Progress report for project 2020-065 "Indicators for density and biomass of exploitable abalone – developing and applying a new approach"

13 September 2022
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Background

The objectives of this project are to use the Victorian Western Zone (WZ) abalone fishery to develop and evaluate a new approach to calculating abalone density and biomass indicators from the combination of three information sources. The three information sources are:

i. Logbook reported catch and effort,
ii. Global Positioning System (GPS) logger records plus depth and catch from fishers, and
iii. Fishery Independent Survey (FIS) observations collected by the government Victoria Fisheries Authority (VFA) and surveys done by the Western Abalone Divers Association (WADA).

The approach to calculating abalone density and biomass indicators is based on methods developed for the WZ fishery since the major mortalities caused by outbreaks of Abalone Viral Ganglioneuritis (AVG) virus during 2006 and 2007 (e.g., Gorfine et al., 2007). The AVG caused significant mortalities, about 60-90% of all sizes of abalone in three of the four Spatial Management Units (SMU). After the AVG outbreaks, parts of the WZ abalone fishery were closed for 3-5 years, depending on the area, with the uninfected SMU (Lady Julia Percy) not being closed by AVG and being fished longer than the SMU with infection. The VFA conducted the FIS program throughout this period, with some minor breaks both pre- and post- the AVG mortalities. The fishery was then slowly reopened, at different times spatially, initially with biomass estimates from FIS and structured fishing surveys in key areas by WADA, and later also with the continuing VFA FIS and extended surveys by WADA. The information available, the methods of analysis and the level of precaution in management decision-making evolved as the fishery reopened and expanded. Initially a very high level of management precaution was applied to the LML (initially 135 mm), to the allowable catch (initially for a harvest fraction of 5% of a lower estimate of the exploitable biomass) and allowing fishing only in areas that were historically productive. This management precaution was relaxed somewhat as information on the stock and its recovery increased and as consistent production from the stock increased.

This project consolidates and summarises the recent approaches and methods used to monitor abalone in the WZ abalone fishery since the AVG mortality. The project also elaborated some technical aspects of these analyses, and some of these developments are described here. These new developments had some different effects but generally they did not provide different interpretations compared to the historical methods, and so the recent methods are accepted as appropriate for abalone assessment. A key part of project, following this consolidation of methods and approaches, is to calibrate past and current and indicators, including those currently under development, and establish a framework for such approaches and their extension in WZ and potentially other abalone fisheries.

The project focuses on legal-sized abalone, but it also includes indices of under-sized abalone that are all under the Legal Minimum Length (LML) and indices of the mature sized abalone some of which are under the LML. During the history of the fishery the regulated LML was changed by government from 120 mm to 130 mm in 2014-15, and also in various areas and times by Fisheries Notice or permit, and from about 2003 the industry voluntarily used a minimum size limit that was larger than the formal LML (see Table 4).

The analysis of commercial catch rate and GPS Logger data are for the LML that was enforced during fishing, so it varies by area and time. The analysis of the FIS data allows for retrospective application of a consistent LML through area and time, and analyses for a consistent "current legal length" (i.e., ≥ 130 mm) or "historical legal length" (i.e., ≥ 120 mm) are provided, in addition to the varying but "regulated LML" (i.e., the legal LML that was sometimes increased by WADA; see Table 4) that was applied in the fishery.

To date the focus of the project has been mostly on reconciling the input data and replicating the analyses that were done historically to recommend a Total Allowable Commercial Catch (TACC) for the fishery. The project has also developed and consolidated the previous approaches. This reconciliation and expansion of methods was needed because the monitoring, analysis methods and fishery management (e.g., LML) changed through time. The initial year for each of the three data types (i.e., catch rate, FIS and GPS logger data) is different. In some cases, this is because the data input began at different times (e.g., when catch rates, FIS and GPS loggers began) and in some cases where the information or analysis was limited or contradictory (e.g., the FIS). In this project the most recent year that include all three types of data is the 2019-20 Fishing Period (i.e., April 2019 to March 2020, noting that later the annual Fishing Period changed to July-June). This is because the last VFA FIS monitoring was on 30 and 31 January and 18 February 2020. However, the catch rate analysis, and some other analysis, include the 2020-21 Fishing Period until March 2021.

Introduction
This report has 6 sections describing the following:
1. The current Harvest Strategy
2. Commercial catch, catch rate and standardisation
3. Fishery Independent Surveys and estimates of density and biomass
4. GPS logger estimates of density and biomass
5. Plans for trial of calibration between FIS and GPS logger estimates of density
6. General comments

For items 2-4 the reconciled data and analysis are reported, with some replication of the past analyses and some new analysis. In some cases, the reconciled data and/or analysis is not exactly the same as what was used in the past, because most data/analysis evolved over time, and so the replication of past estimates is approximate but reasonable. The aim of items 2-4 is to provide a consistent set of data and analysis for relevant comparison. For items 2-4 R code is provided that performs the analysis. The code was primarily developed by Bill Venables, with guidance and coding from Duncan Worthington, and all code was reviewed by both these authors. Item 5 outlines a proposed field trial to collect additional data for calibration between past and planned FIS methods and GPS logger densities.

Replication of the past estimates of absolute and relative abundance from the three monitoring methods is intended to replicate and reconcile the past methods and to provide a firm bases for examination of improved methods of analysis. In addition, a process is also underway to redesign the FIS surveys and have them operated by WADA. Consequently, the project is being used to help inform the redesign of the FIS and a field calibration trial is also being planned.

1. **The current Harvest Strategy**

The WZ fishery is primarily managed through government control of the TACC for each of four Spatial Management Units (SMU). The SMU assessments are based on estimation of the biomass of abalone in various size categories, including the legal sized category, calculated from the VFA FIS and multiplied by a harvest fraction. At a finer space scale there are 38 Reefcodes in the fishery. The approximate status of abalone within each Reefcode is considered when setting the TACC for each SMU, including with information from the government and from commercial divers. Target Reefcode catches are considered and provided to WADA for co-management implementation. This combination considers and integrates abalone status and dynamics at spatial scales of both the SMU and Reefcode.

The current Harvest Strategy (HS) concept was developed as the fishery was re-opened after the AVG outbreak and as information from the fishery and the abalone population increased. Initially fishery-independent monitoring was used to assess the abalone population, followed by structured fishing surveys, and later there was increasing information available from the fishery. The HS concept started to be implemented using various FIS data in about 2009, it was more fully developed by 2011, and it was formally developed and adopted for 2016-20 (Sainsbury, WADA and VFA, 2019). A new harvest strategy is being developed by WADA and VFA, but it is not yet complete and in the interim the 2016-20 harvest strategy is being applied.

The SMU TACCs are formally implemented by VFA. WADA is responsible for in-year review of the SMU TACCs and for managing the recommended catch by Reefcode. The Reefcode catch recommendations are to help prevent localised depletion and encourage recovery consistent with the HS targets, there is an accepted level of flexibility around the recommendations, and there is very good compliance by WADA and divers in meeting the Reefcode recommendations. The HS considers several different sources of information about the under-size, mature and legal sized abalone stock, including from commercial catch rates, abalone size composition, FIS, various specific surveys (e.g., scientific surveys and structured fishing in which divers' fish to a specific plan) and GPS loggers. These data were also used to inform modelling and Management Strategy Evaluation (MSE) testing of prospective harvest strategies (Helidoniotis et. al., 2018).

The current HS uses three primary indicators to assess the fishery, and all are from the FIS. The primary indicators are:
1. Mature biomass estimated from the FIS, and the ratio of mature biomass in the current year to that in 2013.
2. Exploitable biomass or the legal sized biomass, that are abalone above the LML, estimated from the FIS.
3. Standardised numbers of 'pre-recruits' (i.e., less than 120mm, and mostly 100-120mm) estimated from FIS, and a pre-recruit indicator each year that is a two- year running average of the standardised pre-recruit numbers.

The abalone length at maturity is estimated to be 102mm so some of the mature biomass is smaller than the LMLs that have been applied in the fishery. The length at maturity is the estimated average across the WZ. The WZ fishery assessments also calculate an estimate of the biomass of undersize abalone for the past LML of 120 mm (i.e., for abalone ≥102 mm and ≤ 119 mm) and the recent LML of 130mm (i.e., for abalone ≥102 mm and ≤ 129 mm), and these are also calculated here.

To allow comparison of indicators across SMU an LML of 130 mm is applied to the calculation of legal-sized indicators for all SMU, despite some minor variation in the applied LML. An LML of 130 mm is the LML mostly applied after the AVG mortality, also despite some minor variation in LML was also implemented by WADA. Prior to the AVG outbreak, and since the 1970s, the LML was 120 mm, although there were some voluntary increases implemented by WADA from 2003. After the AVG outbreak a precautionary LML of 135 mm was used by WADA and VFA in the three SMU impacted by AVG as fishing resumed. The LML was later reduced to 130mm in all SMU, though an LML of 132 mm was applied in a few areas and years and a voluntary LML of 140mm was applied in the Warrnambool SMU after the 2014-15 fishing season (see Table 3). While the indicator calculations provided here are for an LML of 130 mm across all SMUs, Table 3 shows the effects on the legal-sized biomass of the main changes in the actual LML that was applied in the fishery.

The HS also uses a series of secondary indicators that are calculated from a wide range of information. For each SMU the secondary indicators include the landed catch, the length composition of the landed catch and the length composition of abalone ≥120mm from the FIS. For each Reefcode the secondary indicators include the landed catch above 130 mm, and above and below 135mm, the catch per unit effort, the length composition of the landed catch, the length composition of abalone ≥120mm from the FIS, the length composition of abalone <120mm from the FIS and commercial diver observations. In some years the density of abalone caught in the fishery was estimated from the GPS loggers and diver depth loggers (i.e., the area fished) combined with the diver's daily reported catch, but this was not a formal part of the harvest strategy. Until July 2020 the use of GPS and depth loggers has been voluntary, the coverage varied among divers, and there has been some loss or failure of equipment. From July 2020 a VMS system has been required by regulation to report GPS every 15 min, but WADA has continued to collect GPS position every 1 min.

Estimates of abalone density (i.e., kg/Ha) for Indicators of legal-sized biomass, mature biomass and pre-recruit numbers are calculated from the FIS monitoring. In addition, the density of legal-sized biomass can be estimated from the GPS loggers and catch (i.e., kg landed per Ha of dive event). Total biomass can also be estimated by multiplying these densities (i.e., kg per Ha) by estimates of the area of the fishery and productive reef (i.e., Ha). The extrapolation of biomass is calculated using several assumptions and sensitivity tests of key uncertainties, including simulation tests, which are used to understand the likely reliability of the estimates.

Consideration of the TACC starts with the FIS estimates of the density of legal-sized abalone (i.e., kg per Ha) in each of four SMUs. The abalone density is then multiplied by the estimated productive area of the fishery (Ha) to estimate the legal-sized abalone biomass (kg or t). Several methods were used to estimate the productive area of abalone, including diver observations of the historically and recently productive area, historical maps of productive area, and the location of catches recorded by GPS loggers. Guidance for the TACC for each SMU is then obtained by multiplying the biomass estimated for each SMU by a harvest fraction. Each SMU can have a different harvest fraction depending on the status of its population. An appropriate harvest fraction is important for both the abalone stock and the fishery, and MSE simulation testing was used to identify an appropriate range of harvest fractions. This TACC guidance is then compared with the data from the Reefcodes (e.g., catch rates, size composition) and diver observations and interpretations within each SMU. The diver observations include their estimates of the status of the local population and the catch they think can be taken while achieving HS targets. The consolidated diver-based estimates of the Reefcode catches are added to give further guidance of the TACC for each SMU. If the diver-based guidance of the TACC is lower than the FIS-based guidance, then the diver-based estimate is accepted as the recommended TACC. If the diver-based estimate of the TACC is higher than the FIS-

based indicative TACC then the higher value can be accepted provided that the implied harvest fraction for the SMU is appropriately low and less than 15% (as described in the Harvest Strategy) but otherwise the FIS-based TACC is accepted. The diver-based estimates of the appropriate catch by Reefcode are used by WADA to co-manage local catches and to reduce the risk of localised depletion. The actual catches and intended catches by Reefcode are annually reported to both WADA and VFA.

The performance of the current strategy was simulation tested by CSIRO (Helidoniotis et al., 2015). This testing included uncertainty in many of the abalone biological parameters, the mortality of the AVG in 2006/7, the precision of the FIS monitoring, the TACC estimation including the biomass estimates and harvest fraction, and recruitment variability. Full stock rebuilding was predicted to be slow, with a delay of almost 7 years before measurable recruitment of age-classes unimpacted by AVG could be observable, and with rebuilding under a low harvest fraction (i.e., 0.1) to about 50-80% recovery by 2020. The Harvest Fraction strategy performed well for both rebuilding the abalone stock and maintaining a commercial fishery. It used a low harvest fraction during the early stages of abalone recovery, it was changed variably in different areas depending on stock recovery, and it has been maintained less than a maximum of 15%.

2. Commercial catch, catch rate and standardisation

The commercial catch rate or catch per unit effort (CPUE), and its change through time, is a very common index of biomass and fish stock status. The commercial catch rate is fishery dependent. It results from a combination of many factors including fisher skill, markets, costs, consumer preferences, the physical and ecological environment and the status of the abalone population. Reasonable interpretation of catch rate as an indicator of biomass, or other stock measures, requires many assumptions and standardisation is one method that is commonly used to try to separate change in the abalone population from the other impacts. A wide range of approaches have been taken to analysing and interpreting the catch rate data from the WZ, some are very complex to use and none of them can fully remove the impacts of possible confounding factors. So, the project here has developed a single preferred standardisation of the catch rate that can be applied easily and consistently.

2.1 Standardisation of catch rate

Catch and effort logbook data are provided by VFA to WADA, following provision of privacy release by divers, and held in a secure SQL Server database. These include daily reported catch (kg) and effort (h) for both blacklip and greenlip abalone, by each diver and licence within each Reefcode. The reported catch data is for the LML that was imposed on the fishery, and the estimates of catch rates contain the effects of changes in the LML. VFA occasionally changed the legal LML for different times and areas, and in addition WADA voluntarily implemented a larger LML in some areas and times (see Table 4). The term "legal LML" is used for estimates based on this variable LML that was applied to the fishery. Javascript, SQL and R scripts are used by WADA for analysis and to summarise the data by Reefcode and SMU. While catch and effort are reported per Reefcode, most analysis and interpretation are based on catch rate or Catch Per Unit Effort (in units of kg/h) for the Reefcode with maximum daily catch and the SMU, as reporting of daily effort to minor catch Reefcodes is not validated and is less reliable. For analysis of catch rate, daily catch and effort is allocated to one SMU based on the Reefcode with maximum catch (i.e., the Reefcode and SMU of maximum catch are retained). Reported catch is used with the reported effort to calculate a daily catch rate, with removal of data where effort is 0, greenlip catch is >0, and catch rate is >300 kg/h or <10

kg/h. This removes records which are extreme outliers (e.g., likely reporting or entry errors) and where effort is not reported to species (i.e., although in recent years greenlip effort is separated from blacklip effort). For each SMU the catch, effort and number of divers are summarised in Table 1.

Table 1. Summary of Catch (t), Effort (h) and number of Divers in each Year and SMU from the Catch rate data series. The data are filtered to remove records where Effort = 0 or Greenlip catch was landed. Each year is a quota-year, referenced by the latest year in that period. For most of the table the quota-year is April of one year to March of the following year, but in 2020-21 the quota-year was changed to July-June. The data for July 2020 to June 2021 year is not complete and includes only to March 2021. The full year 2020-21 data will be included in later analysis. Changes in the legal LML are summarised in Table 4.

	Julia Percy			Port Fairy			Portland			Warrnambool		
Year	Catch	Effort	Divers	Catch	Effort	Divers	Catch	Effort	Divers	Catch	Effort	Divers
1980	18.0	317	8	46.3	820	10	81.5	1738	13	25.0	424	9
1981	21.9	321	5	78.9	1299	11	94.3	1691	13	30.5	484	8
1982	29.3	394	6	89.6	1255	12	158.0	2476	12	41.8	654	9
1983	15.4	223	5	58.2	903	12	123.8	2184	10	42.7	626	7
1984	6.6	98	5	63.9	1004	10	131.7	2175	14	44.5	692	6
1985	15.4	236	8	77.9	1341	11	134.3	2425	14	54.3	958	6
1986	18.1	313	6	75.7	1434	9	153.3	2784	11	66.2	1252	8
1987	11.4	234	4	44.9	753	10	128.2	2115	13	40.0	706	7
1988	9.2	142	6	74.6	1260	10	198.0	2809	13	54.0	948	6
1989	16.9	245	7	43.9	657	9	145.0	1650	12	37.0	556	5
1990	17.1	213	6	42.7	620	5	151.6	1582	13	25.8	397	5
1991	13.5	187	5	47.3	653	7	151.9	1829	13	31.9	458	6
1992	20.0	262	8	68.2	943	9	141.1	1782	13	34.4	532	6
1993	47.3	635	8	61.5	947	9	125.9	1679	13	38.8	582	10
1994	27.1	379	5	64.4	1048	8	129.6	1728	14	44.1	757	8
1995	25.3	358	4	66.5	1181	9	127.4	1696	14	44.5	823	7
1996	27.4	362	6	67.5	1136	11	134.9	1816	15	44.3	836	10
1997	30.8	354	6	79.9	1168	9	121.4	1456	11	42.6	661	8
1998	43.6	500	8	60.0	865	11	115.3	1322	12	42.5	662	8
1999	35.3	378	7	73.1	964	12	111.3	1260	16	53.1	763	11
2000	35.7	364	6	71.5	1007	10	105.2	1118	14	59.1	882	8
2001	30.9	325	7	65.0	831	10	112.2	1002	12	65.5	869	10
2002	12.0	140	5	78.6	1009	12	119.2	1101	15	61.8	854	9
2003	19.2	186	5	71.6	1020	10	93.8	888	10	70.6	1036	11
2004	31.9	335	8	68.8	987	14	120.4	1323	15	43.8	732	12
2005	15.6	163	6	59.0	836	11	132.7	1464	14	44.5	656	10
2006	13.3	139	6	57.9	853	11	97.1	1109	11	45.3	705	11
2007	14.9	167	9	12.5	168	10	84.6	992	14	50.6	721	9
2008	21.0	267	8				87.1	922	13			
2009	15.7	229	12									
2010	16.0	203	10	6.7	134	6						
2011	16.0	257	7	9.6	212	7						

Year											
2012	13.9	268	6	13.4	255	6				4.2	94	6
2013	3.7	61	5	21.1	453	6	9.1	144	7	4.6	76	6
2014				13.8	235	6	25.2	297	6	10.0	201	5
2015	2.3	35	6	13.0	256	7	30.9	368	8	9.6	163	5
2016	4.3	56	5	17.6	319	8	28.7	426	8	11.0	209	8
2017	2.9	35	3	16.3	263	6	30.5	327	5	12.6	237	6
2018	4.1	52	4	18.8	293	6	28.2	344	6	11.0	165	5
2019	4.8	57	4	21.7	326	6	30.3	344	5	12.3	186	5
2020	3.1	43	2	19.7	327	7	28.0	327	7	11.5	173	5
2021	5.8	75	5	21.0	290	8	31.2	347	7	11.4	147	8

Standardisation of the catch rate is intended to remove the main effects of diver ability and spatial confounding so that the standardised catch rate can be used as an index of the biomass of exploitable abalone. The Harvest Strategy focuses on the catch rate by SMU, although many other indicators are also used in the stock assessment. Consequently, this project is focused on producing a standardised catch rate for each SMU, while also including the effects of other factors such as the Reefcode and diver experience.

In the history of the fishery, and especially in recent years, several very different standardisations of catch rate have been applied (e.g., Giri and Gorfine, 2019, and VFA, 2019, WADA 2021). The recent WADA standardisation of catch rate used a Generalized Liner Model (GLM) to standardise log (daily catch rate) with terms SMU x FishingPeriod + Reefcode(SMU) + Diver with additive normal errors. The Fishing Period is from 1 April in one year to 30 March the following year, except that a July-June Fishing Period was introduced in 2020-21, and each year is labelled by the final year. This approach removes consistent individual diver effects, but there is also evidence for temporal changes in the effect of divers (i.e., diver learning and ageing) that may be confounded with other changes in catch rate through time and these are investigated using standardisation with effects of diver experience.

The project requires a small number of standardised catch rate analyses for comparison with the other measures of abalone density and abundance from the FIS and GPS data loggers. Consequently, the project developed a series of CPUE standardisations (see Appendix 1). These are based on the different catch rate information available (i.e., different time periods and reporting areas) and different ways to treat diver experience (i.e., constant for each diver through time or variable for each diver through time). The input data are aggregated at two levels (the SMU level where some years included data where reefcode was not reported, and at the Reefcode plus SMU levels where all years included reefcode reporting) and these are examined for two periods (1980-2021 and 2003-2021). The time series of these standardised catch rates are compared with one another, with the raw catch rate and with some of the recent WADA standardised catch rates.

