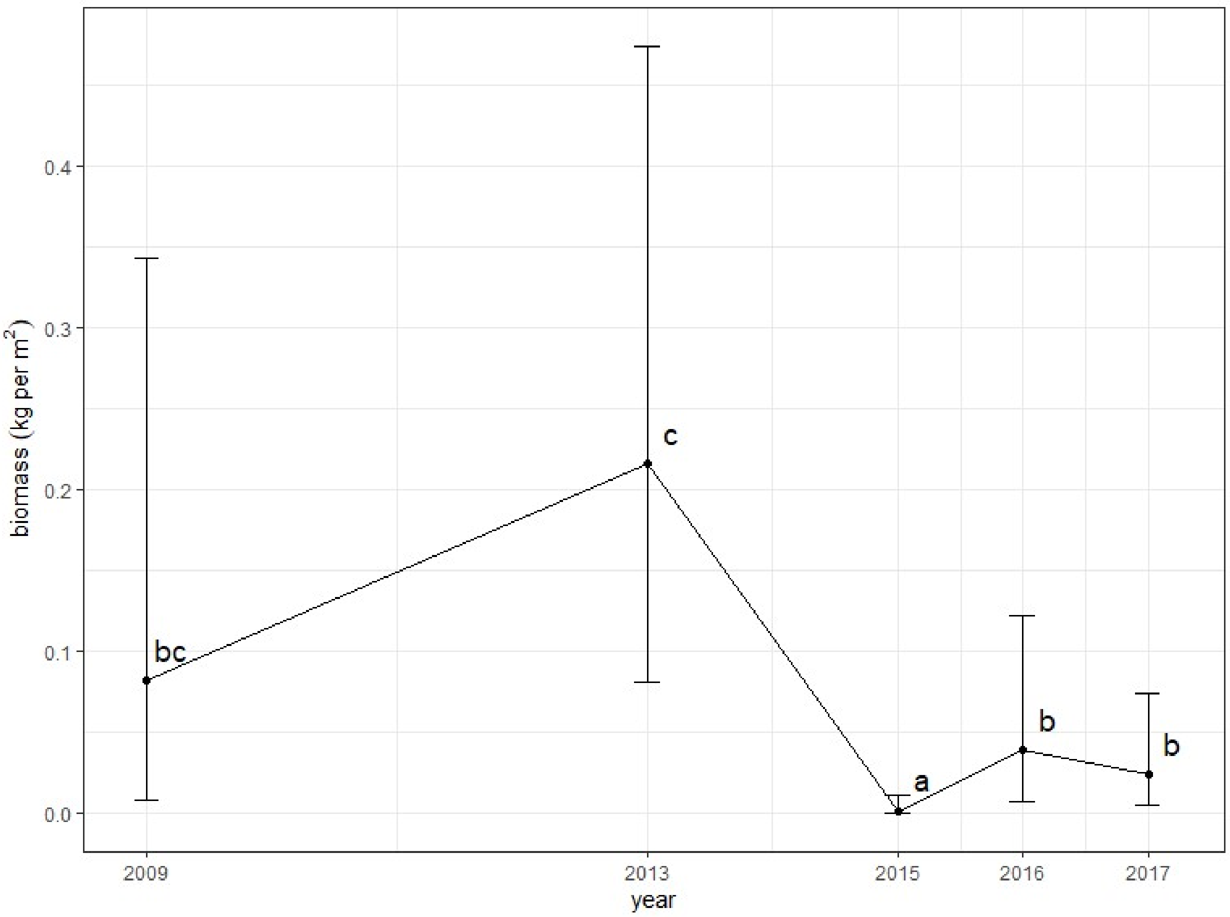

Figure 13: Predicted summer pipi biomass (+/- 95% confidence interval) across five years of sampling. Note, this project collected samples 2015-2018. Groups sharing the same letter are not significantly different from each other (alpha = 0.05, Tukey-adjusted).

Component 2: size at maturity of pipis

Methods

Sample collection

Female maturity was assessed from June 2016 to March 2018. Three transects were randomly chosen during each trip (transects changed from trip to trip), and from each of these 10 pipis were randomly sampled from all collected pipis >20 mm length (see component 1). The length of each sampled pipi was measured and then its maturity status was assessed following the methods of Murray-Jones (1999) whereby a gonad smear was prepared on a microscope slide, viewed under a compound microscope, and inspected for the presence of oocytes.