The standardisation uses two approaches to treat diver experience. The simplest assumes a constant diver effect, and so is similar to the previous WADA standardisation. The other approach uses a variable diver effect based on experience, which here is the number of years of experience in the WZ fishery starting in 1980 (i.e., assuming all divers had 0 experience in 1980 and had gained no experience in other fisheries). Implementation of this standardisation for the 1980-2021 data assumes that all divers begin fishing in 1980 with no previous experience (i.e., experience equals 1 year) and that they gained experience subsequently

each year. It is recognised that the divers in 1980 had a range of previous fishing experience earlier in the WZ fishery or in other abalone fisheries, but the approach taken here ignores that prior experience. This assumption about initial experience is expected to influence the standardisation and its parameter estimates, especially in the 'burn-in' period as the diver experiences are updated, but these effects are mostly limited to the first few years of the standardised trajectories and the later trajectories are generally very similar. The effect of diver experience is seen in the different CPUE levels of the trajectories in Appendix 1, as would be expected, but the overall trajectories of different models, time periods and diver experiences are all very similar. The 2003-2021 standardisation used the 2003 diver experience that were estimated from the 1980-2021 analysis, and so the 2003-2021 standardisation is not affected by the method of initialising diver experience. This is explained in Appendix 1, which includes all of the standardisations from the project, with either variable or constant diver experience. This methodology allows calculation of the standardised catch rate for any given level of diver experience (i.e., 1- and 10-years' experience are presented), or for other values of random variables in the analysis (i.e., average diver, and average Reefcode). For any of these calculations the standardised catch rate is statistically normalised to the average of each of these random variables. Appendix 1 provides the details of the catch rate standardisation some of the observations about diver experience are shown in Figs 1-3, the standardisation results for 1980-2021 are plotted in Fig. 4, and the standardisation results for 2003-2021 are plotted in Fig. 5.

Figure 1. Boxplot of fishery-wide experience (years) for Divers active within each SMU and year for 61 Divers, calculated from the 1980-2021 catch data series and used in standardisation. Boxplot horizontal line shows median, hinges at 25% and 75% percentiles, whiskers show data at up to 1.5x the inter-quartile range above and below the hinge, and red dots show outliers. Hinges and whiskers are not shown when too little variation or too few Divers. Note, as data was not available prior to 1980, any experience prior to 1980 or in other fishery was ignored, and all Divers were allocated 1 year experience in their first year in the data series.
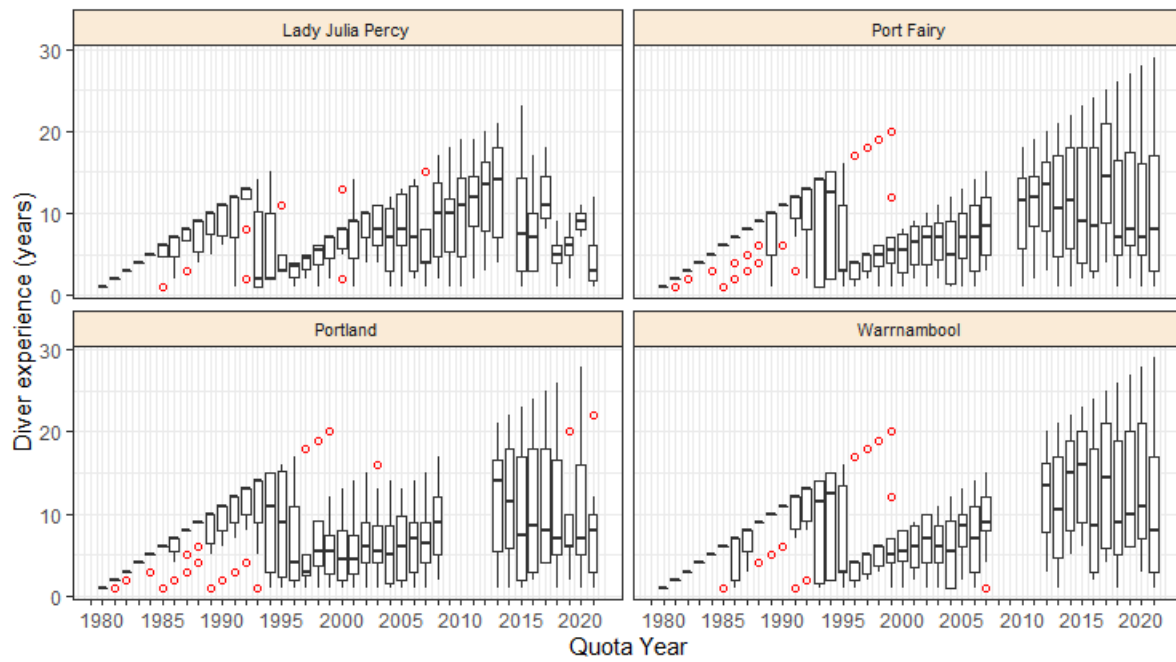
**Figure 2.** Fishery-wide experience (years) for Divers active within each SMU and year for 61 Divers, where each coloured dot represents an individual Diver each year (jittered to display all Divers), calculated from the 1980-2021 catch data series and used in standardisation. Note, as data was not available prior to 1980, any experience prior to 1980 or in other fishery was ignored, and all Divers were allocated 1 year experience in their first year in the data series for the standardisation.
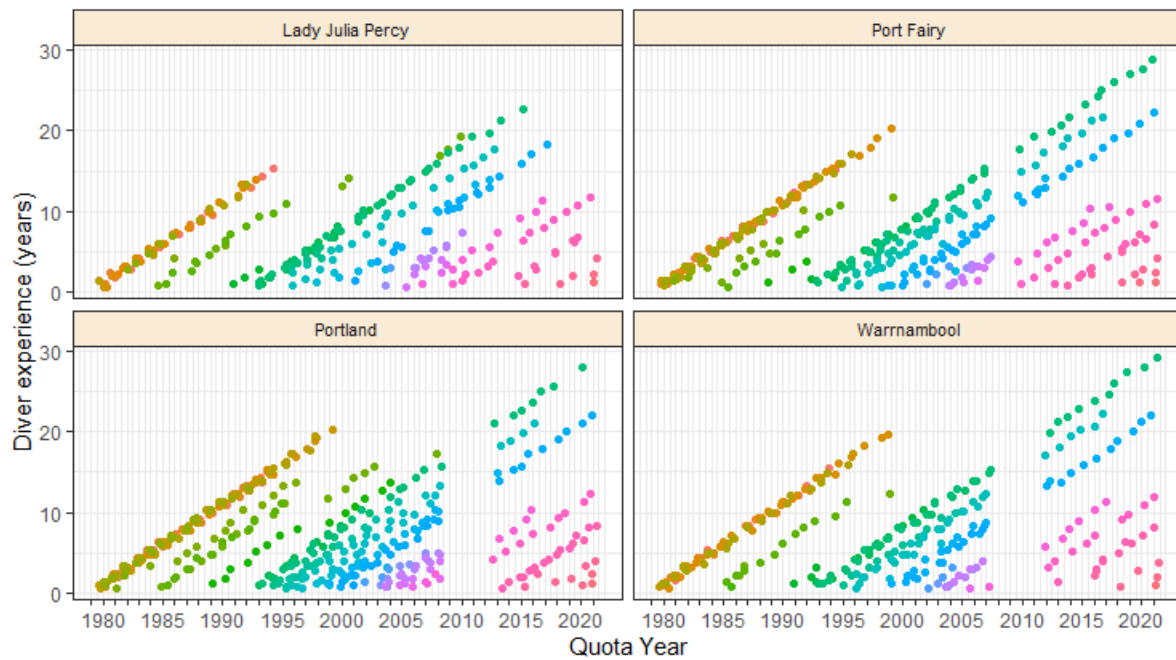
Figure 3. Number of Divers in the fishery active within each SMU and year, calculated from the 1980-2021 catch data series. Since 2010, a lower number of Divers has been active in each SMU, compared to historical numbers. Further, the smaller number of Divers since 2010 include some highly experienced Divers and some relatively inexperienced divers, while the average or median experience has mostly been similar to the historical values (e.g., see Figures 1 and 2).
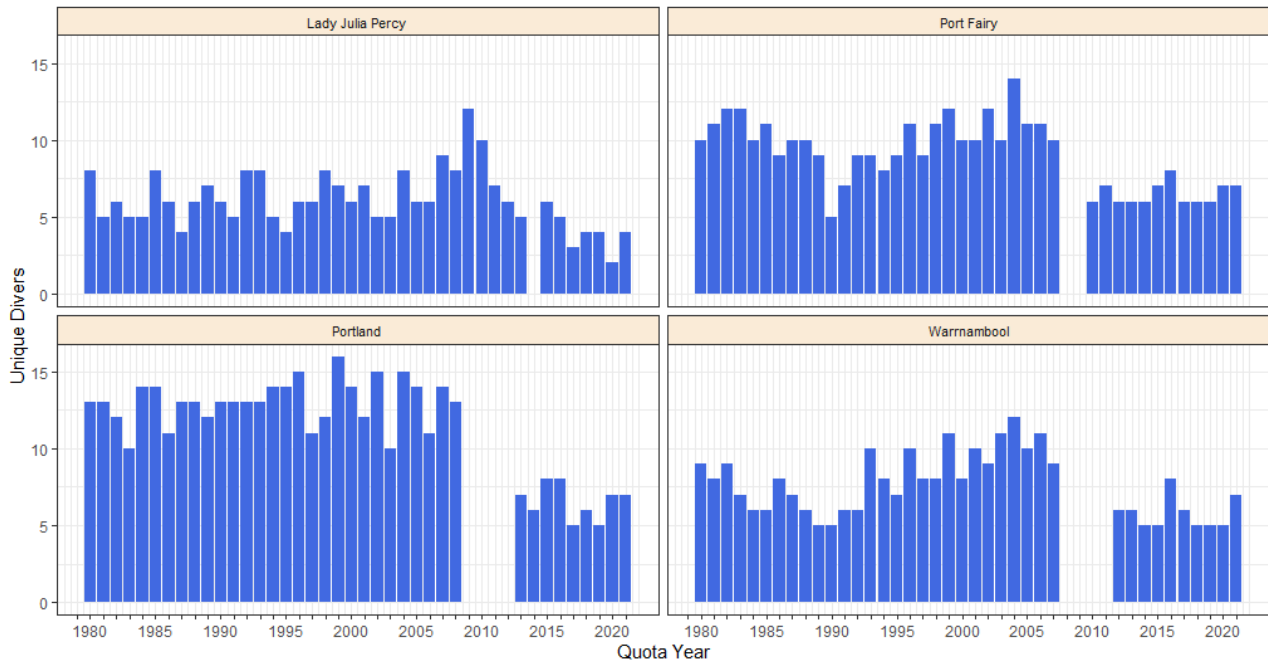
Figure 4. CPUE series for Raw catch rate, and 4 standardised series from the 1980-2021 data. The standardised series are the same as those referred to in Appendix 1 and in Figure 5 below, with NRC = New Reefcode and SMU = Spatial Management Unit, which refer to the spatial scale of the standardisation, and DE1 and DE10 which refer to fixed Diver experience = 1 and 10 years, and NRC_nde refers to New Reefcode with no Diver experience included. Data was not available prior to 1980 so any experience inside or outside the WZ fishery prior to 1980 or in other fishery was ignored, and all divers were allocated 1 year experience in their first year in the data series. This assumption impacts estimates for early years (e.g., 2-3 years) in where the standardisations with diver experience have different trajectories than the raw and the standardisation with no Diver experience.
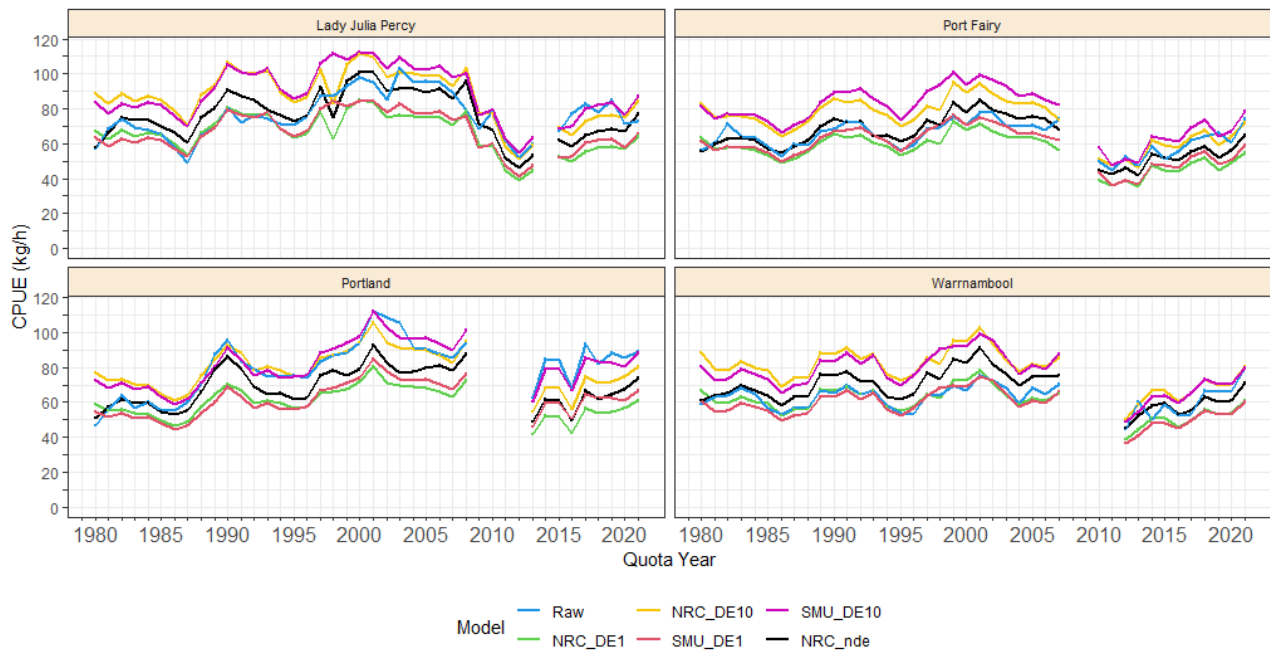
Figure 5. CPUE series for Raw catch rate, and 4 standardised series from the 2003-2020 data. The standardised series are the same as those referred to in Appendix 1 and in Figure 4 above. NRC_nde refers to New Reefcode with no Diver experience included. Diver experience in this series is not allocated as 1 in the first year of the 2003-2021 analysis, but rather is calculated from the full 1980-2021 series, so divers with experience prior to 2003 have this experience included in this analysis.
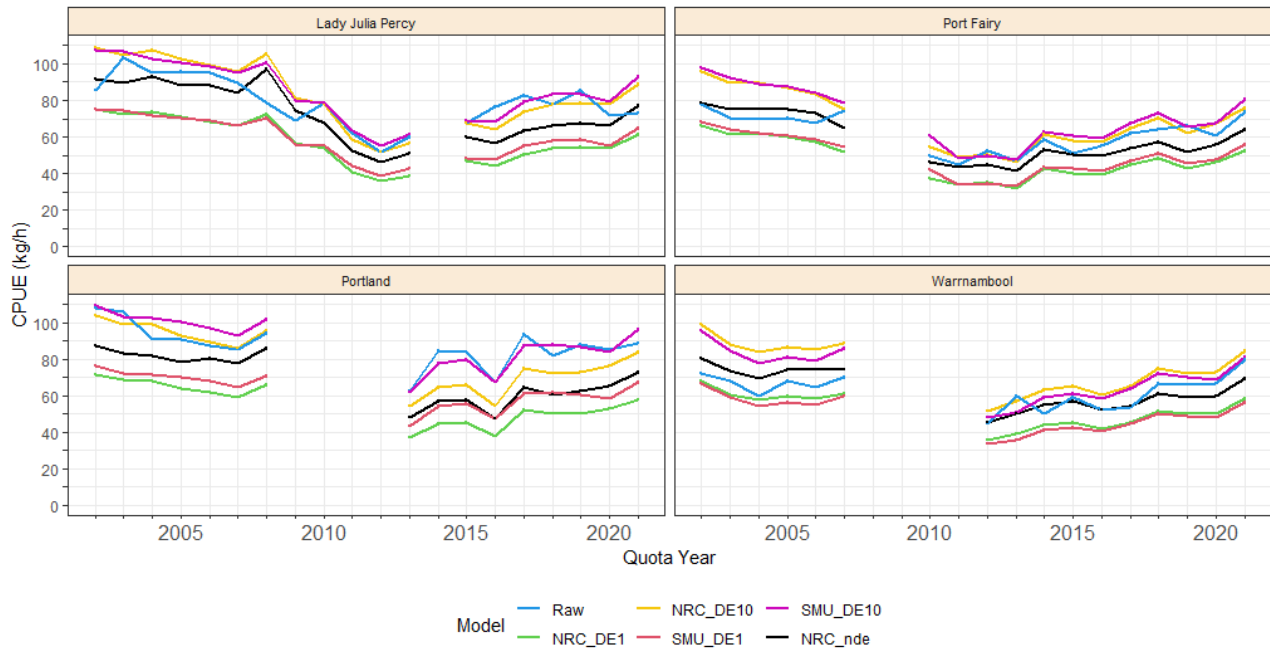
Appendix 1 and Figs 4 and 5 show the effects of variable diver experience with increasing years of experience in the fishery for four combinations of data aggregation and data period. The effect of diver experience on CPUE in two years (pre-AVG in 2005 and post-AVG in 2015) are shown for each SMU. The effects of variable diver experience differ across the reporting periods and reporting area, but the patterns through time are very similar across all these data inputs. Overall, there is a quick increase in fishing effectiveness in the first 1-3 years of fishing (the 'burn-in' period) followed by a slow increase through to about 5-10y of fishing, and then a slow decrease in diver effectiveness by 30y of fishing. The change in fishing efficiency is relatively small but the effects on catch rate interpretation can be important. Appendix 1 shows the effects of including variable diver experience or treating it as constant are shown for the Reefcode plus SMU levels of input data aggregation.

All the variable diver experience shows a very similar time-trends, though they differ in the absolute standardised values. For example, the analysis including the SMU plus NRC data is generally lower than the SMU-only data sets (i.e., this is because values show average differences for different group of divers and reefcodes, and the estimates are for the average of each, for example with more catch from reefcodes with higher catch rate). The constant diver experience models, that include the SMU and the SMU plus NRC data, are similar to those from the variable diver experience. The time trends in standardised catch rates are very similar for all of the models. They all suggest that the legal-sized stock in 2020 was a little below the biomass prior to the AVG outbreak in 2006 (noting differences in LML of from 120 to 130 mm), and they all show a significant increase in legal-sized biomass since the fishery was reopened in 2008 (Pt Fairy SMU) and 2011 (Portland and Warrnambool SMUs). The Lady Julia Percy SMU was not impacted by AVG but it was fished intensively when fishing was closed in the other SMUs. In 2021 the Lady Julia Percy SMU the standardised catch rates had also recovered to be similar to the values prior to the AVG outbreak (i.e., noting the LML differences).

The separation of Reefcode and SMU effects is expected to be important to the project, especially during comparisons of abalone abundance estimates at local spatial scales where Reefcode differences may be important. Further, GPS logger data is able to provide even greater spatial resolution of catch rate (e.g., to sites within reefcodes, but limited by catch reporting aggregation). There is little difference in the trends of standardised catch for the SMU analysis compared to the SMU plus Reefcode analyses. Also, the Reefcode catches are recorded while the Reefcode effort is estimated, while both the catch and effort are recorded for the SMU (i.e., unless divers work across more than one SMU on the same day). These points support the SMU interpretation of standardised catch rate, together with the Reefcode and SMU analysis.

The various standardisation models all show very similar behaviour, but more investigation is needed into the appropriate standardisation models for catch rate, especially at local space scales (e.g., with local comparison of FIS and GPS logger data). This will be an ongoing activity within the project, including comparing the various FIS and GPS logger density and abundance estimates across several of the alternative catch rate standardisation models. At this time the SMU variable diver experience model for the period 1980-2021 and is accepted as being reasonable for this data series, based on the similarity of the predicted trajectories of the standardised catch rates across models and different time series. Similarly, at this time, for the period 2003-2021 the variable diver experience model for the SMU plus Reefcode geographical areas and is accepted as being reasonable for this data series, based on the similarity of the standardised catch rates across models in this time (i.e., noting that models without diver experience may

be investigated for calibration with other indicators). The improved effort recording in the 2003-2021 period, compared to the earlier times, also supports use of this model for periods after 2003. The preferred models for standardising the catch rate will be further evaluated as the project continues.