Statistical analyses

We modelled the probability of female pipis being mature as a function of month and length (mm) using a binomial generalised additive mixed model (GAMM). This model included trip as a random effect to account for the repeated measures nature of our data. We used a cyclic penalised cubic regression spline to model temporal patterns in maturity to ensure that probabilities associated with December wrapped to those associated with January (Wood 2017). Length was modelled using a cubic regression spline. We compared competing models including combinations of month and length and used AICc to identify the best one.

Results

Sexually mature females were found across all trips and made up between 20-50% of the catch (Figure 14). The smallest mature female was 27mm long (Figure 15), although across the 13 sampling events the average minimum size was 35.13mm. The average size of sexually mature females was 40.96mm.

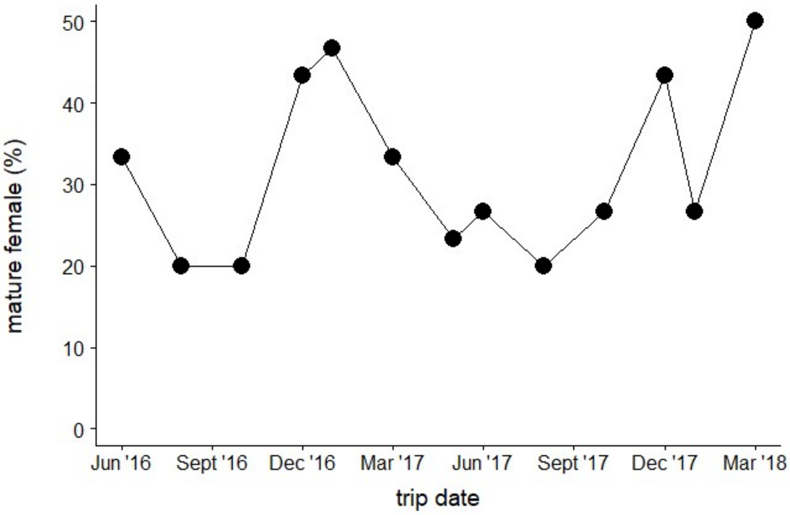

Figure 14: Temporal variation in the proportion of a 30-individual sample collected on each trip that was comprised of mature females. Remaining pipis of unknown status could be mature males or immature individuals of both sexes.

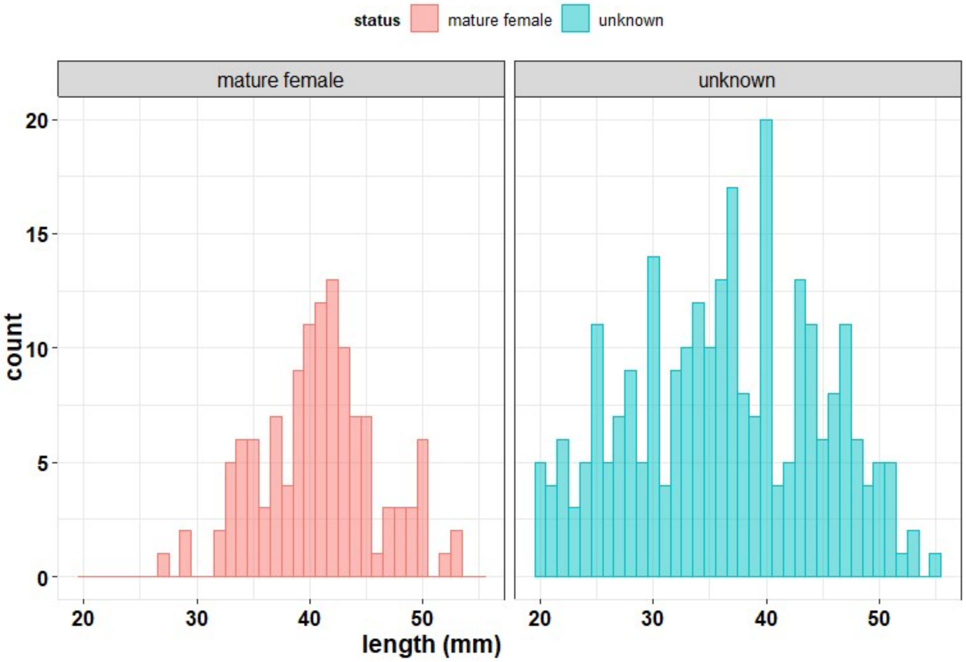

Figure 15: Length frequency histograms of sexually mature females and unknown (adult male and all juveniles) pooled across all trips.

The best model predicting the probability of collecting a mature female pipi included smoothers for length and month (

Table ***5***). Pipis above 40mm had the highest probability of being a mature female (Figure 16a) and mature females were most likely to be collected in the warmer months (November- March; Figure 16b). Caution must be taken when interpreting these results because pipis of unknown status could be juvenile females or males, or mature males. Indeed, it is likely that the presence of potentially large (>50mm) mature males (coded as unknown) in our sample has caused the apparent decline in the probability of maturity at larger sizes.

Table 5: Model selection results for competing models comparing the effects of sample month and individual length on the probability of female pipi maturity. The term ‘s’ represents a smoother fitted to a covariate (see methods for details) and df is degrees of freedom. The top ranked model (with the lowest ΔAICc) is highlighted in bold.

model	**Df**	**log likelihood**	**ΔAICc**
Intercept only	2	-243.3	50.1
s(length)	3	-240.8	47.3
s(month)	4	-218.1	3.8
s(length) + s(month)	**5**	**-215.2**	**0**

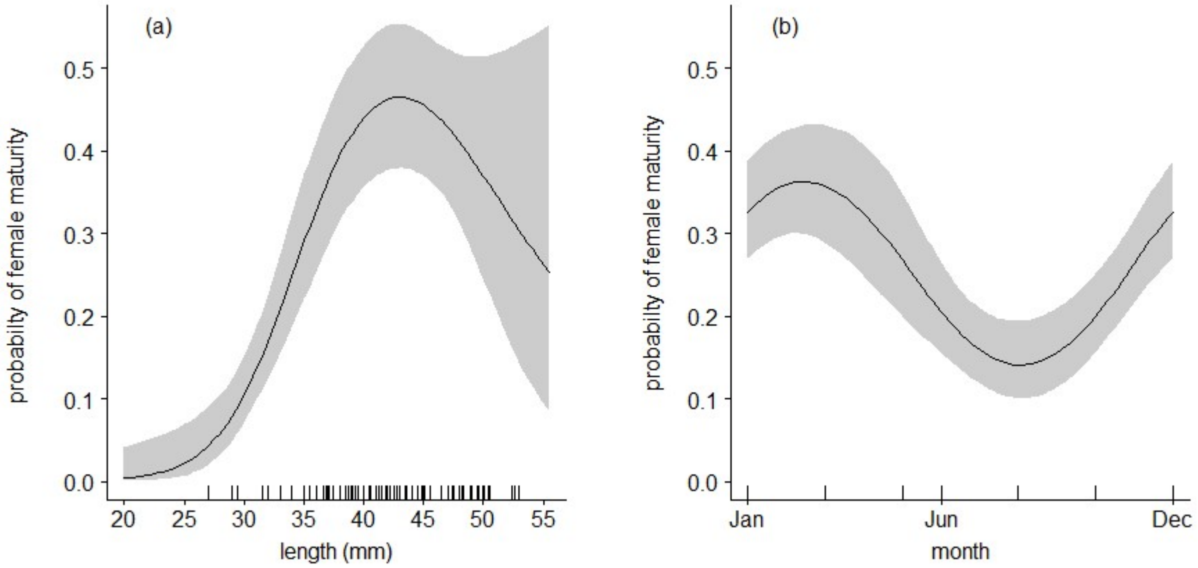

Figure 16: Predicted probability (±95% CI) of collecting a mature female pipi as a function of (a) length and (b) month. Short vertical lines on x axis for both panels indicate the size and collection month of mature females.