2.2 R script for standardisation of catch rate

The R scripts for the catch rate standardisation models are provided in Appendix 1. The appendix provides the detailed R code for the project data and analysis presented, and any further detail can be requested from the authors.

3. Fishery Independent Surveys and estimates of density and biomass

These methods are broadly described in Mundy et. al., (2018).

3.1 FIS surveys

The VFA FIS has been conducted by divers contracted through VFA. After a brief comparison with timed-swims accessing shallower habitat, a program of transect-based surveys was then implemented. The FIS has been running since 1989/90 and with more consistent methodology since 1992, though over time the methodology changed (i.e., VFA 2019, Hart 2017).

- The methodology since 1992 uses 6 transects per site with each transect being 30 m x 1 m. The transects radiate from a central point marked by a buoyed shot-line released from the boat at a fixed GPS point, with transect directions randomly selected from 12 cardinal directions commencing with due north. Counting commences 5 m from center of the site creating an overall site of about 70 m in diameter and 3850 m^2 in area. The 6 transects at each site cover 180 m^2 which is 4.7% of the total site area.
- A sample of abalone lengths is obtained from within, or adjacent to, the transects. Since 1992, there have been three approaches to sampling abalone lengths.
  - First, until 1999 all abalone were counted and measured on the transects.
  - Second, from 2001-2003 abalone on transects were counted and a sample was measured.
  - Third, since 2003 abalone were counted on the transects, and additional abalone collected beyond the end of transects were also measured. The shell length is measured from all abalone collected in a 5-minute swim, up to a total of 25 abalone, at the end of each transect. In this method the abalone measured are not from the transects so there can be differences between abalone sizes on the transect and in the measured abalone.
- Divers estimate abalone length by eye when counting on the transects and count abalone into three categories; Juveniles defined as <80 mm length, Pre-recruits 80-119 mm and Recruits $\geq$120 mm. The juvenile data are not included here because of overall low selectivity and changes through time in the way that the measurements were made.
- The FIS sampled up to 39 sites in the fishery (see Table 2). There were 13 FIS sites from 1992, 37-39 sites from 2005 to 2017, 23 sites from 2018, and the last FIS monitoring was in 2020. The timing of the FIS sampling varied within the Fishing Period and Calendar year, mostly being completed in Dec-Jan-Feb but in some years, sites were sampled from September to May. The basis of selecting of FIS sites is often unclear and has changed through time. Specific design criteria for selecting sites, or reasoning for selection of sites or sampling dates, are not available for most periods. Following establishment of an initial set of FIS sites in 1992 sites were added after 2000 to reflect

the distribution of the commercial catch. However, many of the added sites (and some of the original sites) were in more protected or deeper areas than where the commercial fishery focused and often had lower abalone density than in the areas commonly fished. This was highlighted by the addition of a new site in the Watertower Reefcode in 2017. This new site was near a commercially productive site but was in adjacent, deeper water that was rarely fished and the monitored abalone abundance there dropped quickly. VFA has noted that FIS sites can be in relatively protected water, including deeper water than commercial fishing, so as to allow FIS sampling in a wide range of weather. An independent review (Hart 2017) recommended significant change in the FIS design and from 2018 the number of sites was reduced to 23. Sites were removed if abalone were not recorded in the previous 10 years or if abalone abundance was low or highly variable. Site reduction also included removing some additional sites 'at random', and some sites proposed for removal were not removed because WADA considered that the sites contained reasonable numbers of abalone.

- The total area included in the survey is very small and the maximum of 39 FIS sites cover about 0.7 Ha of the about 993 Ha of productive abalone habitat that is fished. Any FIS program will cover a smaller area than the whole abalone stock, the selection of representative FIS sites is important to interpretation of survey data, and the analysis of the FIS data should recognise these points (including interpretation of the FIS as population density changes). The interpretation of the VFA FIS remains complex and disputed particularly because of site selection, especially whether the sites adequately reflect the abalone population, and whether abalone habitat selection (e.g. larval and adult) causes preferred abalone habitats to maintain higher abalone densities than less preferred habitats as populations decrease (see Appendix 4).

VFA FIS abundance survey data are provided by VFA to WADA and held in a SQL Server database. WADA then uses Javascript, SQL and R scripts for analysis and to summarise the data by Reefcode and SMU. This includes a series of SQL queries that combine abundance and length-frequency data (with outlier checks) to calculate biomass in different size-classes. Data used to calculate biomass are standardised by using either all sites sampled, or current sites sampled (i.e., the sites sampled since 2018), and not by a GLM because the survey design changed through time. Separate analyses are completed for the number of Prerecruits and Recruits using a GLM to standardise the number of abalone with terms SMU x Fishing-Period + Site (SMU) + Diver, with Poisson errors. Annual surveys have been completed for a range of times within the year, but here are related to a fishing period and referred to by the last year in the fishing period (i.e., the 2017/18 is referred to as 2018).

The VFA FIS Survey data were standardised to remove effects of differences among divers and reefcode from key estimates for each SMU and Year. The standardised data are used for general interpretations whereas in the past the unstandardised estimates are used for biomass calculation. The standardised and unstandardised data are usually very similar for each SMU, but they can estimate large differences in the abundance of abalone at individual sites (e.g., variation among the individual sites and divers). A series of simple, GLM and GLMM approaches were investigated for both the full data set (i.e., all sites since 1992) and the more consistent subset (i.e., only currently sampled sites since 2003). Most approaches provide similar estimates of the key indicators of Prerecruit and Recruit abalone and the derived biomass of Under-size, Mature and Legal-sized abalone. This is perhaps not surprising given that the VFA FIS data set since 2003 has a very consistent set of sites and divers, but it reinforces the earlier point that while the FIS estimates may be consistent it is not clear what in the abalone population they are measuring.

Table 2. Summary of details for FIS sites, including the reefcode and SMU, average depth (m), first and last year sampled, total transects sampled and the average number of Prerecruits and Recruits per transect.

Site	SMU and Reefcode	Depth	First Year	Last Year	Total Transects	Average Prerecruits	Average Recruits
	Portland						
156	1.02	14	1992	2016	149	17.5	7
158	1.02	10	2005	2020	96	50.0	16.9
153	1.03	14	1992	2020	178	11.2	9.8
154	1.03	14	1994	2020	162	6.5	4.8
155	1.03	12	1994	2020	160	13.1	12.5
150	1.05	14	1992	2016	121	31.2	16.9
151	1.05	15	2000	2016	104	5.2	3.3
152	1.05	15	2000	2020	125	19.5	9.7
148	1.07	10	2000	2016	106	9.5	6.4
149	1.07	7	2001	2016	99	1.7	1.9
147	1.08	6	1992	2016	153	15.4	3.5
144	2.01	5	2000	2020	127	51.9	8.1
145	2.02	15	1994	2020	163	27.3	17.8
146	2.02	15	1992	2016	148	24.1	10.5
141	2.04	10	2000	2016	103	16.2	7
142	2.04	12	1992	2016	154	16.7	8.8
143	2.04	12	1994	2020	169	17.5	8.6
140	2.05	9	2000	2016	100	14.7	6.7
139	2.06	9	1992	2016	153	12.3	2.4
138	2.09	10	1992	2016	150	8.5	4.1
	Lady Julia Percy						
134	3.02	11	2000	2020	124	10.9	14.2
135	3.03	10	1992	2020	191	22.2	11.8
136	3.04	13	2000	2020	125	23.6	25.8
137	3.04	13	2000	2020	125	26.5	21.1
	Port Fairy						
129	3.05	6	2000	2020	125	40.0	20.7
130	3.05	8	1992	2020	184	11.0	12.5
131	3.05	7	1994	2020	171	15.1	16.5
132	3.05	14	2000	2020	124	38.7	24.4
133	3.05	7	2000	2020	125	17.8	17.7
157	3.07	6	2000	2020	47	7.4	5.4
127	3.08	7	1992	2016	162	16.9	7.5
128	3.08	9	2000	2016	100	5.7	2.7
	Warrnambool						
125	3.09	10	1992	2016	161	10.7	11.2
126	3.09	6	2000	2020	125	27.0	14.4
123	3.10	17	2000	2020	127	15.9	3.6
124	3.10	7	1992	2020	182	24.4	9.9

122	3.11	7	2000	2020	125	6.7	6.6
120	3.12	10	2000	2016	103	6.5	4.8
121	3.14	9	1999	2020	135	8.6	9.3

The definition of legal-sized abalone has changed through time because of changes in the LML, and especially the large increase in the LML when fishing resumed after the AVG mortality in 2006/7 (see Table 4). The analysis of the FIS data allows for retrospective application of a consistent LML through time and area, as well as the varying "regulated LML" (i.e., the legal LML that was sometimes voluntarily increased by WADA) that was applied in the fishery. The FIS analysis is conducted for a consistent "current legal length" (i.e., ≥ 130 mm) and for "historical legal length" (i.e., ≥ 120 mm).

FIS monitoring is used by VFA mainly to interpret abalone trends at the sampled sites, rather than as an indicator of the whole abalone population. But the FIS data are also used to provide population or SMU indicators of 80-120 mm abalone growing into the observable population, and of mature and legal-sized abalone. VFA recognise the value of using the more consistent set of FIS methods and sites used since 2003, and many analyses use these data. VFA also concentrate their interpretation on trends in Prerecruit and Recruit abalone. Smaller abalone are often more cryptic than larger abalone and this changes the selectivity of the survey for different length abalone. Juvenile abalone (i.e., <80mm) have been excluded from FIS analysis because of their low selectivity and the variable sampling methodology, but some length dependent selectivity is still likely to occur within the Prerecruit and Recruit categories.

In addition to the VFA FIS sampling there is also additional FIS sampling undertaken by WADA. The WADA FIS surveys used commercial divers and they measured abalone lengths rather than visually estimating them, but otherwise they used the same methodology as the VFA FIS. In WADA structured fishing surveys divers were allocated selected GPS points and asked to catch a specified quantity of abalone from those locations while logging GPS and depth data, to measure all collected abalone and to record several general observations. Divers were also given some prescribed opportunity to identify and fish sites of their own choosing, where the same data were collected. The sampling design specifically enabled spatial comparisons (e.g., within, near and far from identified historically productive areas), comparisons of individual divers through time, and comparisons of pre-selected survey sites with those selected by divers. The design included survey sites in reef areas that had never been historically productive, and so density estimates from the survey are likely to be more representative of all shallow reef areas rather than just historically productive areas in the fishery.

FIS surveys at Port Fairy also included a comparison of existing VFA survey divers with WADA commercial fishery divers. A total of 80-paired transects were sampled, with Survey (i.e., counts and length category measured by eye) and Commercial divers (i.e., counts and lengths directly measured) survey paired, but on different transects. Survey divers counted 2009 abalone, while Commercial divers counted 1995 abalone, with Survey divers estimating by eye fewer legal-sized abalone than were measured by Commercial divers (i.e., 799 v 1367). Survey and Commercial divers were used to complete subsequent surveys at Warrnambool and Portland. Statistical resampling of the estimated density and biomass of abalone at each of the 40 sites sampled demonstrated that as the number of sites increased there was a rapid asymptote in the estimated average density of abalone and its coefficient of variation (CV). This has implications for interpreting VFA FIS surveys with a low number of sites per SMU as an indicator of density in historically productive areas or of legal-sized biomass. For example, the average abalone density for a

survey site may be reasonably well estimated but, because of habitat and depth related variation in abalone productivity and density, it remains unclear what in the population the FIS sites are representing. A converse argument is that if the FIS consistently under-estimates legal abalone density, then with adequate precaution in the estimation of biomass and/or the TACC harvest fraction it may be adequate for successful fishery assessment. However there is a limit to how much bias in the survey sites can be overcome through the changing the methods to estimate the biomass and harvest strategy.

The results of the surveys provided data for ongoing estimates of stock status and the TACC and, through a joint WADA-VFA Working Group, gave opportunity to locate additional sites for WADA surveys. WADA surveys were completed at Port Fairy in 2009-10 and 2011-12, at Warrnambool in 2011-12, and at Portland in 2012-13. Each survey involved estimating historically productive fishing areas, conducting abundance surveys within these areas to estimate density, and extrapolating the density to estimate the abalone biomass in the estimated historically productive fishing areas. Structured fishing was completed by commercial divers at sites within, near and far from historically productive areas, as well as at sites chosen by divers. All these types of sites provided similar estimates of abalone density (kg/Ha).

Because of the larger number of more representative sites in the WADA surveys compared to the VFA surveys (e.g., at Port Fairy SMU there were 40 WADA sites and 8 VFA sites), and their complimentary distributions, the one-off WADA surveys were used with the annual VFA surveys to estimate biomass and its change. A one-off estimate of biomass density was provided from the WADA surveys by calculating stratified estimates of density in strata within each SMU (e.g. Bridgewater, Nelson, Cape Grant to Lawrence Rocks strata within the Portland SMU). There was no standardisation in this analysis and so FIS counts were used directly. These density estimates were extended with VFA FIS estimates to give annual estimates of abalone density through time by multiplying the absolute WADA survey density estimates by the relative annual proportional change in density estimates from the VFA surveys through time. Divers and other effects were not standardised in this analysis. The combined annual estimate of biomass density was then extrapolated across the historically productive reef within strata within each SMU and summed across strata within the SMU to estimate the total SMU abalone biomass.

The annual population status and TACC for WZ abalone since the AVG mortalities was mainly identified from the various FIS operations, though other secondary information such as CPUE and logger-derived density was also considered. The overall assessment process involved completing fishery-independent surveys and calculating abalone density and biomass. The VFA FIS data was used for this assessment throughout, initially a FIS was also implemented in Port Fairy and jointly managed with South Australian scientists and used WADA and VFA divers (e.g., Mayfield et al., 2011), and this was extended throughout Warrnambool and Portland SMUs by WADA. Biomass were estimated by combining the density and length-frequency data from the FIS surveys with the estimated historically productive area. These was used to estimate two under-size length categories (i.e., 100-120 and 100-130 mm), a legal length category (i.e., larger than the current legal LML) and a length category to represent the mature biomass (i.e., >102 mm).

3.2   Reef area estimates

To calculate the total biomass of abalone the estimated abalone density can be extrapolated from FIS survey sites, or from areas fished with loggers, to an appropriate area of productive abalone reef. In the fishery management plan the estimate of biomass from the FIS monitoring is for the SMU, and this is the focus here, although estimates for other areas (e.g., the Reefcode etc) are possible and sometimes made. To estimate biomass after the AVG mortality the active commercial divers were asked to identify the most historically productive areas of reef. The estimation of historically productive areas was done

collaboratively by identifying the areas in over-head imagery, digitising and reviewing. In this way estimates of historically productive areas were made by divers for reefs at the Crags in the Port Fairy SMU, the rest of the Port Fairy SMU, the Warrnambool SMU and the Portland SMU. For example, the red lines in Fig 7 show the historically productive area identified in the Mills, Killarney and Cutting Reefcodes in the Warrnambool SMU. These discussions also helped with examination of the VFA FIS sites and design of extra sites for WADA Structured Fishing and surveys. Fig. 6 shows the location of the additional WADA sampling sites, and Fig 7 shows the catch rates measured at the WADA Structured Fishing sites.

Figure 6. Productive reef area estimates at Mills, Killarney and Cutting Reefcodes in the Warrnambool SMU. Historically productive areas, within the red lines, were identified by commercial divers. The Warrnambool Structured Fishing survey sites are the numbered green points. The WADA abundance survey sites are the white-yellow points overlaying green Structured Fishing sites. From Figure 74 of Mundy et al., (2018).
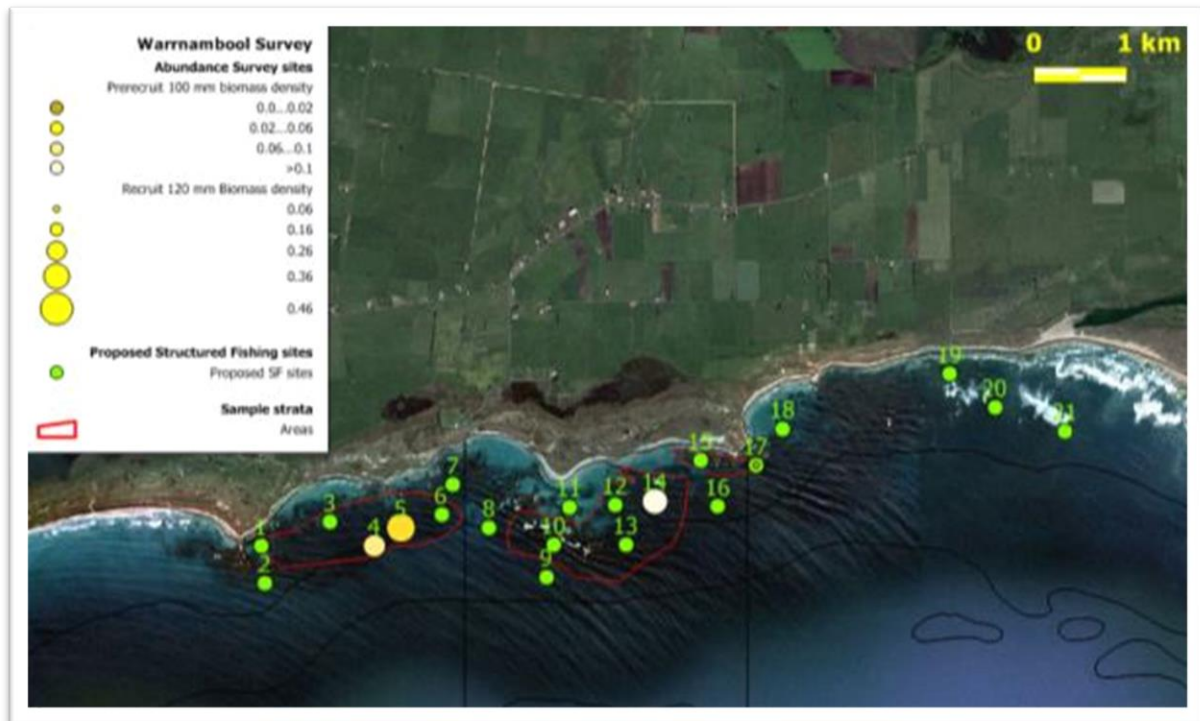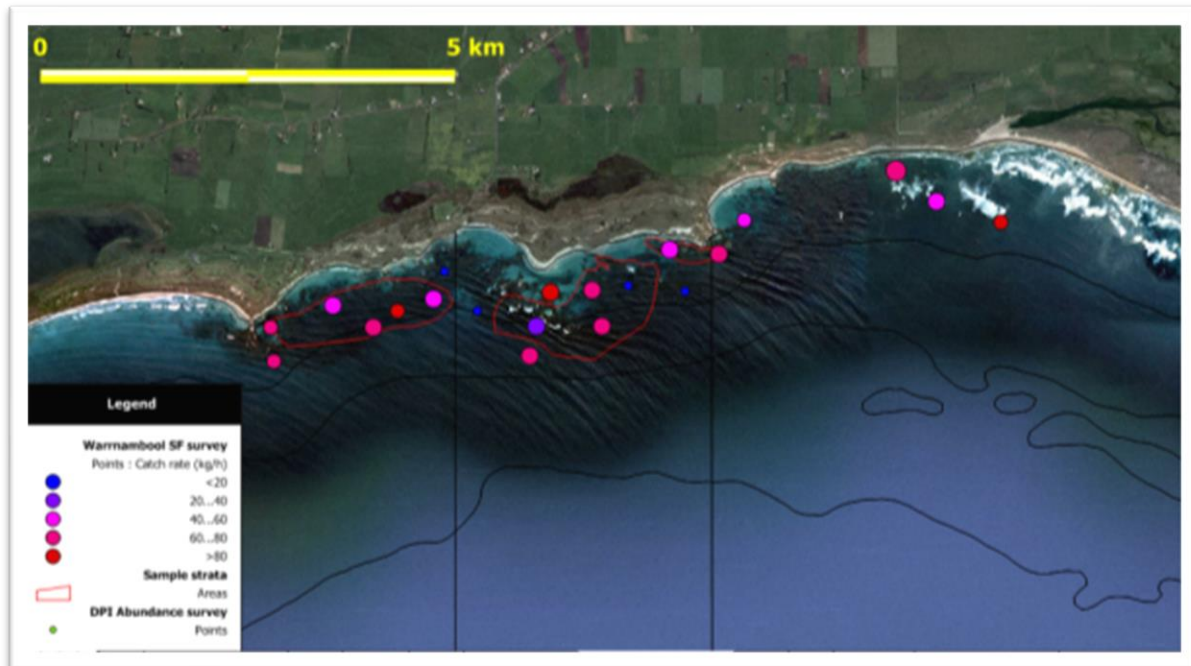
Figure 7. Productive reef area estimates at Mills, Killarney and Cutting Reefcodes in the Warrnambool SMU, as in Fig. 6. Catch rate of abalone from the Warrnambool Structured Fishing survey are shown in blue-red colours. From Figure 75 of Mundy et al., (2018).

GPS loggers also provide information about the area of reef visited by commercial divers, and this can also be used in several ways to estimate the productive area of reef. For example, the area of individual dive events can be combined across all divers within a year (e.g., the union of dive events summarised by the area estimated to enclose 90% of points from the dive event). Alternatively, the presence of a dive event in an area could be recorded by the presence of a GPS record or number of records from a dive event, or contours of the dive event, within a grid of contiguous hexagonal areas of reef (e.g., 1 Ha grid, or a grid of any defined size and shape). Grid cells with such activity can then be summed within a time-period to provide an estimate of the area of productive reef.

There are several ways that this method can be applied from GPS loggers across different years of fishing. For example, the most recent year alone may be used to estimate the productive area, the combined area in the past say 3y of fishing could be combined to estimate the productive area, or the total area ever fished could be used to estimate the productive area. A preferred approach in the WZ fishery assessments is the rolling 3y average, though there have been variations to this through time and area. All logger-based methods were able to provide estimates of the productive area of reef that were similar to the area currently used in biomass estimation as part of the current WZ Harvest Strategy.

There are limited other independent data with which to calibrate and validate the logger-based methods of estimating the area of productive reef. Lidar-based data and derived habitat suitability models can provide some validation for the estimates produced from loggers (see Table 3). Lidar data about reefcode area, estimates of reef area, and two habitat suitability models have been calculated for all reefcodes in WZ, and

can be compared to estimates produced by diver experience and logger-based estimates for all reefcodes. Estimates of productive reef area for Reefcodes are generally similar and consistent for the various Reefcodes, though there are differences and in particular the Lidar coverage does not include some of the abalone reefs deeper than about 20m depth. Calculations of productive area from GPS loggers use data from current actual abalone fishing, so are likely to be a more reliable indicators of the current area of productive abalone reef. Commercial diver and some scientific estimation of productive habitat also use actual abalone fishing experience, but the reliability of records and comprehensiveness of observations can be unknown. For all these methods there remains the questions of how best to combine years of observed fishing to estimate the currently productive area or to reflect fishing prior to the use of GPS loggers.

Table 3. Estimated area (Ha) per reefcode in WZ of the Reefcode, Lidar, Reef, abalone habitat, historically productive reef and logger use. Further detail about calculation of each measure is summarised in the footnote and in FRDC2011-201.

	i) Total Reefcode area	ii) Total Lidar area 5 m	iii) Lidar Reef mixed 5 m	iv) Lidar Reef 5 m	v) Habitat Model 5 m	vi) Habitat Model 100 m	vii) McShane 1981	viii) Loggers 3 years 2019-21	ix) Loggers 1 year 2021-22	x) TAC
Portland	9109	7156	949	296	657	483-795	326	271-359	174-238	376
Lady Julia Percy	412	-	-	-	-	478-837	77	47-64	36-53	59
Port Fairy	2401	1560	563	249	360	514-968	100	249-319	156-210	215
Warrnambool	6744	4453	2189	762	1432	522-1088	122	266-352	174-223	343

i)   Total area of Reefcode to 40 m depth contour.

ii)   Total area of Lidar 5 x 5 m raster data to 40 m depth contour. Note Lidar mostly limited to <30 m.

iii)   Area of Reef and Reef-sediment from 5 x 5 m Lidar raster. Classification model from Lidar and ground-truth, with Reef $\geq$70% reef and Reef-sediment $\geq$25% reef.

iv)   Area of Reef from 5 x 5 m Lidar raster. Classification model from Lidar and ground-truth, with Reef $\geq$70% reef.

v)   Area of Suitable habitat with score >0.25 from 5 x 5 m Lidar raster. Classification as Suitable habitat from model based on logger data for WZ (i.e., WZ classification model), and dominated by depth, rugosity (i.e., surface v planar area) and complexity (i.e., change in slope).

vi)   Area of Suitable habitat (from WZ classification model) from 5 x 5 m Lidar raster averaged by 100 m hexagonal grid and counted for grids with mean score $\geq$0.25 and $\geq$0.4.

vii)   Area of historically most productive abalone reef estimated by McShane (1981).

viii) Area with GPS logger activity while abalone fishing within a 100 m hexagonal grid over 3 years. Alternatives are presented for grid cell activity >20 min and >10 min per Ha.

ix)   Area with GPS logger activity while fishing within a 100 m hexagonal grid over 1 year. Alternatives are presented for grid cell activity >20 min and >10 min per Ha.

x)   Historically productive area estimated by divers and used in TAC setting from 2009-2022.

A range of approaches have been used in the WZ fishery assessments to investigate the sensitivity of different methods to estimate productive reef area. These include ranges from Lidar combined with two different abalone habitat models, previous scientific assessments, commercial diver experience and GPS Logger observations (see Table 10). Recent abalone fishery assessments have considered this range of estimations, and several combinations have been used as a part of sensitivity trials. The WZ fishery assessments estimate the preferred productive area based on the diver estimations, GPS logger estimates and past fishery outcomes using different approaches. The current project will investigate the estimation of productive area to help develop guidance on appropriate methods to estimate productive abalone habitat. The preferred estimates of the productive area of abalone habitat in each WZ SMU are:

- Portland = 376 Ha
- Lady Julia Percy = 59 Ha
- Port Fairy = 215 Ha (387 Ha during an earlier estimate calculated during a period of higher catch)
- Warrnambool = 343 Ha

These are the productive reef areas that have been used as the preferred values both in this project and in recent WZ abalone stock assessments.

3.3   Estimation of Biomass density and total Biomass from FIS

The details of the calculations used by the project are provided in Appendix 2.

Estimates of the density of biomass are calculated from abundance surveys by combining data on the density of abalone, abalone sizes and weights and the productive area of abalone production. Details of these methods changed, using various interpretations and analysis of all the data available, as they were developed, tested, and applied. In 2016 the approach was formally adopted by VFA and WADA in the 2016-20 fishery Harvest Strategy. In this strategy the VFA FIS estimates of biomass were the primary method to calculate the TACC. Alternative estimates and evidence, such as trends in the CPUE, FIS trends, legal biomass from GPS logger observations, and diver observations, were additional parts of this 'weight-of-evidence' approach to recommending the TACC.

The FIS analysis here is based in the methods in most recent WZ TACC analysis with some consolidation of the methodology and extension of the indicators calculated.

Two sets of VFA FIS data were separated. Specifically:

- The two sets of VFA FIS data are for 1992-2020 and 2003-2020.
- The 1992-2020 data includes all the FIS sites sampled. It provides a long-term interpretation, but the annual number of sites and the observation methodology were variable. These data were standardised to estimate abalone biomass and density.
- The 2003-2020 provides recent interpretations, including both before and after the 2006/7 AVG mortality. The monitoring methodology was reasonably consistent throughout. In 2018 there was a reduction in the number of FIS sites and a change in the way that the FIS sites were used to calculate density. Before 2018 biomass density was estimated from calibration and stratification of sites within the SMU, while after 2018 the biomass density was estimated by averaging across the FIS sites within the SMU. The 2003-2020 data used here contains the reduced set of FIS sites monitored after 2018, so it has consistent FIS sites and monitoring methods. Estimates of abalone density and biomass were calculated by averaging the raw FIS data, and by standardising the FIS data.

For each FIS data set two calculations are needed for each SMU.

- The first calculation is of the density of abalone numbers by size category (i.e., individuals/m^2). This combines the FIS counts with the length frequency samples. FIS surveys divers count the abundance of abalone in two size classes, Prerecruits (<120 mm) and Recruits ($\geq$120 mm). The surveyed area is known so the density of individuals in these two size classes can be calculated (i.e., Density of Individuals of Prerecruit and Recruit, DI$_{prerecruit}$ and DI$_{recruit}$). To estimate the density of individuals of different length-classes the individual density of the Prerecruit and Recruit classes are multiplied by the proportion of individuals of the length-class in the length-frequency sample. This recognises that the length frequency distribution can be different from the survey counts. That is,

$$DI_{class} = DI_{Prerecruit}\left(\frac{N_{class}}{N_{Prerecruit}}\right) + DI_{Recruit}\left(\frac{N_{class}}{N_{Recruit}}\right)$$

where DI_{class} is the density of individuals per m^{-2} in a chosen length 'class', N_{class} is the number of individuals in the chosen length 'class' in the survey length-frequency sample, and N$_{Prerecruit}$ and N$_{Recruit}$ respectively refer to the numbers of pre-recruits and of recruits in the two survey length-frequency classes. Density of individuals is calculated for three size classes of abalone, Legal-sized (i.e., $\geq$130 mm, though density for other LML values such as 120 mm are also calculated), Mature (i.e., $\geq$102 mm, the length at 50% maturity from CSIRO modelling) and Under-size (i.e., $\geq$100 and $\leq$130 mm, though density for other LML values such as 120 mm are also calculated).

- The second calculation is of the abalone biomass density (i.e., kg/m^2 or t/Ha) and biomass (i.e., kg) for the size classes of the stock indicators. The biomass density for each size class (e.g., Density Biomass Mature) with contributions from Prerecruits and Recruits is calculated by applying a length-weight relationship using:

$$\sum_{Prerecruits} DB_{class} + \sum_{Recruits} DB_{class} \qquad where\ DB_{class} = DI_{class}\left(\frac{W_{class}}{N_{class}}\right)$$

$$DB_{class} = \left(\frac{\sum W_{class}}{\sum N_{class}}\right)\sum_{class} DI_{class}$$

where DB_{class} is the density of biomass in a chosen indicator length 'class' and DB is the total density of biomass summed across all length classes. W_{class} is the sum of weights from the length-weight relationship (i.e., Weight = 3.34x10^{-4} x Length$^{2.857}$ from Helidoniotis et al., 2015) for abalone in 1 mm length classes from the length-frequency sample, and this is applied separately for Prerecruits and Recruits before summing across appropriate length-classes to produce indices of the density of biomass for Undersize, Mature and Legalized abalone at each site, which are then averaged across sites within each SMU. These calculations used estimates of abundance that were not standardised by a GLM, although differences caused by standardisation in recent years are mostly small, and both standardised and un-standardised abundance data are presented.

Estimates of total biomass are estimated by multiplying the biomass density of the chosen size class with the productive area of reef (i.e., *A*). The productive area was selected to estimate the area of the fishery-effective productive population.

$$B_{class} = A \times DB_{class}$$

The estimates of the biomass density and biomass of legal, mature and undersize abalone classes are provided in Appendix 2. In Appendix 2 the legal biomass is defined in several ways, including the currently legal biomass (i.e., constant LML of 130 mm for all years), the historical legal biomass (i.e., constant LML of 120 mm for all years) and the regulated legal biomass (i.e., variable LML applied by year and SMU as in Table 4). The biomass of currently legal, mature and undersize abalone are shown in Figure 8.

Figure 8. The biomass of currently legal (≥ 130 mm), mature (≥ 102 mm) and undersize (102-130mm) abalone categories for 1992-2020 calculated from the FIS monitoring. These plots, and the plots for the separate analysis of 2003-2020 are provided in Appendix 2. Note that the analysis here is for the currently legal biomass from a fixed LML of 130 mm, so it differs from the legal biomass estimates in Table 4 that uses the time and SMU varying LML applied to the fishery. Year refers to the Quota Year, but not all FIS sites were sampled within the corresponding Quota Year, see Appendix 2.
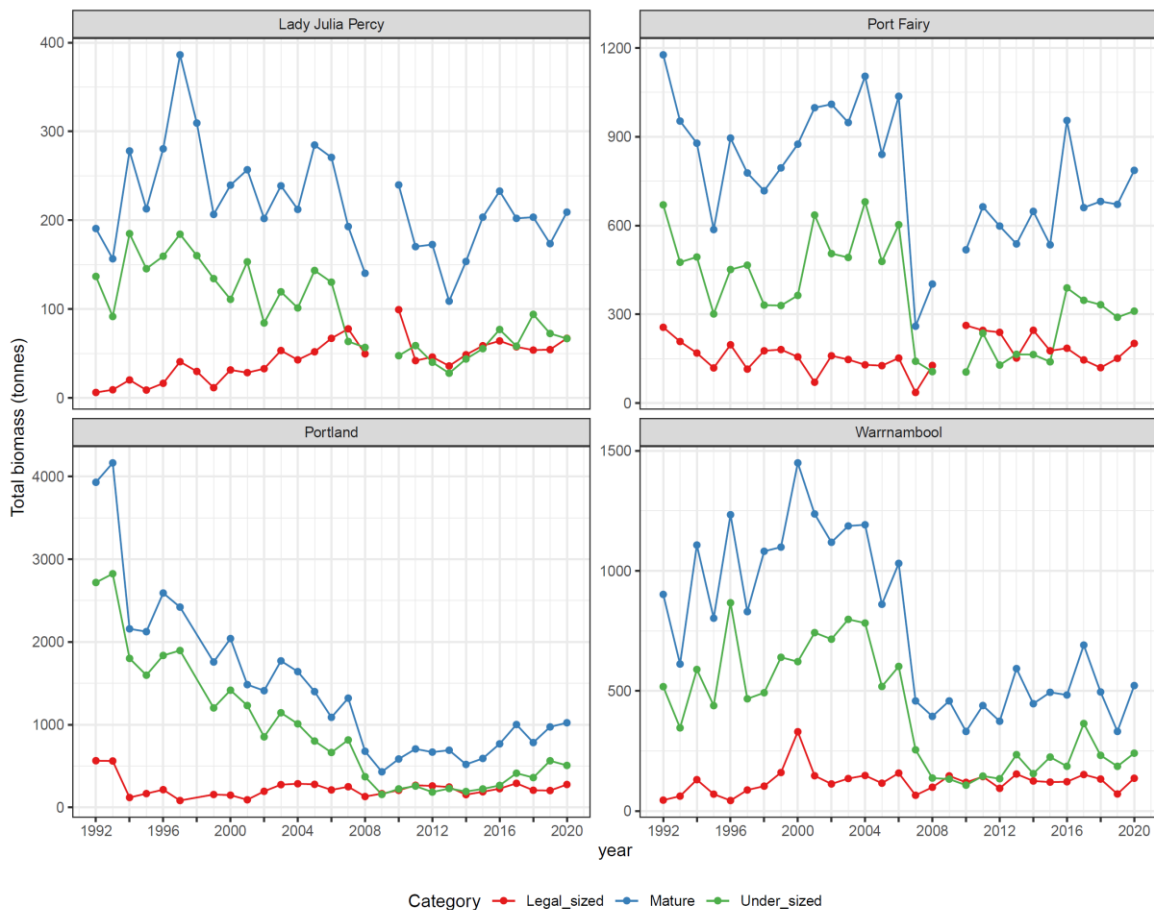
The estimates of legal biomass above the regulated LML in each year and SMU are given in Table 4. The biomass density and the total biomass of the abalone, showing the currently legal biomass with a constant LML of 130mm, are given in Table 5, while Table 6 compares these estimates of biomass density from the current project with those from past WZ TAC processes. Comparing Tables 4 and 5 shows the effects of different LML assumptions on the estimated legal biomass. Table 4 uses the actual LML applied in the fishery and shows that the legal biomass available to the fishery decreased as the LML was increased, while Table 5 uses a constant LML of 130mm and shows a reasonably stable currently legal biomass above that size. Table 7 provides estimates of biomass density and total biomass of mature abalone, while Table 8 compares these estimates of biomass density from the current project with those from the past. Similarly, Table 9 provides estimates of biomass density and total biomass of undersize abalone, while Table 10 compares these estimates of biomass density from the current project with those from the past. The estimates from the past WZ fishery assessments and the current project differ slightly because of small changes in the data and estimation methods, but they are all very similar.

Table 4. Regulated LML with estimates of legal biomass (t) from the FIS and fishery Area, with Catch (t) for each year and SMU. The total legal biomass is abalone above the regulated LML (mm) for each year. LML values marked with * indicated that a larger LML were used by industry within the SMU, including in Portland SMU where LML remained at 135 mm in some Reefcodes during 2013-2015, at Crags Reefcode in Port Fairy SMU where LML was 132 mm during 2014-15, and at Levys Reefcode in Warrnambool SMU where LML was 140 mm in 2014-15 and subsequent years. Each year is a fishing quota year.

	Portland			Lady Julia Percy			Port Fairy			Warrnambool		
Area	376 Ha			59 Ha			215 Ha			343 Ha		
Year	LML	Biomass Total	Catch	LML	Biomass Total	Catch	LML	Biomass Total	Catch	LML	Biomass Total	Catch
2003	120	479	120.4	120	123	31.9	120	417	68.8	120	411	43.8
2004	*120	461	132.7	*120	115	15.6	*120	395	59.0	*120	428	44.5
2005	*120	445	97.1	*120	146	13.3	*120	325	57.9	*120	341	45.3
2006	*120	324	84.6	*120	142	14.9	*120	395	12.5	*120	452	50.6
2007	*120	392	87.1	*120	123	21.0	*120	109		*120	194	
2008	120	229		120	81	15.7	120	253		120	269	
2009	120	201		120		16.0	120	128	6.7	120	309	
2010	120	277		130	86	16.0	135	140	9.6	120	217	
2011	120	335		130	35	13.9	135	96	13.4	120	286	4.2
2012	120	385	9.1	130	37	3.7	135	106	21.1	120	240	4.6
2013	135	204	25.2	130	30		135	61	13.8	135	47	10.0
2014	*130	120	30.9	130	46	2.3	130	202	13.0	130	123	9.6
2015	*130	164	28.7	130	44	4.3	*130	144	17.6	*130	103	11.0
2016	130	195	30.5	130	56	2.9	130	155	16.3	*130	185	12.6
2017	130	274	28.2	130	49	4.1	130	150	18.8	*130	129	11.0
2018	130	207	30.3	130	51	4.8	130	132	21.7	*130	145	12.3
2019	130	201	28.0	130	52	3.1	130	157	19.7	*130	136	11.5
2020	130	230	31.2	130	61	5.8	130	205	21.0	*130	235	11.4

Table 5. Estimates of biomass density (t per Ha) and total biomass (t) for each SMU from the FIS above and a constant LML of 130 mm (i.e., the current legal biomass). Each year is a fishing quota year.

	Portland		Lady Julia Percy		Port Fairy		Warrnambool	
Area	376 Ha		59 Ha		215 Ha		343 Ha	
Year	Biomass Density	Biomass Total	Biomass Density	Biomass Total	Biomass Density	Biomass Total	Biomass Density	Biomass Total
2003	0.416	156	0.951	56	0.530	114	0.433	149
2004	0.444	167	0.678	40	0.482	104	0.463	159
2005	0.407	153	0.890	53	0.480	103	0.345	118
2006	0.328	123	0.965	57	0.615	132	0.479	164
2007	0.404	152	1.077	64	0.133	29	0.184	63
2008	0.219	82	0.810	48	0.418	90	0.274	94
2009	0.292	110			0.150	32	0.369	127
2010	0.364	137	1.451	86	1.085	233	0.342	117
2011	0.452	170	0.594	35	0.909	195	0.374	128
2012	0.512	193	0.621	37	0.983	211	0.293	100
2013	0.542	204	0.503	30	0.654	141	0.420	144
2014	0.320	120	0.780	46	0.941	202	0.355	122
2015	0.435	164	0.751	44	0.668	144	0.309	106
2016	0.518	195	0.955	56	0.720	155	0.321	110
2017	0.729	274	0.824	49	0.697	150	0.443	152
2018	0.551	207	0.865	51	0.615	132	0.412	141
2019	0.534	201	0.887	52	0.731	157	0.224	77
2020	0.612	230	1.034	61	0.954	205	0.392	134

Table 6. Estimates of biomass density (t per Ha) and total biomass (t) for each SMU from the FIS for Legal abalone above a constant length of 130 mm (i.e., the current legal biomass) from the 2022 Fishery Assessment and from this project. Each year is a fishing quota year.