Discussion

Our results suggest that Venus Bay pipis spawn year-round, with a peak of spawning activity during summer. This pattern is consistent with spawning in other parts of the pipis range: New South Wales pipis generally had mature ovaries year round although they were less common in July (Murray-Jones 1999) whilst in South Australia mature individuals were found year round with a peak in spring-summer (King 1976; Ferguson 2013). The minimum size at maturity for Venus Bay pipis detected in our study (27mm) is the same as that in NSW (27mm; Murray-Jones 1999). A more useful metric for fisheries assessment, however, is the length at which 50% of individuals are mature (L_{50}). NSW L_{50} is 37mm (Murray-Jones 1999) whilst SA pipis are smaller (28 mm or 36 mm depending on study; King 1976; Ferguson 2013). We could not directly estimate L_{50} in our samples due to difficulties in identifying sexually mature males. Nonetheless, the average minimum size of mature females across all our samples (~35mm), and the high probability of females being mature ≥40mm, suggests that there are similarities in maturation patterns across pipi's geographic range.

The recreational harvest at Venus Bay predominantly occurs over the summer months and is concentrated around beach access points (Victorian Fisheries Authority 2018a). It is possible that harvesting could impact on the productivity (number of offspring produced) of Venus Bay's pipi population as it coincides with the period of peak spawning. Likewise, the targeted harvesting of larger individuals that also release more eggs (Murray-Jones 1999) could impact on recruitment success. The minimum size of 35mm for the Victorian commercial fishery (Victorian Fisheries Authority 2018b) offers some protection to pipis as individuals will get a chance to breed once before capture. The commercial fishery is also subject to catch quotas and zoning to ensure it remains sustainably managed.

There is no minimum legal size for recreational anglers. We believe that current levels of recreational harvest may be having an impact on Venus Bay's pipi fishery productivity but there are relatively high abundances of larger pipis away from beach access points that will continue to produce offspring. Further, the ubiquity of new recruits across the beach, and the importance of environmental variation in determining recruitment patterns (component 1) suggest that other factors aside from harvest can be important in determining stock size.

The temporal pattern of inferred spawning based on our maturity assays aligns with seasonal peaks in observed recruitment (component 1). The large numbers of small pipis detected in our corer survey in December to February are likely to be ~2-3 months old, meaning that they originated from spawning that occurred in October to December. More research is needed before we can speculate on whether Venus Bay experiences high or low levels of self-recruitment (pipis spawned on Venus Bay return to Venus Bay). This is important from a fisheries management perspective because populations strongly reliant on self-recruitment become more vulnerable to the impacts of localised fishing (Strathmann *et al.* 2002; Botsford *et al.* 2009).

Component 3: Exploration of movement patterns

Methods

In early January 2017, 2000 pipis >30mm were collected from Venus Bay Beach and tagged with uniquely coded glue-on shellfish tags (Figure 17). The tagged pipis were released into the surf at the Beach 1 access point (Figure 14). The following day (6/1/17), over 150 members of the public helped us try and find the tagged pipis at this location in an event called 'The Great Pipi Hunt'. Subsequent recapture dates and locations were reported by the public via email. Core reported search effort was within 5-6 km northwest and 2km southest of the Beach 1 access point.

Figure 17: Tagged pipis prior to release.

Results

74 (3.7%) of the 2000 tagged pipis were recaptured over a period of 12 months, with three pipis recaptured twice. The majority of pipis were recaptured within 200m of the release point (Figure 18), and during the first four weeks of the study. Two pipis were recaptured in the following summer after 357 and 367 days. There was no clear relationship between distance moved by pipis and their time at liberty: the biggest movement of just over 2km was recorded in week 4 (Figure 19), whilst a pipi caught in week 11 had only moved 125m. 29 pipis moved

greater than 200m from their release point. 11 of these moved to the northwest and 18 to the southeast.