Year	Portland Assessment	Portland Project	Lady Julia Percy Assessment	Lady Julia Percy Project	Port Fairy Assessment	Port Fairy Project	Warrnambool Assessment	Warrnambool Project
2003	0.417	0.416	0.950	0.951	0.530	0.530	0.434	0.433
2004	0.471	0.444	0.680	0.678	0.483	0.482	0.463	0.463
2005	0.452	0.407	0.893	0.890	0.481	0.480	0.346	0.345
2006	0.329	0.328	0.968	0.965	0.616	0.615	0.478	0.479
2007	0.449	0.404	1.080	1.077	0.133	0.133	0.183	0.184
2008	0.221	0.219	0.813	0.810	0.419	0.418	0.240	0.274
2009	0.293	0.292			0.150	0.150	0.430	0.369
2010	0.385	0.364	1.453	1.451	1.086	1.085	0.398	0.342
2011	0.503	0.452	0.598	0.594	0.909	0.909	0.373	0.374
2012	0.513	0.512	0.620	0.621	0.984	0.983	0.293	0.293
2013	0.515	0.542	0.503	0.503	0.765	0.654	0.420	0.420
2014	0.322	0.320	0.783	0.780	0.943	0.941	0.412	0.355
2015	0.436	0.435	0.753	0.751	0.668	0.668	0.309	0.309
2016	0.519	0.518	0.958	0.955	0.720	0.720	0.377	0.321
2017	0.729	0.729	0.828	0.824	0.698	0.697	0.553	0.443
2018	0.553	0.551	0.868	0.865	0.617	0.615	0.412	0.412
2019	0.535	0.534	0.890	0.887	0.735	0.731	0.224	0.224
2020	0.615	0.612	1.035	1.034	0.955	0.954	0.394	0.392

Table 7. Estimates of biomass density (t per Ha) and total biomass (t) for each SMU from the FIS for Mature abalone above a constant length of 102 mm. Each year is a fishing quota year.

	Portland		Lady Julia Percy		Port Fairy		Warrnambool	
Area	376 Ha		59 Ha		215 Ha		343 Ha	
Year	Biomass Density	Biomass Total	Biomass Density	Biomass Total	Biomass Density	Biomass Total	Biomass Density	Biomass Total
2003	2.881	1083	4.077	241	3.931	845	3.147	1079
2004	2.713	1020	3.658	216	4.641	998	3.084	1058
2005	2.682	1008	4.750	280	3.616	777	2.317	795
2006	2.058	774	4.589	271	4.367	939	2.769	950
2007	2.518	947	3.102	183	1.123	241	1.175	403
2008	1.268	477	2.278	134	1.588	341	1.180	405
2009	0.809	304			0.892	192	1.259	432
2010	1.119	421	4.042	238	2.236	481	0.892	306
2011	1.335	502	2.799	165	2.791	600	1.198	411
2012	1.363	512	2.890	171	2.524	543	1.025	352
2013	1.380	519	1.848	109	2.286	491	1.570	539
2014	1.103	415	2.609	154	2.528	544	1.217	417
2015	1.194	449	3.431	202	2.094	450	1.323	454
2016	1.651	621	3.898	230	3.761	809	1.292	443
2017	2.591	974	3.414	201	3.093	665	2.109	723
2018	2.127	800	3.428	202	3.245	698	1.519	521
2019	2.599	977	2.894	171	3.180	684	0.938	322
2020	2.713	1020	3.539	209	3.713	798	1.557	534

Table 8. Estimates of biomass density (t per Ha) and total biomass (t) for each SMU from the FIS for Mature abalone above a constant length of 102 mm, from the 2022 Fishery Assessment and this project. Each year is a fishing quota year.

Year	Portland Assessment	Portland Project	Lady Julia Percy Assessment	Lady Julia Percy Project	Port Fairy Assessment	Port Fairy Project	Warrnambool Assessment	Warrnambool Project
2003	3.079	2.881	4.085	4.077	3.940	3.931	3.151	3.147
2004	2.718	2.713	3.665	3.658	4.649	4.641	3.090	3.084
2005	2.686	2.682	4.763	4.750	3.623	3.616	2.321	2.317
2006	2.063	2.058	4.598	4.589	4.374	4.367	2.773	2.769
2007	2.523	2.518	3.110	3.102	1.124	1.123	1.177	1.175
2008	1.269	1.268	2.283	2.278	1.591	1.588	1.180	1.180
2009	0.810	0.809			0.890	0.892	1.260	1.259
2010	1.121	1.119	4.050	4.042	2.239	2.236	0.891	0.892
2011	1.407	1.335	2.805	2.799	2.797	2.791	1.197	1.198
2012	1.364	1.363	2.895	2.890	2.530	2.524	1.026	1.025
2013	1.384	1.380	1.850	1.848	2.290	2.286	1.573	1.570
2014	1.105	1.103	2.615	2.609	2.534	2.528	1.220	1.217
2015	1.196	1.194	3.438	3.431	2.098	2.094	1.326	1.323
2016	1.751	1.651	3.903	3.898	3.765	3.761	1.294	1.292
2017	2.596	2.591	3.418	3.414	3.098	3.093	2.114	2.109
2018	2.130	2.127	3.435	3.428	3.250	3.245	1.522	1.519
2019	2.601	2.599	2.898	2.894	3.185	3.180	0.938	0.938
2020	2.716	2.713	3.545	3.539	3.718	3.713	1.558	1.557

Table 9. Estimates of biomass density (t per Ha) and total biomass (t) for each SMU from the FIS for Unders abalone with a constant length of 102-130 mm. Each year is a fishing quota year.

	Portland		Lady Julia Percy		Port Fairy		Warrnambool	
Area	376 Ha		59 Ha		215 Ha		343 Ha	
Year	Biomass Density	Biomass Total	Biomass Density	Biomass Total	Biomass Density	Biomass Total	Biomass Density	Biomass Total
2003	2.465	927	3.126	184	3.401	731	2.714	931
2004	2.269	853	2.980	176	4.159	894	2.621	899
2005	2.274	855	3.860	228	3.135	674	1.972	676
2006	1.730	650	3.623	214	3.751	806	2.290	785
2007	2.114	795	2.025	119	0.990	213	0.991	340
2008	1.048	394	1.468	87	1.170	252	0.906	311
2009	0.517	194			0.742	160	0.890	305
2010	0.754	284	2.591	153	1.152	248	0.550	189
2011	0.883	332	2.205	130	1.882	405	0.823	282
2012	0.851	320	2.269	134	1.541	331	0.732	251
2013	0.838	315	1.345	79	1.632	351	1.150	394
2014	0.783	294	1.829	108	1.587	341	0.863	296
2015	0.759	285	2.680	158	1.426	307	1.014	348
2016	1.133	426	2.943	174	3.042	654	0.971	333
2017	1.862	700	2.589	153	2.396	515	1.666	571
2018	1.576	593	2.563	151	2.630	565	1.108	380
2019	2.065	776	2.007	118	2.449	527	0.714	245
2020	2.101	790	2.505	148	2.759	593	1.165	400

Table 10. Estimates of biomass density (t per Ha) and total biomass (t) for each SMU from the FIS for Unders with a constant length of 102-130 mm, from the 2022 Fishery Assessment and this project. Each year is a fishing quota year.

Year	Portland Assessment	Portland Project	Lady Julia Percy Assessment	Lady Julia Percy Project	Port Fairy Assessment	Port Fairy Project	Warrnambool Assessment	Warrnambool Project
2003	2.079	2.465	3.133	3.126	3.406	3.401	2.717	2.714
2004	2.273	2.269	2.988	2.980	4.167	4.159	2.627	2.621
2005	2.278	2.274	3.868	3.860	3.140	3.135	1.977	1.972
2006	1.732	1.730	3.628	3.623	3.759	3.751	1.966	2.290
2007	2.118	2.114	2.030	2.025	0.991	0.990	0.991	0.991
2008	1.049	1.048	1.470	1.468	1.169	1.170	0.781	0.906
2009	0.517	0.517			0.106	0.742	0.893	0.890
2010	0.718	0.754	2.598	2.591	1.154	1.152	0.550	0.550
2011	0.884	0.883	2.208	2.205	1.884	1.882	0.823	0.823
2012	0.809	0.851	2.270	2.269	1.543	1.541	0.733	0.732
2013	0.801	0.838	1.348	1.345	1.634	1.632	1.151	1.150
2014	0.707	0.783	1.833	1.829	1.591	1.587	0.863	0.863
2015	0.723	0.759	2.688	2.680	1.429	1.426	1.016	1.014
2016	1.023	1.133	2.948	2.943	3.048	3.042	0.971	0.971
2017	1.863	1.862	2.595	2.589	2.398	2.396	1.670	1.666
2018	1.578	1.576	2.565	2.563	2.635	2.630	1.110	1.108
2019	2.068	2.065	2.013	2.007	2.453	2.449	0.714	0.714
2020	2.105	2.101	2.510	2.505	2.763	2.759	1.168	1.165

The earlier estimates of density (t/Ha) reported in the WZ stock assessments through to 2014 are shown in Figure 9.

Figure 9. Estimated density of abalone (kg per Ha) in the Recruits size-class (i.e., >120 mm) averaged across 5 sites in the DEPI survey since 2007 (filled circles + Standard Deviation among sites, with range shown by dashed lines), and across 13 sites in the WADA survey in 2009 (green circle + Standard Deviation among sites). Open circles show the density of abalone >135 mm calculated from the DEPI survey and length-frequency. From Figure 78 of Mundy et.al (2018).
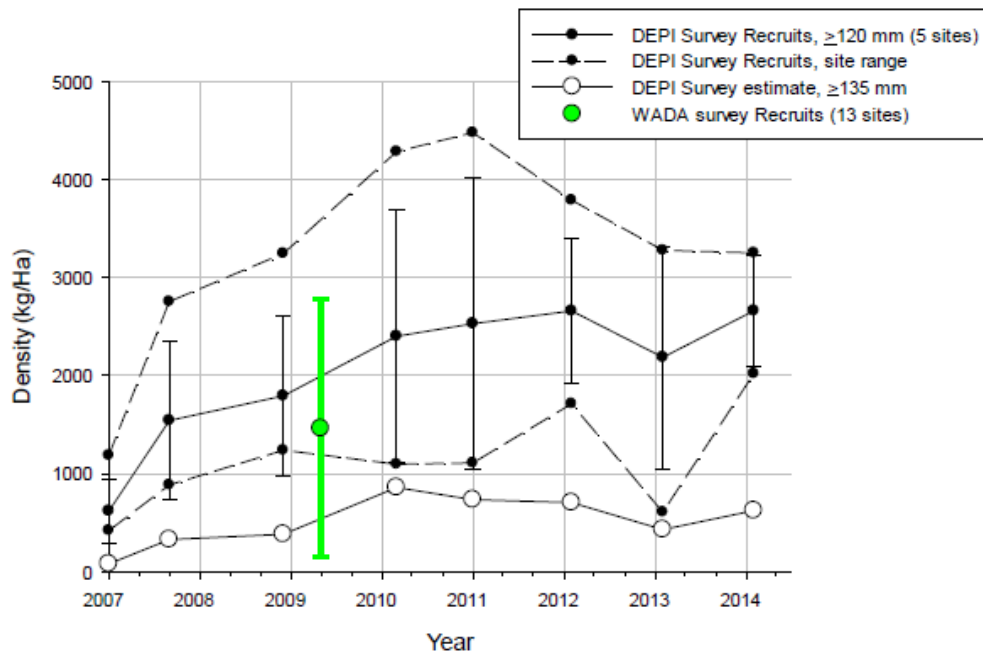
3.4   R script to repeated FIS biomass calculations

The R script for these calculations from the FIS is given in Appendix 2. The appendix provides the detailed R code for the project data and analysis presented, and any further detail can be requested from the authors.

4.   GPS logger estimates of density and biomass

4.1   General description

A general description of the GPS logger system and the calculation of various indicators using them are provided in Mundy (2012) and Mundy et. al (2018). This includes some estimates of density (Mundy et. al, 2018) and various spatial measures of fishing effort, catch and the distribution of productive fishing areas.

A harvest strategy based on a range of data sources and information, including biomass estimates, has been developed and investigated in association with the annual assessment and TAC setting process for the Western Zone (WZ) abalone fishery. After the impact of AVG in 2006, commercial fishing was stopped.

After 3 years of commercial fishery closure an abundance survey was begun in some Reefcodes using commercial divers fishing to a spatially structured design. This Structured Fishing survey made use of GPS loggers and diver depth loggers to record dive events, in combination with records of catch, abalone lengths and other observations at each Structured Fishing survey site. These Structured Fishing surveys provided complimentary information to a long-term abundance VFA FIS survey that continued through this period. With the wider recommencement of WZ fishing in 2009-10 these estimates of the abalone biomass helped informed the TAC setting process, and by 2012 a biomass-based harvest strategy was established and used. The use of GPS loggers was voluntary in the WZ fishery until 1 July 2020 and mandatory after that time. Prior to July 2020 the coverage of fishing with GPS loggers varied among divers, and there was some loss or failure of equipment (the GPS logger coverage rates are shown in Appendix 3).

Estimates of biomass were initially calculated from both the FIS abundance surveys and the GPS logger information from Structured Fishing surveys. This was done by combining estimates of the density and size of abalone with estimates of the area of productive reef, so as to extrapolate survey densities and estimate biomass available to the fishery. While both abundance surveys and GPS logger data sources have proven useful, resources were not available in the WZ to continue structured fishing or extend the abundance surveys at appropriate spatial and temporal scales. Specifically, it was difficult to continue a structured fishing survey because of the level of support and resources required (i.e., although this could have been done if prioritised), and the harvest strategy focused on using the FIS data (i.e., the VFA FIS data supported by the additional WADA survey data) to calculate abalone density and the TACC. In addition to these FIS-based estimates of density and biomass, until 2016 the density and biomass of exploitable abalone was also calculated from commercial fishing and reported in the fishery assessment reports. Consequently, the independent estimates of exploitable density and biomass from the FIS and from the GPS loggers could be compared and used to judge sensitivity of the assessments. This section provides a summary of the recent use of estimates of biomass in the fishery, and the development of new methods based on information available from GPS loggers during normal commercial fishing.

Biomass is not frequently estimated for abalone populations, particularly because of the difficulties caused by size-dependent crypsis of abalone, survey selectivity (including effects from both variable detection by divers and the uncertain representativeness of sites through time), large variation in abalone density at a range of spatial scales, and the need to extrapolate density estimates from very small-scale surveys to much larger areas of reef. Similarly, fitting population models to estimate abalone biomass, with the complex spatial structure of abalone populations and limited data, has also proved difficult though there have been some successful applications (e.g., Helidoniotis et al., 2015). The development and use of GPS loggers in recent years can provide an additional method to estimate biomass of exploitable abalone populations, which can be compared and calibrated to estimates from other methods.

Estimates of legal-sized density and biomass from logger information from commercial fishing can have important benefits compared to scientific abundance surveys. In particular the logger estimates make use of the extensive searching time and broad spatial coverage of commercial divers during fishing (i.e., equivalent to about a thousand hours per year in WZ, and usually covering a large fraction of productive reef), so that density estimates are based on much larger samples of abalone over much broader areas than is feasible using small transects at a limited number of sites. Despite the advantages of logger information, it remains a fishery dependent method that can be influenced the same factors that can influence interpretation of other data collected from commercial fishing (e.g., targeting, catch rates, size composition etc). The fishery selection effects, including fishing not being able to sample under-size abalone, can be overcome through well-designed scientific surveys but design of a robust survey is difficult

for abalone that are widely distributed and that reaggregate, and surveys will inevitably cover only a small area of the fishery. Each of the methods that can estimate density biomass (i.e., abundance surveys, modelling and GPS loggers) have their own strengths and weaknesses, and so can provide complimentary information for interpretation and cross validation.

In this section we describe the data and calculate density and biomass of exploitable abalone from GPS logger data in the WZ fishery since the resumption of fishing after AVG. The GPS logger estimates of exploitable abalone density and biomass are then compared to estimates from abundance surveys and population modelling to calibrate and validate the estimates produced. Comparisons of logger-based estimates of biomass with other methods are made within the Crags reefcode, both because it has the greatest coverage by abundance surveys and, unlike most reefcodes, both abundance survey and model-based estimates of biomass have been calculated. With appropriate validation, the use of logger data offers a simple and intuitive method to estimate exploitable biomass through time and guide estimation of sustainable catch.

GPS logger data are provided by divers who operate a combined abalone GPS logger (i.e., recording GPS location at 1-minute intervals) and abalone measuring board (i.e., recording GPS at regular intervals and as abalone are measured) on their boat, and a depth logger (i.e., recording depth for depths >0.5 m at 10 sec to 1 minute intervals) on the diver. A range of procedures have been developed and implemented since about 2009, to operate the loggers and collect, manage, store and analyse the data. Scielex measuring logger memory sticks, and Sensus depth loggers, were used by divers while fishing and they are collected at least once a year or as data is needed for interpretation. Diver's post the individually labelled memory sticks to a technician for download, and an empty stick is then returned to the divers. Succorfish GPS loggers are also used by divers on all of a day's fishing and is a required Vessel Monitoring System (VMS) reporting to VFA. Succorfish GPS loggers send data to the Succorfish servers in the cloud, mostly within 10 seconds of logging a GPS point on the boat, although this process can take more time where reception is limited. Scielex abalone measuring boards and depth loggers are now connected by bluetooth and send GPS, abalone lengths and diver depths direct to a cloud site.

Quality assurance procedures for loggers are limited and have been developed in response to the low risk of error from high quality automated digital devices. Succorfish and Sensus loggers turn on and collect data automatically, while Scielex measuring loggers, following manual activation, operate automatically triggered by the movement of abalone through the measuring device. All divers and deckhands are trained and most have extensive experience handling abalone and operating the measuring loggers. Measuring and Depth loggers initially required manual download, and were posted to a technician for download, with memory sticks also containing the diver's name. Measuring and Depth logger data are now sent direct to a cloud site. These and similar procedures have been used in WZ for over a decade, and similarly in other states, and have a record of being able to provide quality, reliable data from the GPS loggers.

Following collection and download of the data, measuring loggers and depth loggers are backed up on-site and off-site on cloud servers, and a full copy of the logger database is archived each year. Quality control procedures involve the matching and consistency of the date and time of a diver's measuring logger, GPS logger and depth logger data with the logbook catch data received from VFA. Data are also filtered by specific range checks for abalone lengths (i.e., blacklip <180 mm), depth and spatial position (i.e., within Reefcode and historical fishing areas). Loggers with the most recent technology rarely make minor transcription errors, but they can occur, and clear errors are either edited where alternative information is not compromised (i.e., based on a recent position) or deleted. A combination of automated scripts (i.e.,

javascript, SQL, R, Latex) are used to summarise, analyse and present the logger data. These procedures have been used in WZ for over a decade, and similarly in other states, and have a record of being able to deliver quality output from the logger data.

Following download of data from loggers, or on arrival at the cloud site, all files are archived and imported into a secure SQL database. A series of javascript, R and SQL queries are used to produce summaries of lengths (e.g., raw mean lengths calculated from lengths $\geq$135mm and <180mm), dive events and performance indicators. Estimates of mean length per day and reefcode are calculated where there are more than 50 abalone measured. A GLM is used to standardise the mean lengths with terms SMU x Fishing Period + Reefcode + Diver with normal errors. Daily dive events from logger data are also linked to daily catch data from logbooks to calculate the weight of abalone landed per area of dive event (i.e., the biomass density in kg/ha). This density can be used directly as a stock indicator or to estimate the legal biomass for a given area. For analysis, daily estimates of biomass density are calculated, with removal of data where biomass density is >5000 or <50 kg/Ha or where logged dive times are <50% or >200% of logbook reported times. A GLM is used to standardise log (daily biomass density) with terms SMU x FishingPeriod + Diver with normal errors, and estimates are adjusted for bias as they are back transformed. Ongoing development of the data logger program will require development of procedures for the new Succorfish Bluetooth Depth loggers.

4.2 Density and biomass calculation from GPS logger data

Estimates of the density, and hence biomass, of exploitable abalone can be calculated from the data provided by GPS loggers. The GPS loggers used in WZ are held on the diver's boat, and the diver is tethered to the boat by a hookah hose of ~50 m. As the boat moves during the day, the spread of GPS points can provide an estimate of the area of reef visited by the diver during a day, with diver depth loggers identifying GPS points where the diver was in the water. In addition, daily catch (i.e., kg) by Reefcode is reported to VFA and can be linked to the daily area of reef visited by the diver (i.e., Ha) to produce an estimate of the density of abalone (i.e., kg/Ha). The density estimates from the GPS loggers are fisher dependent and so they are likely to be affected by the same factors the effect commercial catch rates (i.e., kg/h) such as selectivity/crypsis, diver-specific effects, market, weather and other factors. Density estimates from FIS-based abundance surveys can also be affected by some of these issues, as well as challenges of survey design and area coverage, though some of the commercial issues do not apply to FISA-based estimates.