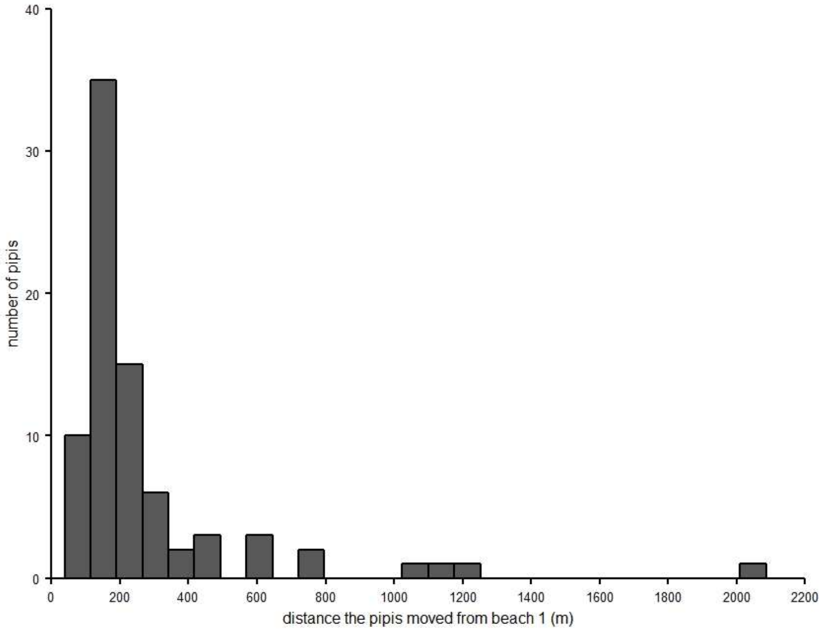

Figure 18: Frequency histogram of pipi recaptures as a function of distance from release location (Beach 1 access point).

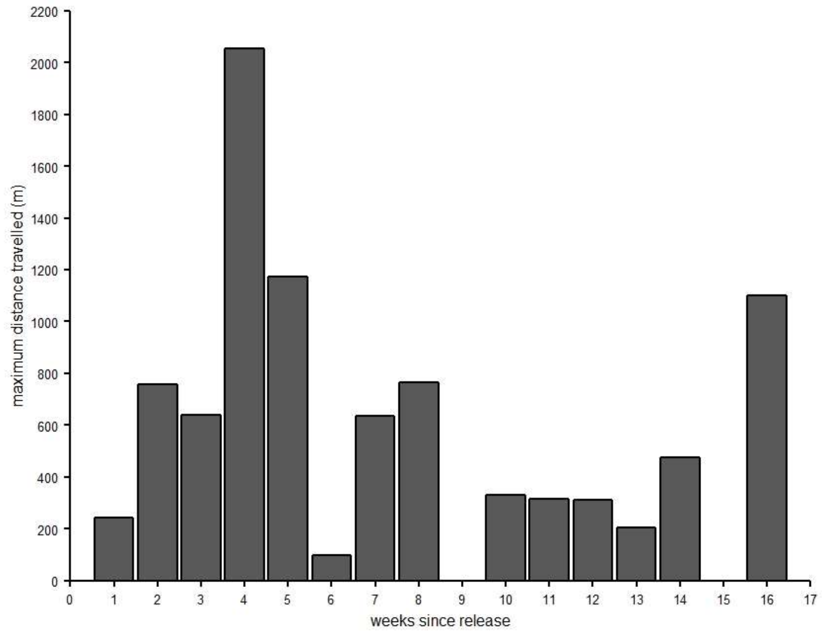

Figure 19: Maximum distance travelled by pipis during the first 17 weeks of the study. Note, the two pipis caught in weeks 51 and 53 are not shown here- they moved 211m and 1187m respectively.

Discussion

Our data suggests that some adult pipis, despite actively moving up and down the shore with the tide cycle, do not move very far along the beach even over the course of a year. It is important to recognise that we have relied heavily on recreational anglers to report recaptures and therefore our data set is biased to where and when anglers harvest (here 5-6 km NW and 2 km SE Beach 1).

It is plausible that some tagged pipis may have moved considerably further to the southeast away from access points, but that these movements were not detected due to limited sampling effort occurring in these areas. That said, one third of recaptured pipis that made movements >200m did so to the northwest towards beach access 2-5 (Figure 1) where considerable recreational harvest effort occurs. The furthest one of these pipis moved was 2km where it was recaptured at Beach 3. Considerable recreational harvest also occurs within 2km to the southeast of Beach 1 yet relatively few pipis were recaptured here. These results suggest that if larger movements were more common, then more pipis would likely have been detected to the northwest given that recreational harvesters were active up to 6km in this direction from the release point. A similar tagging study undertaken in the Coorong by Nature Glenelg Trust also reported restricted pipi movements (pipi at liberty for 409 days moved just 1.2km; Whiterod 2019).

Restricted adult movements could increase the vulnerability of pipi populations to local depletion due to harvesting. This is because new adults are unlikely to move into an area and replenish harvested individuals. Instead, the recovery of pipi biomass after harvest will most likely occur due to the recruitment and growth of juveniles.

Photo: Venus Bay

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Appendix

Supplementary Table 1: Detailed description of how each environmental variable was calculated

Variable	Name	Calculation / Description
date and time	$Dtime$	a string for the date and time of each sample i
previous day	$.d$	$.d_i = \sum_{date_{i-1}} \left(\frac{predictor\ vairable_i}{n}\right)$
previous week	$.w$	$.w_i = \sum_{date_{i-1}}^{date_{i-5}} \left(\frac{predictor\ variable_i}{n}\right)$
previous month	$.pm$	$.pm_i = \sum_{date_{i-1}}^{date_{i-30}} \left(\frac{predictor\ variable_i}{n}\right)$
previous two months	$.p2m$	$.p2m_i = \sum_{date_{i-1}}^{date_{i-60}} \left(\frac{predictor\ variable_i}{n}\right)$
slope	$slope$	$slope_i = \frac{(h2_{ij} - h1_{ij})}{(d2_{ij} - d1_{ij})}$
previous slope	$Plope$	$Pslope_i = \frac{(h2_{ij-1} - h1_{ij-1})}{(d2_{ij-1} - d1_{ij-1})}$
Tide height	$tideHeight$	$if\ tideHeight_i = I \rightarrow true = th_i,$ $false = th_i \times -1$
Tide cycle	$tideCycle$	$if\ tideCycle_i = I \rightarrow true = tc_i + 50,$ $false = tc_i$
Beach slope – extra variables		

device height	h	$h_j = \left(a_j - \frac{a_{j+1}}{100}\right) \times -1$	where a is the height of the device, b is the distance of the device from the top of the transect and j is each significant change in slope along the transect
device distance	d	$d_j = \left(b_j - b_{j+1}\right) \times 100$	
Tide – extra variables			
greater than tide time	GT	The time of the closest tide measurement that is greater than $Dtime_i$	
less than tide time	LT	The time of the closest tide measurement that is less than $Dtime_i$	
greater than tide height	GH	The tide height at GT_i	
less than tide height	LH	The tide height at LT_i	
Incoming or outgoing tide	$I\ or\ O$	$if\ GT_i > LT_i \rightarrow true = O, false = I$	
low tide	$lowT$	$lowT_i = \min(GT_i\ and\ LT_i)$	
high tide	$highT$	$highT_i = \max(GH_i\ and\ LH_i)$	
t height	th	$th_i = LH_i + (GH_i - LH_i) \times \frac{\cos\left(\pi\left(\left(\frac{Dtime_i - LT_i}{GT_i - LT_i}\right) + 1\right) + 1\right)}{2}$	
t cycle	tc	$tc_i = \left(\frac{th_i - lowT_i}{highT_i - lowT_i}\right) \times 50$	

References

Ansell, A.D. (1983) The biology of the genus Donax. *Sandy beaches as ecosystems*, pp. 607-635. Springer.

Arlinghaus, R. (2006) On the apparently striking disconnect between motivation and satisfaction in recreational fishing: the case of catch orientation of German anglers. *North American Journal of Fisheries Management,* **26,** 592-605.

Arlinghaus, R., Cooke, S.J., Lyman, J., Policansky, D., Schwab, A., Suski, C., Sutton, S.G. & Thorstad, E.B. (2007) Understanding the Complexity of Catch-and-Release in Recreational Fishing: An Integrative Synthesis of Global Knowledge from Historical, Ethical, Social, and Biological Perspectives. *Reviews in Fisheries Science,* **15,** 75-167.

Botsford, L.W., Brumbaugh, D.R., Grimes, C., Kellner, J.B., Largier, J., O'Farrell, M.R., Ralston, S., Soulanille, E. & Wespestad, V. (2009) Connectivity, sustainability, and yield: bridging the gap between conventional fisheries management and marine protected areas. *Reviews in Fish Biology and Fisheries,* **19,** 69-95.

Burnham, K.P. & Anderson, D.R. (2002) *Model Selection and Inference: a Practical Information-Theoretic Approach,* second edn. Springer-Verlag, New York, USA.

Clark, A. (2017) *The Catch: The Story of Fishing in Australia*. National Library of Australia.

Cooke, S.J. & Cowx, I.G. (2004) The role of recreational fishing in global fish crises. *Bioscience,* **54,** 857-859.