GPS loggers in the WZ fishery collect the GPS position of the boat at regular time intervals and when abalone are measured with a GPS-enabled measuring board. Depth loggers are attached to divers and used to log when they are at depths >0.5 m), which are defined as a dive event. The depth logger does not record the actual depth of the diver on the logger, rather it records when the diver is deeper than 0.5m, through diver depth can be estimated from the GPS position and known depth contours. The time of dive events used to isolate the times of vessel GPS points that are associated with the dive event. The GPS records from individual dive events (i.e., boat GPS locations when the diver was at >0. 5m depth) are summarised using Kernel Density Estimation (Mundy 2012) to describe the spatial density of GPS points during the dive event. The Kernel Density Estimation approach includes calculation of various measures from the data, including the distribution of kernel points and the Kernel Density Utilisation Distributions (KUD). This is implemented by estimating spatial, bivariate-normal distributions for each GPS point from a dive event, which are then combined for all points within the dive event and normalised to produce contours of the area enclosing different percentages of the points from the dive event (Figure 10). The

area searched by the diver during the dive event can then be estimated by the area of different percent contours. For example, areas enclosing 50% and 90% of the estimated density of GPS points from each dive event are routinely calculated for the WZ abalone analysis. These areas (i.e., Ha) can be summed for all dive events by each diver during a day to estimate the total area searched by the diver per day. This is then linked to the reported daily catch (i.e., kg) by each diver to provide an estimate of the density of abalone encountered by the diver (i.e., kg/Ha) each day. Two approaches have been used to calculate these estimates per reefcode or SMU, and include raw averages and standardisation (i.e., as is done for CPUE in kg/h). These individual diver estimates by day and area are then combined to estimate the exploitable density and biomass in a given area and time encountered by all divers combined.

Figure 10. Method of developing a summary of a dive event. (a) GPS points every 10 seconds where diver depth is >0.5 m, (b) kernel point density (i.e., estimated density of points per 5 x 5 m shown by pink-red colours) and contours (i.e., estimated density of points per 5 x 5 m grid shown by blue lines), (c) kernel point volume contours (i.e., enclosing estimated percent of points with highest density from dive event) and (d) kernel point volume contours enclosing estimated 50% and 90% of points, with related area (i.e., Ha).
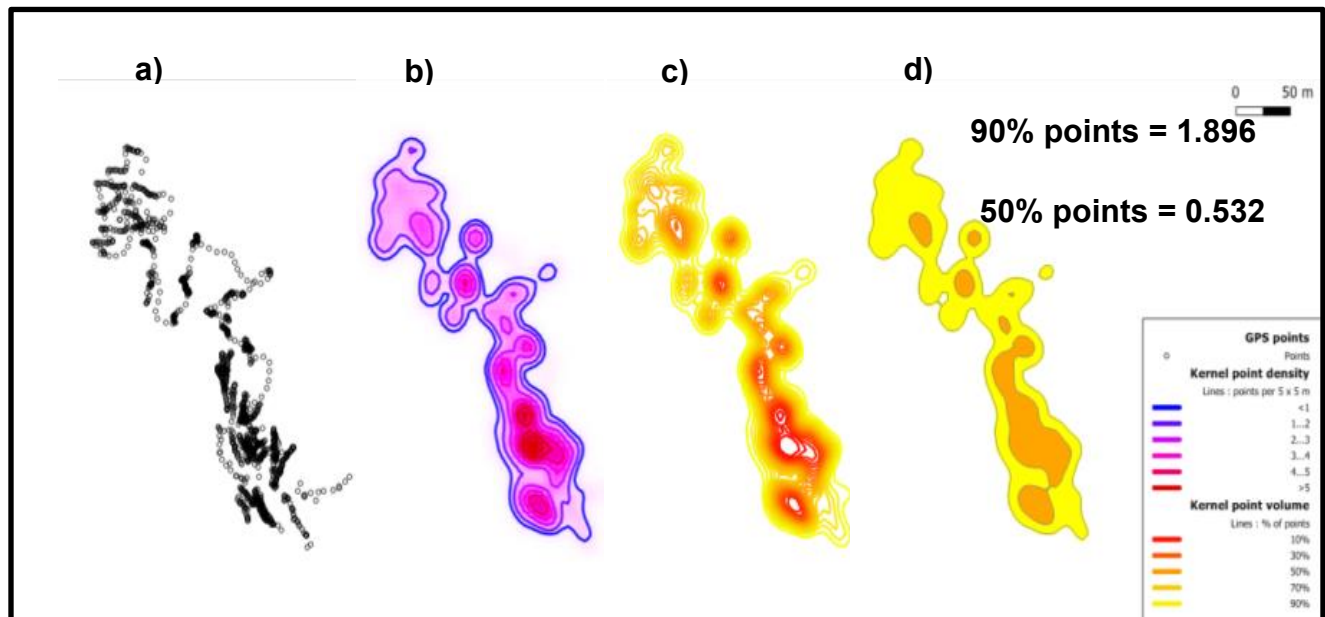
The densities of legal biomass estimated from GPS loggers in the previous WZ assessments and from this project are shown in Table 11. The estimates of legal biomass from this project are shown in Figure 11. The legal biomass for these GPS -based estimates uses the LML that was in place at the time, and so it varies through time (see Tables 4 and 11).

Figure 11. Estimate of total Legal-sized biomass (t) estimated with loggers, from the daily catch and area of Dive events (in t per Ha) extrapolated to the area of the fishery within each SMU. These estimates involve the LML that was applied in the fishery in each year and SMU.
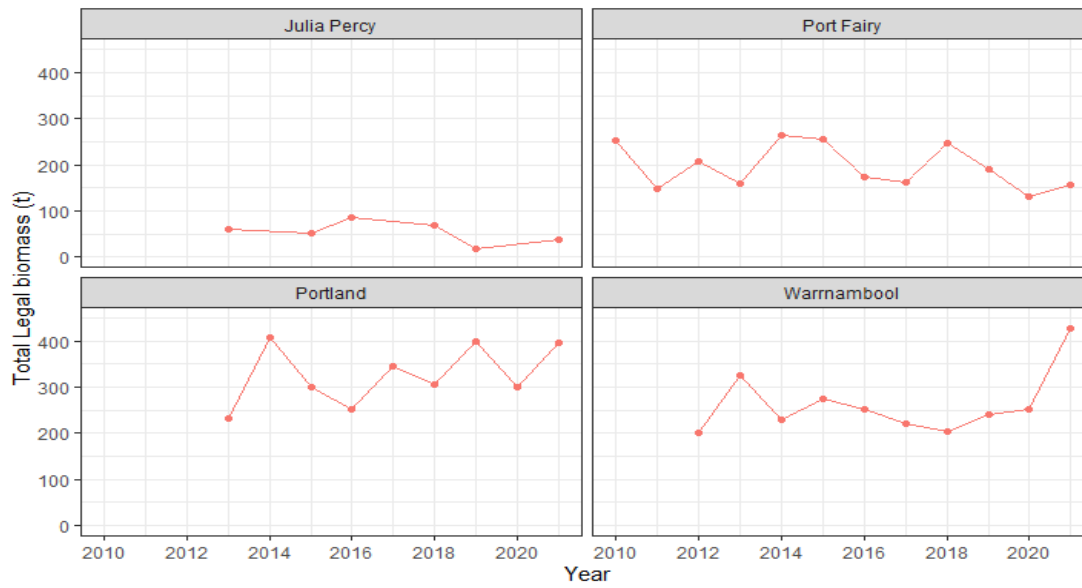
Table 11. Estimated Legal biomass density (t per Ha) from GPS Loggers within each SMU with LML from the WZ 2017 Fishery Assessment and from this Project. Note the Project includes more data than the 2017 Assessment, including more data prior to 2017, and a different standardisation approach including a larger set of divers. The Legal biomass is abalone ≥LML for each year and SMU. LML values marked with * indicated that a larger LML were used by WADA within the SMU, including in Portland SMU where LML remained at 135 mm in some Reefcodes during 2013-2015, at Crags Reefcode in Port Fairy SMU where LML was 132 mm during 2014-15, and at Levys Reefcode in Warrnambool SMU where LML was 140 mm in 2014-15 and subsequent years. Each year is a fishing quota year.

Year	Portland			Lady Julia Percy			Port Fairy			Warrnambool		
	LML	Assess	Project	LML	Assess	Project	LML	Assess	Project	LML	Assess	Project
2010	120			130			135	0.956	0.934	120		
2011	120			130			135	0.620	0.702	120		
2012	120			130			135	0.894	0.880	120	0.586	0.752
2013	135	0.585	0.812	130	1.099	1.163	135	0.738	0.624	135	0.832	0.736
2014	*130	1.070	1.051	130			130	1.086	0.864	130	0.652	0.754
2015	*130	0.849	0.869	130	0.754	1.170	*130	1.164	1.080	*130	0.870	0.824
2016	130	0.663	0.838	130	1.100	1.153	130	0.737	0.762	*130	0.697	0.740
2017	130		1.061	130			130	1.020	0.698	*130	0.641	0.709
2018	130		0.955	130			130		0.956	*130		0.732
2019	130		1.180	130		0.672	130		0.752	*130		0.751
2020	130		0.979	130			130		0.583	*130		

The density estimates from past fishery assessments and the current FRDC project are very similar, and differences reflect the evolving data set and methods applied.

4.3   Summary and use of GPS logger biomass calculations

Estimates of the density of abalone and area of productive reef from loggers can be used to estimate the biomass of abalone available to the fishery. Estimates of density, and therefore biomass, from loggers can be relatively simple and cheap (i.e., including in-kind contribution by divers to operate the loggers), intuitive in their calculation and interpretation, and can produce similar estimates to other methods of estimating biomass. When provided in an intuitive decision-structure, together with other complimentary information, as has been developed in the WZ abalone fishery TAC setting process, estimates of biomass from GPS loggers provide a useful contribution to the current TAC setting process. They may also contribute to future formal harvest strategy in the WZ fishery.

There are a range of different methods to combine logger and catch data to estimate the density of abalone, and the appropriate area of productive reef to extrapolate density and calculate biomass. In the WZ fishery, the density of abalone was estimated from the combination of daily catch and the area visited by a diver, in which the area was estimated to be the area under 50% of the GPS points from dive events during each day. While other methods could be used, this method provided estimates of density similar to those from independent abundance surveys (see Figure 12). Further, the productive area of reef was estimated by a variety of methods, but historical estimates by divers and the method based on the presence of >20 abalone measurements in a 1 Ha grid, have been used in development of TAC advice in WZ. While there are few other methods able to provide estimates of the productive area of reef for

comparison and verification (e.g., Lidar and habitat models), there are independent methods available to calculate biomass (e.g., population models) that can provide further information for calibration and validation of methods to use data collected by GPS loggers during commercial fishing to calculate biomass available to the fishery.

Figure 12. Previous estimates of density of abalone ≥135 mm (kg/Ha) within the Crags reefcode from 5 sites in the DEPI survey since 2007 (filled circles ±SD among sites = population SE, with range shown by dashed lines), from 13 sites in the WADA survey in 2009 (green circle ± SD among sites = population SE), from loggers used in Structured Fishing during 2009-2011 (blue circle ±SE) and from loggers used in commercial fishing from 2011-12 to 2013-14 (red circle ±SE). Horizontal error bars on logger-based estimates show the approximate range of time of the fishing. From Figure 80 of Mundy et. al (2018).
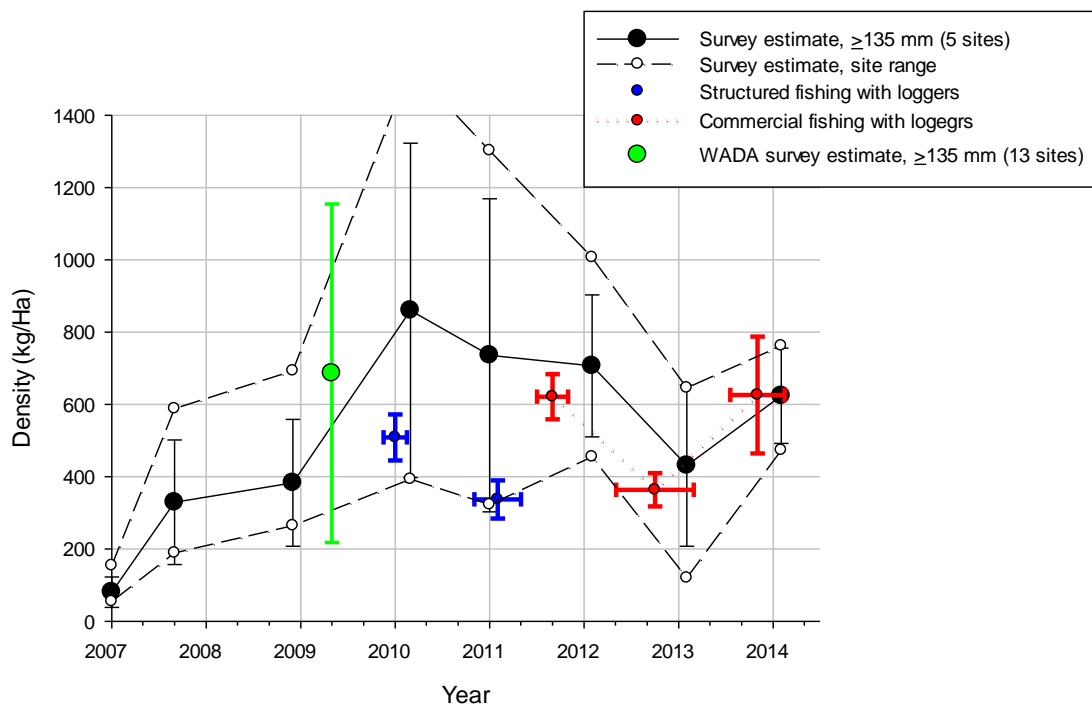
Despite these benefits, many uncertainties remain about the preferred technique of combining the logger data to calculate biomass, and their influence on accuracy and precision of that estimate. These uncertainties range from technical issues (e.g. how to determine and deal with lost logger data within a day, standardization, scale of calculation and application, timing of data collection, analysis and review) to factors such as the crypsis of abalone, selectivity of different divers and weather conditions, all of which will clearly influence estimates of density from the combination of logger and catch data, but importantly these factors will influence any measure, including relatively expensive independent survey estimates of density. These factors are similar to those that influence the interpretation of commercial fishery catch rates, but the spatial information available from loggers provides the opportunity to remove some key confounding factors (e.g., area visited or swept by the diver estimated by the area of the dive even) and make direct fine-scale comparisons (e.g., at a site within a reefcode) through time. Perhaps most importantly, as divers are often able to maintain fishing catch rates (i.e., logbook kg/h), it will be important

to determine how estimates of density from the logger data (i.e., fine-scale, standardised kg/Ha) compare, and whether they can provide an early warning of other changes.

A harvest strategy to catch a specific proportion of the available biomass will result in catch that is too high if estimates of biomass are biased too high. Consequently, it is appropriate to use techniques that produce more conservative estimates of biomass and harvest fraction, particularly because of uncertainty in the methods to calculate biomass from logger data and their accuracy. The current application of biomass estimates in the WZ harvest strategy uses a productive area estimate 44% lower than estimated by the preferred technique using logger data, as part of an approach to ensure conservative estimates of productive area, and so biomass, are used in guiding catch. Techniques developed here include estimates of density calibrated to abundance survey estimates but estimates of productive area may have greater uncertainties because there are few other methods available for comparison.

Estimate of biomass from GPS logger data are calculated from estimates of density and productive area, which can also be estimated by independent methods (e.g., density by abundance surveys, area by Lidar habitat models). Estimates of biomass through time are also made during fitting of population models, and these estimates provide a further opportunity for calibration and validation of estimates produced by GPS loggers. Several estimates of biomass are available from population models developed in WZ (i.e., abalone model used by Victorian government prior to AVG as described in Gorfine et. al 2001, Gorfine et. al, 2007 and Helidoniotis et. al, 2015). Preliminary comparison of estimates of biomass from GPS loggers and population models were similar, but more detailed comparison was beyond the scope of this project. Despite that, there remains a need to extend comparisons of biomass among methods to provide further calibration and validation of both methods. A recent national Workshop considering strategic priorities for harvest strategy development rated further calibration of methods a high priority. Further development of methods for estimating biomass from GPS loggers, that could be used in TAC setting and catch controls as part of a harvest strategy, are still required and will depend on several other factors including the level of logger use, resources for analysis, frequency of review and level of precaution required.

4.4 R script to repeat biomass calculations from GPS Loggers

The R script for these calculations from the GPS logger data is given in Appendix 3. The appendix provides the detailed R code for the project data and analysis presented, and any further detail can be requested from the authors.

5. Plans for trial of calibration between FIS and GPS logger estimates of density

On 27/4/2022 a meeting was held with the Project Steering Committee including Travis Baulch (VFA abalone manager), Harry Peeters (Executive Officer, WADA), Craig Fox (Chairman, WADA), Duncan Worthington and Keith Sainsbury to consider finer space-scale calibration of density estimates from FIS and GPS loggers. The existing data estimates density from GPS for a large area, effectively at the space scale of the area fished by a diver in a day because the reported daily catch is needed to estimate the abalone density. Conversely the density estimates from the FIS are at very local spatial scale. This disparity makes calibration difficult, and it is proposed that special calibration trials be conducted. These trials would record GPS catch data at the bag-lift and so would be more comparable with the FIS estimates. This suggested improvement in the calibration was agreed in principle by FRDC. The calibration would need to be done with FIS sampling and GPS Logger sampling being done at the same time. The VFA FIS has been

stopped and it was intended that WADA would establish a new FIS system. However, the recent outbreak of AVG in the western part of the WZ fishery has disrupted the establishment of the WADA FIS sites.

The PowerPoint presentation given at the meeting is attached in Appendix 4, with the key questions for the meeting given on the last slide. The agreed outcome of the meeting was:

Should the calibration be done?	Yes
How many calibration sites	Difficult to tell until we get some trial data to determine variability. Some information from past FIS and logger sites, comparing as best as is possible the FIS and local logger densities, and that will be useful but limited. Need some sampling trials to begin this analysis more fully.
Where should the calibration sites be?	Should include VFA and WADA FIS sites. These can be sampled in any order. The WADA sites have yet to be determined but they will be, probably starting late 2022 and then into 2023. The Portland SMU will be difficult to work initially but should be possible later. The initial focus will be in the eastern SMUs.
When should the sites be calibrated?	The calibration will be across both 2022 and 2023. - The 2022 calibration will include VFA and WADA FIS sites in the eastern SMUs. This will test the sampling methodology, measure sampling variance, and allow sample sizes to be calculated. - The 2023 calibration will examine a more complete set of calibration sites. It may include the Portland SMU.

The proposal is to conduct an initial calibration trial in 2022 in the eastern part of the WZ, with a more complete calibration conducted when the WADA FIS sites are more fully established. This will require an extension of the project into 2023.

6. General comments

The project has reconciled/consolidated and summarised the various historical approaches, inputs and methods for analysis of the commercial catch rates, FIS, and GPS loggers. It has also repeated and developed the historical analysis of commercial catch rates, FIS, and GPS logger data, and R scripts for these calculations are provided. This allows for clarity about the analysis methods, comparison of the estimates from the three data sources, and provides independent replication of the estimates.

The data compilations and initial analyses conducted by the project were not as easy as was initially expected. This is because of the evolution of the monitoring and analysis methods that have been applied in the Western Zone fishery, particularly (but not only) after the major AVG mortalities in 2006. In some cases (e.g., catch rate standardisation) several very different methods had been applied historically and so a revised set of standardised catch rate data was developed. Several of the other monitoring and analytical methods had also changed through time (i.e., including the most recent reduction of the VFA FIS soon after

the project commenced). However, the analysis that has been conducted here will allow comparison of the density and biomass estimates on the time and space scales that have been used in the WZ fishery past, and this will allow direct comparisons of "apples with apples". It also provides the basis for addressing the major objectives of the project, that are to calculate and calibrate logger-derived density from observations of commercial catch rate, loggers and surveys.

The project has so far focused on consolidating and extending the indirect and direct estimates of abalone biomass that were used in recent WZ stock assessments. The three sources examined are commercial catch rates, FIS monitoring and GPS logger monitoring, and each has different advantages and disadvantages. The commercial catch rates are fishery dependent and spatially widespread, but they are influenced by the LML, diver, weather and market influences. The FIS is independent of fishing and can monitor abalone both above and below the LML, but it samples a very small area of the fishery and its reliability depends on consistent monitoring methodology and appropriate selection of FIS sites. The GPS loggers are fishery dependent so they share the advantages and disadvantages of commercial catch rates, though some effects of changed diver behaviour (e.g., the area fished, diver effectiveness and spatial differences) can be removed in the GPS Logger analysis, and the fraction of fishing that is monitored varies across area and time. The project has not yet made quantitative comparisons of these indicators, but some general and tentative overall observations can be made:

- The commercial catch rate (kg/h) in all SMUs has substantially increased since the AVG mortality in 2006/7 (see Appendix 1 and Figures 4 and 5). Different standardisations change the correspondence between the raw and standardised catch rates, but all show a similar temporal pattern. The standardised catch rates are all lower than the raw catch rates, and in some SMUs (e.g., Portland and some years in Pt Fairy) the difference is particularly large, though the relativities between the raw and standardised catch rate changes with different standardisation methods. The commercial catch rates suggest that the relative biomass of legal abalone in 2021 is very similar to before the AVG mortality, despite the increase in the LML over that period from 120 mm to 130 mm (with various transitional changes to LML occurring in different areas and years).

- The biomass (t) of currently legal (≥130 mm), mature and under-size abalone estimated from the FIS are shown in Figure 8 and Tables 5, 7 and 9, while biomass density (t/Ha) of these categories are provided in Appendix 2. The current LML of 130 mm was applied through this FIS analysis, though a fixed historical LML of 120 mm is examined in Appendix 2 and the regulated LML that changes through time is reported in Table 4. The estimated currently legal biomass (≥130 mm) has remained about the same in all SMUs since the AVG mortality. Lady Julia Percy had no AVG mortality but as part of re-opening the WZ fishery it was intentionally and intensively fished after the AVG infections elsewhere. The current legal biomass has increased at Lady Julia Percy since 2010. The estimated mature biomass, though variable, has substantially increased in most SMUs since the AVG mortality, especially in Port Fairy and Portland, though there was relatively little overall increase at Lady Julia Percy. The estimated mature biomass in 2020 was about half of the pre-AVG abundance in Lady Julia Percy, Port Fairy and Portland. The pattern seen in Warrnambool is different, with only a slow increase in the mature biomass and in 2020 the abundance was like just after the AVG mortality. The patterns in under-size abalone are like those of mature abalone. There is an increase in under-size abalone abundance post-AVG in Port Fairy and Portland, while Lady Julia Percy remains at about the same level it was after the AVG mortalities. These three SMUs have recent under-size abalone abundance that is about half the pre-AVG levels. The under-size abalone abundance in Warrnambool is estimated to be similar that seen directly after the AVG

mortality. The reduced recovery estimated for Warrnambool may be driven by the patchiness of the abalone recovery in space and time after the AVG mortalities combined with some FIS sites being in relatively poor abalone habitat and there being large variation in recovery between a small number of sites (i.e., 5) that strongly effect the SMU estimates.

- The legal biomass (t) estimated from the GPS loggers and commercial catch are shown in Figure 11, with biomass density shown in Appendix 3. The LML in these estimates is the LML applied in each year and area. The legal biomass is reasonably constant through time in all the SMUs.

- The measures of the legal biomass from the FIS and GPS loggers have very similar trajectories and suggest that this biomass has been approximately similar since the AVG mortality. However, the commercial catch rates have increased substantially during this time, and they may exaggerate the recovery of the legal biomass.

- Post-AVG there has been a recovery of both the mature and undersize abalone. In 2020 both these sizes of abalone were a bit more than half of their pre-AVG abundance.

The project has identified several issues that it will continue to examine and develop. These include the methods for catch rate standardisation and particularly use of finer spatial scale data from FIS sampling and the GPS loggers. But the main focus of the project in future will be on the analysis, comparison and calibration, at a range of spatial and temporal scales, of the density and biomass estimates from the GPS loggers, FIS and commercial catch rate data. The density and biomass estimates from the catch rates, FIS and GPS loggers have very different implied space scales. For the catch rate standardisation, the implied space scales are the SMU and the Reefcode (as in the current analysis), while each FIS site covers about 180m^2, and the current GPS logger estimates use the area fished by a diver in a day (which can be small in some cases but Reefcode or larger in other cases). The GPS loggers give fine space scale observations, but the wide space-scale of catch reporting limits the density estimates. Statistical comparison of density and biomass estimates is difficult because of these different space scales. There are three approaches that the project will use in its next phase.

i.   Make the estimates on a space scale that is as small as possible across the data sources. This approach is what was originally described for the project. It is a reasonable approach, but it may encounter difficulties with the course GPS logger data. There is a possibility that for a period of time some divers may have recorded fine scale catch, these observations should be accessible to the project, and they may help with analysis.
ii. Make the estimates on an intermediate space scale, such as an area that is about at the scale of several FIS sites and that may better match the diver daily area fished.
iii. Conduct trial calibrations between the FIS and GPS logger estimates when both are on more similar space scales. This was proposed to happen in calendar year 2022, and FRDC has already agreed to this. However, the recent AVG outbreak in the western part of the WZ has delayed establishment if the new WADA FIS sites, and this has delayed the calibration. Currently it is planned to do some initial calibration trials in the eastern WZ late 2022, using a combination of VFA FIS sites and perhaps some new WADA sites, with a more complete calibration being undertaken in 2023. An application to extend the project into 2023 will be provided to FRDC.

The project has not held any meetings of the project advisory group. In part this was because the project was repeating past analysis and in part because of COVID constraints. There is a plan for the Australian

Abalone Council will hold a meeting in 2022, following cancellation of the 2021 meeting. It is intended that the project will attend this meeting and hold an advisory group meeting then.

Currently there is no report available for the 2022 WZ TACC Workshop report. The workshop was held, TACCs were decided, and Mr Patrick Home was present for this meeting. VFA is responsible for producing the report of this meeting but so far it has not produced a draft. Still hoping!

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Appendix 1: Catch and Effort Standardisation Models

2022-09-13

Contents

Tables

Figures

1 Introduction

In this document we develop four candidate standardisation models for catch and effort in the Western Zone. The models all havee a similar form but deal with data at different levels of aggregation, as outlined below.

Year terminology

An operational year for the fishery begins on 1 April in one calendar year and ends on 31 March in the following calendar year. This leads to a possible ambiguity. In this document we use the terms *'quota year'* and *'assessment year'*, in context, for the calendar year in which the fishing year *ends*.

1.1 Data aggregation levels

The four models considered here all have the same structure, but use different versions of the input data. These are

1. The data aggregated to the `SMU` level for `Catch` and `Effort`, for quota years 1980-2021.

2. The data aggregated to the (new) `ReefCode` level, 1980-2021.

3. The data aggregated to the `SMU` level, 2003-2021.

4. The data aggregated to the `ReefCode` level, 2003-2021.

The data used to fit these models *excludes* observations made after 2021-03-31, i.e. after the end of assessment year 2021.

1.2 The 'diver experience' term

One modelling difficulty we explore here is the possible need to allow for a change in diver effectiveness with age, i.e. as 'diver experience' increases. Here we use a polynomial form for the dependency of the catch response on on diver experience and examine its performance.

2 Models

These are specified in the following code chunk.

```
mod_SMU <- lmer(log(Blacklip) ~ offset(log(Effort)) + SMU +  poly(log(diver_ex), 4) +
                  QuotaYear + (1|Month) + (1 + log(diver_ex)|Diver) + (1|SMU:QuotaYear),
               data = Catch_SMU, control = lmerControl(optimizer = "bobyqa"))

mod_NRC <- lmer(log(Blacklip) ~ offset(log(Effort)) + SMU +  poly(log(diver_ex), 4) +
                  QuotaYear + (1|Month) + (1 + log(diver_ex)|Diver) + (1|ReefCode) +
                  (1|SMU:QuotaYear),
               data = Catch_NRC, control = lmerControl(optimizer = "bobyqa"))

mod_SMU_0220 <- update(mod_SMU, data = Catch_SMU_0220)
mod_NRC_0220 <- update(mod_NRC, data = Catch_NRC_0220)
```

The models all have the same form, namely

- The response is `log(Blacklip)` i.e. the blacklip catch per diver per day on a log scale.

- The offset for `log(Effort)` allows predictions to be made at the `log(CPUE)` scale.

- There fixed categorical main effects for `SMU` and `QuotaYear` and a fixed polynomial main effect in `log(diver_ex)` of degree 4.

- There are random main effects for `Month`, to allow for intra-annual variation and, where the data set allows, a random main effect for `ReefCode` to allow for variation between reef codes within `SMU`

- There is a random categorical main effect for `Diver` and a correlated random coefficient on `log(diver_ex)`, the effect of which will be to allow different divers to start their process of improvement with experience at differing rates.

There are two levels of *aggregation* for the data, namely at the `ReefCode` level and at the coarser `SMU` level, and for each of these there are data sets with the full temporal record, 1980-2021 and with the shortened temporal record, 2003-2021, corresponding to the period when the "new" reef codes were in force. These four data sets define the four models fitted above.

2.1 A formal description

A more formal algebraic description of the model is as follows. Let C_i be the blacklip catch, made with effort F_i by diver d in quota year y, in month m, on reef code r, in SMU s.
Moreover let the diver's experience in that year be X_{yd}. In algebraic terms the model may then be expressed as

$$\log C_i = \log F_i + \mu + \nu_s + P_4\left(\log X_{yd}, \boldsymbol{\beta}\right) + \eta_y + M_m + (B_{0d} + B_{1d}\log X_{yd}) + R_r + (SY)_{sy} + E_i$$

where the terms have the following meaning:

- μ, ν_s and η_y are the intercept, *fixed* main effect for SMU and *fixed* main effect for quota year,

- $P_4\left(\log X_{yd}, \boldsymbol{\beta}\right)$ is a *fixed* polynomial term of degree 4 in $\log X_{yd}$ with coefficient vector $\boldsymbol{\beta}$,

- M_m is a *random* main effect for month with distribution $M_m \sim \mathrm{N}(0, \sigma_M^2)$,

- The pair (B_{0d}, B_{1d}) are correlated *random* intercept and slope adjustments, pertaining to diver d. They are modelled as having a bivariate normal distribution given by

$$\begin{bmatrix} B_{0d} \\ B_{1d} \end{bmatrix} \sim \mathrm{N}\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \delta_{11}^2 & \delta_{11}\delta_{22}\rho \\ \delta_{11}\delta_{22}\rho & \delta_{22}^2 \end{bmatrix}\right)$$

where $\delta_{11}^2, \delta_{22}^2$ are the variance components and ρ is the correlation between random intercept and random slope adjustments.

- R_r is a *random* main effect for reef code with distribution $R_r \sim \mathrm{N}(0, \sigma_R^2)$,

- $(SY)_{sy}$ is a *random* interaction with distribution $(SY)_{sy} \sim \mathrm{N}\left(0, \sigma_{SY}^2\right)$,

- E_i is a *random* residual error, $E_i \sim \mathrm{N}\left(0, \sigma^2\right)$.

Note the the leading term, $\log F_i$, is a fixed offset and so does not have a coefficient attached to it.

2.2 Prediction and implicit normalisation

For standardisation of the CPUE we use the model to predict the log catch for fixed, prescribed values for the ancillary terms in the model. These are:

- The effort is specified as $F_i = 1$, effectively making the prediction to be of log CPUE,

- The diver experience is fixed at $X_{yd} = 1$, thus emulating the performance of neophyte diver, and hence removing as far as possible the effect of diver experience,

- The random terms M_n, R_r, B_{0d}, B_{01} and E_i are omitted from the prediction, effectively holding them at zero, that is, at neutral values.

- The prediction involves all other fixed terms, μ, ν_s and η_y, as well as the random interaction $(SY)_{sy}$.

This technique of holding some predictors at fixed nominal values and omitting random terms modelled as having mean zero in the prediction effectively *normalises* the predictions at a consistent, implicit level thus removing the need to use some form of more artificial normalisation involving, for example, linking the standardised series to the crude CPUE series in some way.

2.3 Model outputs

First we look at the variance components and correlations. The `vcov` columns give either the variances or the covariances, depending on the context; the `sdcor` columns give either the standard deviations or the correlations, again depending on context.

The protocol used in the tables below is somewhat involved; the details are as follows

- The first column gives the grouping level of the random effect

- Columns labelled `Col. 1` and `Col. 2` determine the predictors involved in the random effect itself.

- The columns labelled `vcov_*` give either *variance component estimates* if the entry in `Col. 2` is blank, or *covariance component estimates* if it is not blank. Where a covariance is involved, it is between the variables named in `Col. 1` and `Col. 2`.

- The columns labelled `sdcor_*` give either *standard deviations* when `vcov_*` is a variance component, or *correlations* when it is a covariance component.

- The suffices, `_NRC` or `_SMU` denote the aggregation level of the data uses to fit the model.

Table 1: Variance components, covariances, standard deviations and correlations, full data set

Group	Col. 1	Col. 2	vcov_NRC	sdcor_NRC	vcov_SMU	sdcor_SMU
SMU:QuotaYear	(Intercept)		0.0035	0.0588	0.0055	0.0741
Diver	(Intercept)		0.1616	0.4020	0.1557	0.3946
Diver	log(diver_ex)		0.0280	0.1673	0.0247	0.1572
Diver	(Intercept)	log(diver_ex)	-0.0500	-0.7436	-0.0453	-0.7307
ReefCode	(Intercept)		0.0119	0.1089		
Month	(Intercept)		0.0012	0.0350	0.0012	0.0341
Residual			0.1220	0.3493	0.0924	0.3040

Table 2: Variance components, covariances, standard deviations and correlations, 2003-2021 data set

Group	Col. 1	Col. 2	vcov_NRC	sdcor_NRC	vcov_SMU	sdcor_SMU
SMU:QuotaYear	(Intercept)		0.0047	0.0685	0.0026	0.0510
Diver	(Intercept)		0.1956	0.4422	0.1913	0.4374
Diver	log(diver_ex)		0.0301	0.1736	0.0343	0.1852
Diver	(Intercept)	log(diver_ex)	-0.0607	-0.7905	-0.0642	-0.7925
ReefCode	(Intercept)		0.0352	0.1876		
Month	(Intercept)		0.0038	0.0618	0.0048	0.0690
Residual			0.1584	0.3980	0.0922	0.3037

Some points to note in looking at these tables are the following.

1. The variance components associated with the random intercept, SMU×`QuotaYear` are all relatively small, indicating that the two factors are very close to additive. There are large main effects for both, however.

2. The random intercept components for `Diver` are large; the components for the random coefficient for `Diver` on `log(diver_ex)` are on a different scale and hence not easily assessed for size here.

3. The correlations between the random intercept and slope for `Diver` are all in the range -0.76 to -0.80, indicating that divers entering the fishery with an *initial* high effectiveness *initially* improved with experience at a slower rate than average, and vice versa those with a lower initial effectiveness improved faster.

4. The random intercepts for `Month` have a tiny variance component and those for `ReefCode`. (where these are estimated), are relatively small, indicating at most minor effects.

5. The residual variance is relatively high, but lower for the `SMU` aggregated data models than for the corresponding `NRC` models. This is probably due to the averaging effect obtained by the coarser level of aggregation in the former.

2.4   Fixed effect for diver experience

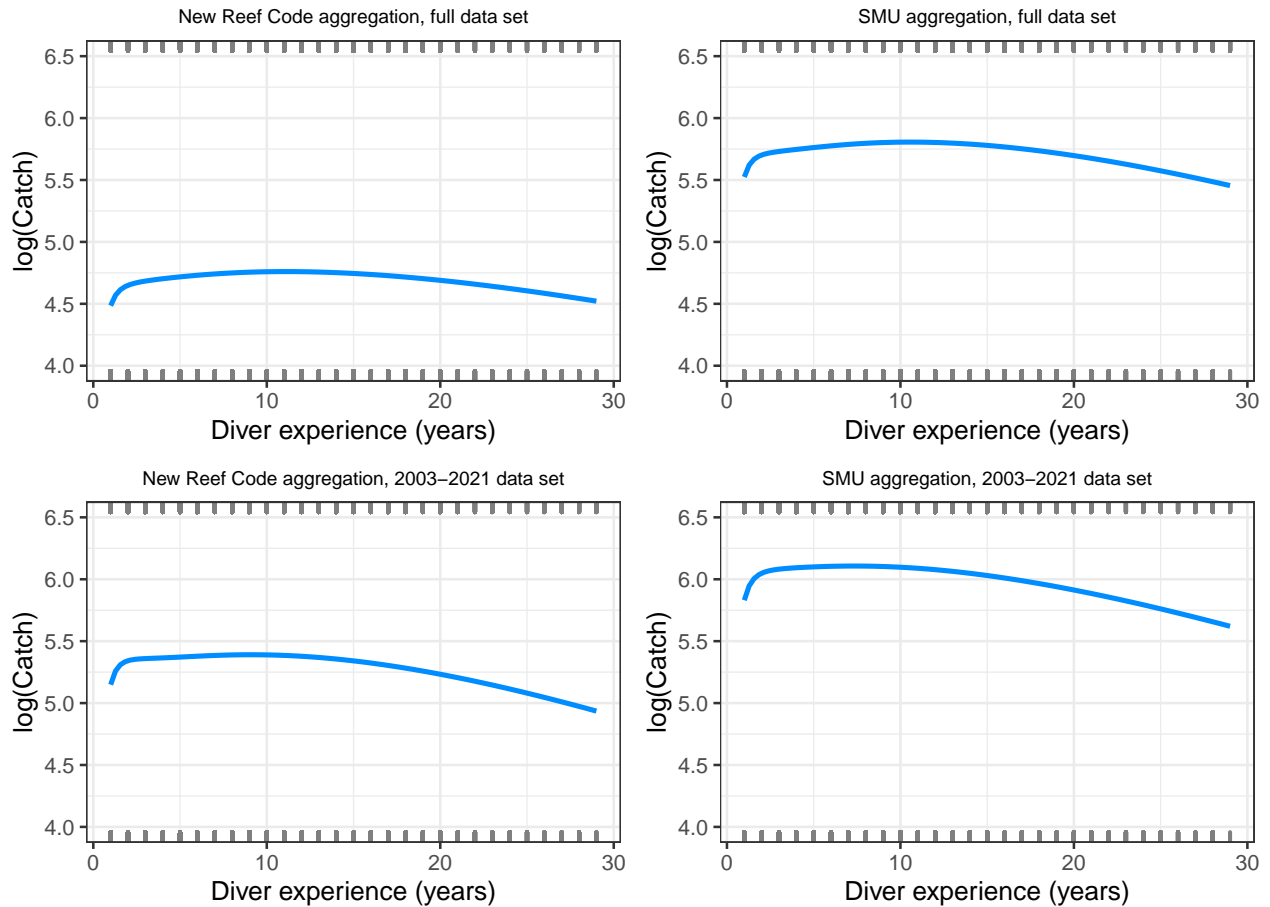The following graphic gives the diver experience main effect component for each of the four fitted models.

Figure 1: Main effect for diver experience, in the log(Catch) scale, for the four fitted models. The vertical axis location is arbitrary.

2.5 The diver experience main effect in the CPUE scale

To illustrate the diver experience effect, the following diagram shows the *predicted* mean CPUE for varying diver experience levels, for each SMU, using two specific quota years 2006 and 2016. The model used is that with the full data set at the `SMU` aggregation.
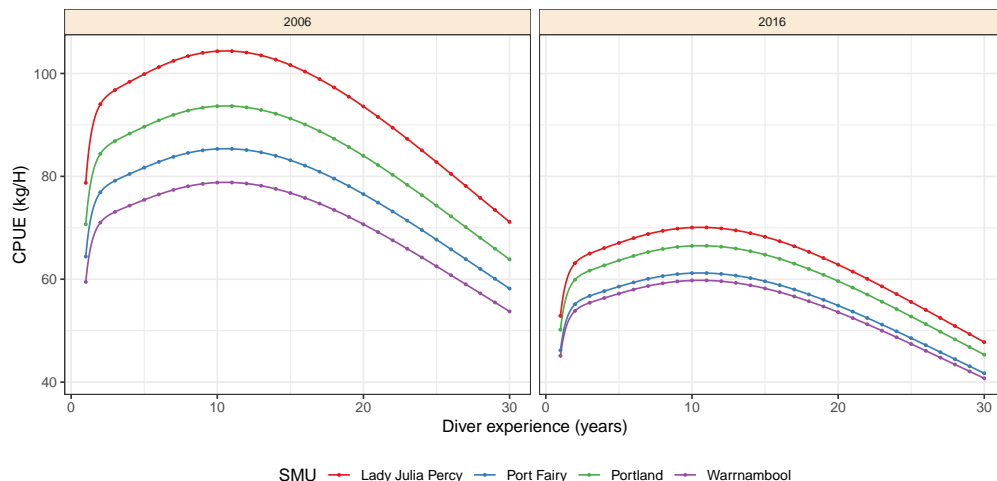

Figure 2: CPUE at levels of diver experience for each SMU in quota years 2006 and 2016

2.6 Model effectiveness assessments

One way to assess the performance of the models is to look at their conditional and marginal multiple correlation coefficients, R^2.