Cooke, S.J., Twardek, W.M., Lennox, R.J., Zolderdo, A.J., Bower, S.D., Gutowsky, L.F.G., Danylchuk, A.J., Arlinghaus, R. & Beard, D. (2018) The nexus of fun and nutrition: Recreational fishing is also about food. *Fish and Fisheries,* **19,** 201-224.

Defeo, O. (2003) Marine invertebrate fisheries in sandy beaches: an overview. *Journal of Coastal Research***,** 56-65.

Early, J., Lewis, Z., Scarr, M. & Scarpaci, C. (2013) Stock assessment of Venus Bay Pipis, 2011. Final Recreational Fishing Grants Program Research Report, Melbourne.

Ellers, O. (1995) Behavioral control of swash-riding in the clam *Donax variabilis*. *The Biological Bulletin,* **189,** 120-127.

Feiner, Z.S., Chong, S.C., Knight, C.T., Lauer, T.E., Thomas, M.V., Tyson, J.T. & Höök, T.O. (2015) Rapidly shifting maturation schedules following reduced commercial harvest in a freshwater fish. *Evolutionary Applications,* **8,** 724-737.

Ferguson, G. & Mayfield, S. (2006) The South Australian goolwa cockle (*Donax deltoides*) fishery. *SARDI Research Report Series,* **150,** 30.

Ferguson, G. & Ward, T. (2014) Support for havesting strategey development for South Australia's Lakes and Coorrong fishery for pipi (*Donax deltoides*). *Fisheries Research and Development Corporation Final Report*.

Ferguson, G.J. (2013) Pipi (*Donax deltoides*) Fishery. Fishery stock assessment report for PIRSA Fisheries and Aquaculture. *SARDI Research Report Series No. 731*. South Australian Research and Development Institute (Aquatic Sciences), Adelaide.

Fisheries Victoria (2014) Fisheries (Victorian Pipi) Notice No. 12/2014. *Victoria Government Gazette*. Melbourne.

Frankel, D. (2017) *Between the Murray and the Sea: Aboriginal Archaeology of Southeastern Australia*. Sydney University Press.

Godfrey, M.C.S. (1989) Shell midden chronology in southwestern Victoria: reflections of change in prehistoric population and subsistence? *Archaeology in Oceania,* **24,** 65-69.

Gray, C.A. (2016) Tide, time and space: scales of variation and influences on structuring and sampling beach clams. *Journal of Experimental Marine Biology and Ecology,* **474,** 1-10.

Henry, G.W. & Lyle, J.M. (2003) National recreational and indigenous fishing survey.

Hilborn, R., Amoroso, R.O., Anderson, C.M., Baum, J.K., Branch, T.A., Costello, C., de Moor, C.L., Faraj, A., Hively, D., Jensen, O.P., Kurota, H., Little, L.R., Mace, P., McClanahan, T., Melnychuk, M.C., Minto, C., Osio, G.C., Parma, A.M., Pons, M., Segurado, S., Szuwalski, C.S., Wilson, J.R. & Ye, Y. (2020) Effective fisheries management instrumental in improving fish stock status. *Proceedings of the National Academy of Sciences,* **117,** 2218-2224.

Holles, S., Simpson, S.D., Radford, A.N., Berten, L. & Lecchini, D. (2013) Boat noise disrupts orientation behaviour in a coral reef fish. *Marine Ecology Progress Series,* **485,** 295-300.

Kailola, P.J., Williams, M.J., Stewart, P.C., Reichelt, R.E., McNee, A. & Grieve, C. (1993) *Austraian Fisheries Resources*. Bureau of Resource Sciences, Department of Primary Industries and Energy, and the Fisheries Research and Development Corporation, Canberra.

King, M.G. (1976) The life history of the Goolwa cockle *Donax (Plebidonax) deltoides* (Bivalvia: Donacidae), on an ocean beach, South Australia. . *Unpublished Internal Report No. 85*. South Australian Department of Fisheries, Adelaide.

King, M.G. (1985) A review of the Goolwa cockle. SAFIC 9, 14.

Lewin, W.-C., Weltersbach, M.S., Ferter, K., Hyder, K., Mugerza, E., Prellezo, R., Radford, Z., Zarauz, L. & Strehlow, H.V. (2019) Potential environmental impacts of recreational fishing on marine fish stocks and ecosystems. *Reviews in Fisheries Science & Aquaculture,* **27,** 287-330.

Lewis, Z., Giri, K., Versace, V.L. & Scarpaci, C. (2013) Applying stock indicators for assessment of a recreational surf clam (*Donax deltoides*) fishery in Victoria, Australia. *Journal of the Marine Biological Association of the United Kingdom,* **93,** 1381-1387.

Malcolm, H.A., Williams, J., Schultz, A.L., Neilson, J., Johnstone, N., Knott, N.A., Harasti, D., Coleman, M.A. & Jordan, A. (2018) Targeted fishes are larger and more abundant in 'no-take'areas in a subtropical marine park. *Estuarine, Coastal and Shelf Science,* **212,** 118-127.

Mapstone, B.D., Little, L.R., Punt, A.E., Davies, C.R., Smith, A.D.M., Pantus, F., McDonald, A.D., Williams, A.J. & Jones, A. (2008) Management strategy evaluation for line fishing in the Great Barrier Reef: Balancing conservation and multi-sector fishery objectives. *Fisheries Research,* **94,** 315-329.

McLachlan, A., Dugan, J.E., Defeo, O., Ansell, A., Hubbard, D., Jaramillo, E. & Penchaszadeh, P. (1996) Beach clam fisheries. *Oceanography and Marine Biology: an Annual Review*.

McLachlan, A. & Hesp, P. (1984) Surf zone diatom accumulations on the Australian coast. *Search,* **15,** 230-231.

Miller, A.D., Versace, V.L., Matthews, T.G., Montgomery, S. & Bowie, K.C. (2013) Ocean currents influence the genetic structure of an intertidal mollusc in southeastern Australia – implications for predicting the movement of passive dispersers across a marine biogeographic barrier. *Ecology and evolution,* **3,** 1248-1261.

Morrongiello, J.R., Sweetman, P. & Thresher, R.E. (2019) Fishing constrains phenotypic responses of marine fish to climate variability. *Journal of Animal Ecology,* **88,** 1645-1656.

Murray-Jones, S. (1999) Conservation and management in variable environments: the surf clam, *donax deltoides*, . Doctor of Philosophy thesis, University of Wollongong.

Murray-Jones, S. & Steffe, A.S. (2000) A comparison between the commercial and recreational fisheries of the surf clam, Donax deltoides. *Fisheries Research,* **44,** 219-233.

P. McPhee, D., Leadbitter, D. & A. Skilleter, G. (2002) Swallowing the bait: is recreational fishing in Australia ecologically sustainable? *Pacific Conservation Biology,* **8,** 40-51.

Parks Victoria (2003) *Cape Liptrap Coastal Park management plan*. Parks Victoria, Melbourne.

Parry, G.D. (2014) Monitoring of the pipi (*Donax deltoides*) at Cape Liptrap Coastal Park, Venus Bay, Victoria, December 2013. Marine Ecological Solutions, Queenscliff.

Post, J.R., Sullivan, M., Cox, S., Lester, N.P., Walters, C.J., Parkinson, E.A., Paul, A.J., Jackson, L. & Shuter, B.J. (2002) Canada's recreational fisheries: The invisible collapse? *Fisheries,* **27,** 6-17.

Strathmann, R.R., Hughes, T.P., Kuris, A.M., Lindeman, K.C., Morgan, S.G., Pandolfi, J.M. & Warner, R.R. (2002) Evolution of local recruitment and its consequences for marine populations. *Bulletin of Marine Science,* **70,** 377-396.

Venturelli, P.A., Hyder, K. & Skov, C. (2017) Angler apps as a source of recreational fisheries data: opportunities, challenges and proposed standards. *Fish and Fisheries,* **18,** 578-595.

Victorian Fisheries Authority (2018a) Recreational pipi fishery https://vfa.vic.gov.au/recreational-fishing/pipis-now-and-forever.

Victorian Fisheries Authority (2018b) Victorian pipi fishery management plan 2018. Victorian Fisheries Authority (VFA), Melbourne.

Victorian Fisheries Authority (2020) Catch limits and closed seasons- pipis.

Whiterod, N. (2019) http://natureglenelg.org.au/the-great-goolwa-cockle-challenge-continues/.

Wood, S.N. (2017) *Generalized additive models: an introduction with R*. Chapman and Hall/CRC.