- The *conditional* value is got by allowing *all* the random effects to act as predictors, and offers a measure of how well the model reproduces the data itself.

- The *marginal* value only uses the fixed effects and those random effects to be used in standardisation to be included, allowing the other random effects to be considered as residuals. In our case, this gives a measure of how well standardisation uses the data.

The following Table shows the conditional (R_a^2) and marginal (R_b^2) coefficients for all four fitted models.

Table 3: Conditional (R2a) and marginal (R2b) multiple correlation measures for the fitted models

model	R2a	R2b
NRC	0.8956	0.8347
NRC_0220	0.8258	0.7180
SMU	0.7448	0.5489
SMU_0220	0.8097	0.6531

Note that AIC comparison of these models is not possible as all four use different data sets.

3 Comparison of standardised and raw CPUE series

The following grpahic shows a comparison of the standardised CPUE series produced by the four models with the raw CPUE series.

Figure 3: CPUE series for Raw and four model standardisation models

3.1 Comparison with a simpler model omitting diver experience

The current model used for catch standardisation differs in many respects from the models considered here, though there are many points of similarity. The currently used model differs mainly from the present model in that it assumes diver experience, or rather its effect on catch rate, remains constant throughout the diver's active period in the fishery. It uses data at the reef code aggregation level, so to compare this model with those shown above we now fit a model that omits `diver_ex`, but in all other respects is similar to those above. We use the full data set and the time restricted 2003-2021 data set.

The following chunk specifies the model in more precise detail.

```
mod_NRC_nde <- lmer(log(Blacklip) ~ offset(log(Effort)) + SMU + QuotaYear +
                    (1|Month) + (1|Diver) + (1|ReefCode) + (1|SMU:QuotaYear),
                  data = Catch_NRC, control = lmerControl(optimizer = "bobyqa"))

mod_NRC_0220_nde <- update(mod_NRC_nde, data = Catch_NRC_0220)
```

These models are compared with the corresponding models incorporating diver experience in the following display.
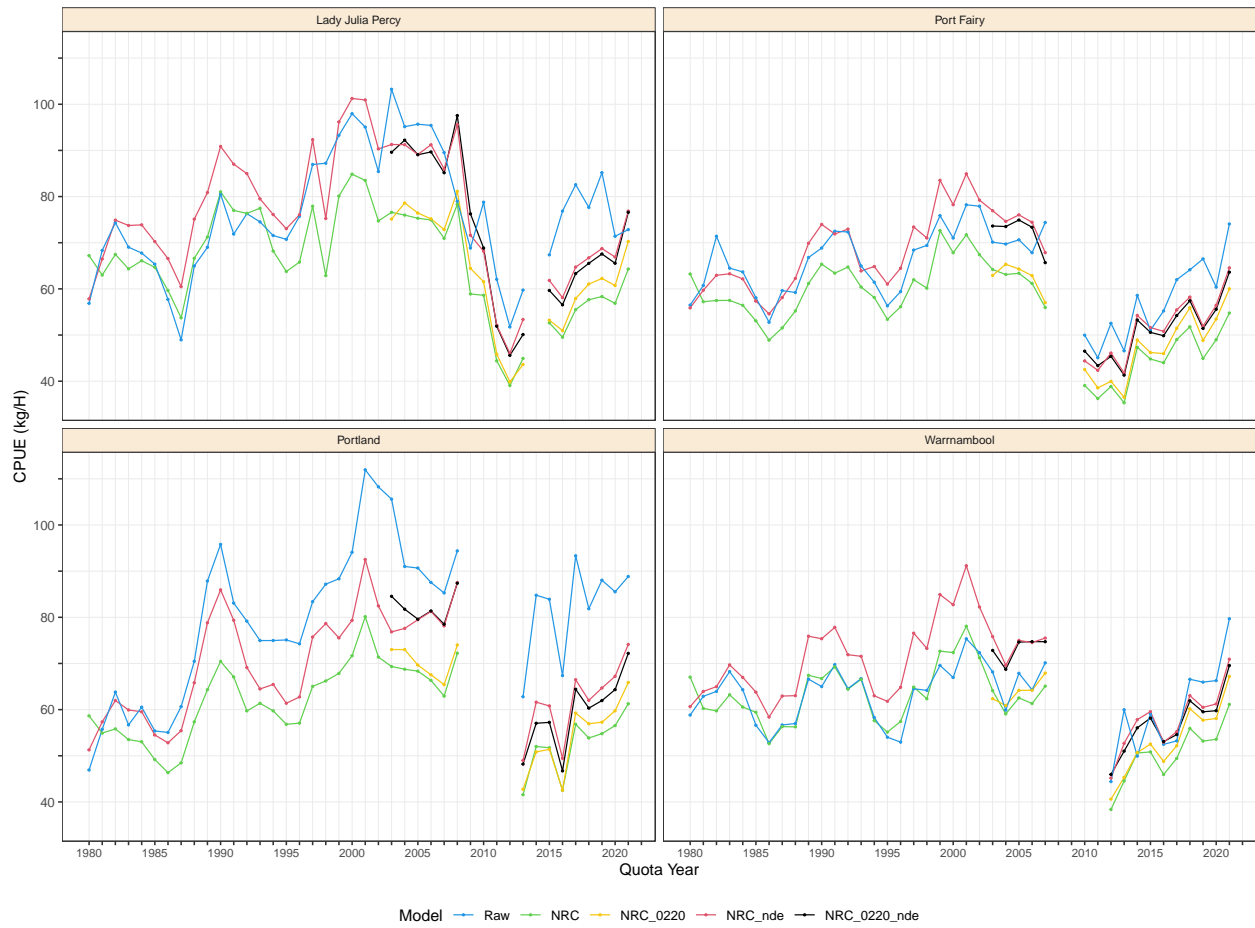
Figure 4: CPUE series for Raw and two model standardisation models one including diver experience and one without. Models with names ending in 'nde' have no diver experiende terms.

A Addendum: Model summaries

The following output is a default summary for all four models considered in this document.

```
####################################################################
##            New Reef Code aggregation, full data set           ##
####################################################################

summary(mod_NRC)
```

```
Linear mixed model fit by REML ['lmerMod']
Formula: log(Blacklip) ~ offset(log(Effort)) + SMU + poly(log(diver_ex),
    4) + QuotaYear + (1 | Month) + (1 + log(diver_ex) | Diver) +
    (1 | ReefCode) + (1 | SMU:QuotaYear)
   Data: Catch_NRC
Control: lmerControl(optimizer = "bobyqa")

REML criterion at convergence: 32831.3

Scaled residuals:
     Min       1Q   Median       3Q      Max
-16.0772  -0.4060   0.0708   0.5303   5.0697

Random effects:
 Groups        Name         Variance Std.Dev. Corr
 SMU:QuotaYear (Intercept)  0.003463 0.05885
 Diver         (Intercept)  0.161611 0.40201
               log(diver_ex) 0.027999 0.16733  -0.74
 ReefCode      (Intercept)  0.011851 0.10886
 Month         (Intercept)  0.001227 0.03503
 Residual                   0.121990 0.34927
Number of obs: 43191, groups:
SMU:QuotaYear, 157; Diver, 61; ReefCode, 32; Month, 12

Fixed effects:
                         Estimate Std. Error t value
(Intercept)              4.318168   0.122947  35.122
SMUPort Fairy           -0.165272   0.075156  -2.199
SMUPortland             -0.121673   0.062603  -1.944
SMUWarrnambool          -0.103152   0.072073  -1.431
poly(log(diver_ex), 4)1 13.187901   4.691307   2.811
poly(log(diver_ex), 4)2 -8.333257   1.621790  -5.138
poly(log(diver_ex), 4)3 -0.435290   0.860102  -0.506
poly(log(diver_ex), 4)4 -2.954825   0.577854  -5.113
QuotaYear1981           -0.084115   0.053463  -1.573
QuotaYear1982           -0.063977   0.064453  -0.993
QuotaYear1983           -0.072156   0.073638  -0.980
QuotaYear1984           -0.083135   0.081033  -1.026
QuotaYear1985           -0.127522   0.086222  -1.479
QuotaYear1986           -0.213309   0.091733  -2.325
QuotaYear1987           -0.198179   0.096626  -2.051
QuotaYear1988           -0.085357   0.100331  -0.851
```

```
QuotaYear1989              0.030900    0.103442    0.299
QuotaYear1990              0.099769    0.106255    0.939
QuotaYear1991              0.076496    0.108602    0.704
QuotaYear1992              0.032541    0.110610    0.294
QuotaYear1993              0.033657    0.112294    0.300
QuotaYear1994             -0.050594    0.113993   -0.444
QuotaYear1995             -0.112139    0.115318   -0.972
QuotaYear1996             -0.080506    0.116702   -0.690
QuotaYear1997              0.049663    0.117577    0.422
QuotaYear1998             -0.016821    0.118424   -0.142
QuotaYear1999              0.135177    0.118819    1.138
QuotaYear2000              0.145160    0.119438    1.215
QuotaYear2001              0.201990    0.119932    1.684
QuotaYear2002              0.106942    0.120579    0.887
QuotaYear2003              0.067198    0.121425    0.553
QuotaYear2004              0.038431    0.121939    0.315
QuotaYear2005              0.049926    0.122807    0.407
QuotaYear2006              0.027537    0.123411    0.223
QuotaYear2007             -0.006627    0.124689   -0.053
QuotaYear2008              0.125812    0.129090    0.975
QuotaYear2009             -0.179532    0.140507   -1.278
QuotaYear2010             -0.304538    0.132757   -2.294
QuotaYear2011             -0.480855    0.132563   -3.627
QuotaYear2012             -0.508312    0.130312   -3.901
QuotaYear2013             -0.434345    0.130170   -3.337
QuotaYear2014             -0.214279    0.132778   -1.614
QuotaYear2015             -0.247575    0.132966   -1.862
QuotaYear2016             -0.341949    0.133538   -2.561
QuotaYear2017             -0.195407    0.135261   -1.445
QuotaYear2018             -0.154811    0.137104   -1.129
QuotaYear2019             -0.195595    0.138544   -1.412
QuotaYear2020             -0.170581    0.140741   -1.212
QuotaYear2021             -0.059066    0.142476   -0.415
```

```
################################################################
##                 SMU aggregation, full data set            ##
################################################################

summary(mod_SMU)

Linear mixed model fit by REML ['lmerMod']
Formula: log(Blacklip) ~ offset(log(Effort)) + SMU + poly(log(diver_ex),
    4) + QuotaYear + (1 | Month) + (1 + log(diver_ex) | Diver) +
    (1 | SMU:QuotaYear)
   Data: Catch_SMU
Control: lmerControl(optimizer = "bobyqa")

REML criterion at convergence: 10769.1

Scaled residuals:
     Min       1Q   Median       3Q      Max
-17.5052  -0.4829   0.0565   0.5759   5.4018
```

```
Random effects:
 Groups        Name         Variance Std.Dev. Corr
 SMU:QuotaYear (Intercept)  0.005489 0.07409
 Diver         (Intercept)  0.155693 0.39458
               log(diver_ex) 0.024713 0.15720  -0.73
 Month         (Intercept)  0.001162 0.03408
 Residual                   0.092429 0.30402
Number of obs: 21542, groups:  SMU:QuotaYear, 157; Diver, 61; Month, 12

Fixed effects:
                         Estimate Std. Error t value
(Intercept)              4.283300   0.114439  37.429
SMUPort Fairy           -0.132439   0.019745  -6.707
SMUPortland             -0.109762   0.020420  -5.375
SMUWarrnambool          -0.153594   0.020381  -7.536
poly(log(diver_ex), 4)1  8.439226   3.289238   2.566
poly(log(diver_ex), 4)2 -7.272106   1.251485  -5.811
poly(log(diver_ex), 4)3 -1.261853   0.721807  -1.748
poly(log(diver_ex), 4)4 -3.059455   0.506215  -6.044
QuotaYear1981           -0.084417   0.063948  -1.320
QuotaYear1982           -0.042952   0.073161  -0.587
QuotaYear1983           -0.046839   0.081380  -0.576
QuotaYear1984           -0.043793   0.088233  -0.496
QuotaYear1985           -0.089483   0.092568  -0.967
QuotaYear1986           -0.183684   0.097638  -1.881
QuotaYear1987           -0.157417   0.102294  -1.539
QuotaYear1988           -0.054262   0.105814  -0.513
QuotaYear1989            0.066393   0.108749   0.611
QuotaYear1990            0.147024   0.111535   1.318
QuotaYear1991            0.129998   0.113769   1.143
QuotaYear1992            0.087686   0.115701   0.758
QuotaYear1993            0.104899   0.117270   0.895
QuotaYear1994            0.005383   0.119003   0.045
QuotaYear1995           -0.047627   0.120349  -0.396
QuotaYear1996            0.007567   0.121767   0.062
QuotaYear1997            0.145702   0.122690   1.188
QuotaYear1998            0.191033   0.123583   1.546
QuotaYear1999            0.218319   0.123885   1.762
QuotaYear2000            0.216829   0.124567   1.741
QuotaYear2001            0.284815   0.125154   2.276
QuotaYear2002            0.225227   0.126031   1.787
QuotaYear2003            0.187249   0.126509   1.480
QuotaYear2004            0.125961   0.127024   0.992
QuotaYear2005            0.146515   0.128036   1.144
QuotaYear2006            0.125590   0.128811   0.975
QuotaYear2007            0.114667   0.130140   0.881
QuotaYear2008            0.191947   0.136569   1.405
QuotaYear2009           -0.136404   0.151301  -0.902
QuotaYear2010           -0.190680   0.141549  -1.347
QuotaYear2011           -0.406553   0.140846  -2.887
```

```
QuotaYear2012          -0.437045    0.137973   -3.168
QuotaYear2013          -0.340433    0.137167   -2.482
QuotaYear2014          -0.115489    0.139730   -0.827
QuotaYear2015          -0.149167    0.139720   -1.068
QuotaYear2016          -0.211939    0.140387   -1.510
QuotaYear2017          -0.062058    0.142330   -0.436
QuotaYear2018          -0.020312    0.144308   -0.141
QuotaYear2019          -0.059435    0.145660   -0.408
QuotaYear2020          -0.076952    0.147924   -0.520
QuotaYear2021           0.046836    0.149690    0.313

#################################################################
##       New Reef Code aggregation, 2003-2021 data set        ##
#################################################################

summary(mod_NRC_0220)

Linear mixed model fit by REML ['lmerMod']
Formula: log(Blacklip) ~ offset(log(Effort)) + SMU + poly(log(diver_ex),
    4) + QuotaYear + (1 | Month) + (1 + log(diver_ex) | Diver) +
    (1 | ReefCode) + (1 | SMU:QuotaYear)
   Data: Catch_NRC_0220
Control: lmerControl(optimizer = "bobyqa")

REML criterion at convergence: 8153.5

Scaled residuals:
     Min       1Q   Median       3Q      Max
-14.0214  -0.4459   0.0777   0.5538   3.3185

Random effects:
 Groups        Name         Variance Std.Dev. Corr
 SMU:QuotaYear (Intercept)  0.004694 0.06851
 Diver         (Intercept)  0.195580 0.44224
               log(diver_ex) 0.030145 0.17362  -0.79
 ReefCode      (Intercept)  0.035183 0.18757
 Month         (Intercept)  0.003819 0.06180
 Residual                   0.158379 0.39797
Number of obs: 7737, groups:
SMU:QuotaYear, 65; Diver, 36; ReefCode, 32; Month, 12

Fixed effects:
                        Estimate Std. Error t value
(Intercept)              4.29399    0.12654  33.934
SMUPort Fairy           -0.16461    0.13009  -1.265
SMUPortland             -0.07053    0.10962  -0.643
SMUWarrnambool          -0.08954    0.12601  -0.711
poly(log(diver_ex), 4)1  0.07505    3.77520   0.020
poly(log(diver_ex), 4)2 -6.82219    2.13500  -3.195
poly(log(diver_ex), 4)3 -1.79098    1.17460  -1.525
poly(log(diver_ex), 4)4 -2.42140    0.69625  -3.478
QuotaYear2004            0.01470    0.05448   0.270
```

```
QuotaYear2005                   0.00512    0.05696    0.090
QuotaYear2006                  -0.01232    0.05954   -0.207
QuotaYear2007                  -0.03846    0.06377   -0.603
QuotaYear2008                   0.08301    0.07749    1.071
QuotaYear2009                  -0.13655    0.10399   -1.313
QuotaYear2010                  -0.28494    0.08911   -3.198
QuotaYear2011                  -0.48136    0.09087   -5.297
QuotaYear2012                  -0.52513    0.08836   -5.943
QuotaYear2013                  -0.48552    0.09021   -5.382
QuotaYear2014                  -0.27916    0.09777   -2.855
QuotaYear2015                  -0.29401    0.10095   -2.912
QuotaYear2016                  -0.37178    0.10516   -3.535
QuotaYear2017                  -0.21204    0.11130   -1.905
QuotaYear2018                  -0.15251    0.11762   -1.297
QuotaYear2019                  -0.19034    0.12278   -1.550
QuotaYear2020                  -0.16173    0.12950   -1.249
QuotaYear2021                  -0.03567    0.13372   -0.267
```

```
###################################################################
##              SMU aggregation, 2003-2021 data set            ##
###################################################################

summary(mod_SMU_0220)
```

```
Linear mixed model fit by REML ['lmerMod']
Formula: log(Blacklip) ~ offset(log(Effort)) + SMU + poly(log(diver_ex),
    4) + QuotaYear + (1 | Month) + (1 + log(diver_ex) | Diver) +
    (1 | SMU:QuotaYear)
   Data: Catch_SMU_0220
Control: lmerControl(optimizer = "bobyqa")

REML criterion at convergence: 2531.6

Scaled residuals:
     Min       1Q   Median       3Q      Max
-15.5257  -0.4855   0.0366   0.5748   4.0444

Random effects:
 Groups        Name        Variance Std.Dev. Corr
 SMU:QuotaYear (Intercept) 0.002598 0.05097
 Diver         (Intercept) 0.191333 0.43742
               log(diver_ex) 0.034289 0.18517  -0.79
 Month         (Intercept) 0.004761 0.06900
 Residual                  0.092242 0.30371
Number of obs: 4795, groups:  SMU:QuotaYear, 65; Diver, 36; Month, 12

Fixed effects:
                   Estimate Std. Error t value
(Intercept)        4.365953   0.082317  53.038
SMUPort Fairy     -0.176842   0.026704  -6.622
SMUPortland        0.032492   0.027778   1.170
SMUWarrnambool    -0.189843   0.028735  -6.607
```

```
poly(log(diver_ex), 4)1 -0.630109    3.009661   -0.209
poly(log(diver_ex), 4)2 -6.653576    1.812053   -3.672
poly(log(diver_ex), 4)3 -1.380762    0.977081   -1.413
poly(log(diver_ex), 4)4 -1.614032    0.556991   -2.898
QuotaYear2004           -0.029074    0.042355   -0.686
QuotaYear2005           -0.015573    0.045060   -0.346
QuotaYear2006           -0.030428    0.048225   -0.631
QuotaYear2007           -0.040969    0.052724   -0.777
QuotaYear2008            0.019172    0.064569    0.297
QuotaYear2009           -0.180036    0.086981   -2.070
QuotaYear2010           -0.248110    0.078914   -3.144
QuotaYear2011           -0.461870    0.080099   -5.766
QuotaYear2012           -0.518856    0.080242   -6.466
QuotaYear2013           -0.474453    0.082901   -5.723
QuotaYear2014           -0.260444    0.089038   -2.925
QuotaYear2015           -0.266053    0.093603   -2.842
QuotaYear2016           -0.331379    0.098412   -3.367
QuotaYear2017           -0.176749    0.105083   -1.682
QuotaYear2018           -0.110925    0.111894   -0.991
QuotaYear2019           -0.150714    0.117391   -1.284
QuotaYear2020           -0.165596    0.124396   -1.331
QuotaYear2021           -0.009256    0.129217   -0.072
```

Appendix 2: Fishery Independent Survey Indicators

2022-09-13

Contents

1 Introduction

These notes are to document aspects of the Fishery Independent Survey (FIS) data, and in particular the method that has been used to generate density estimates. I will also outline an alternative method that could be used to generate similar indices.

The survey is conducted hierarchically: For each `QuotaYear` of the survey, each visited `ReefCode` has a number of fixed `Site`s, and within each `Site` a number of transects, (nominally of size 30×1 m), are "fished" and the number of abalone sighted is recorded. This `TotalCount` is broken down into three sub-counts by length class, namely `Juvenile` (up to 80mm), `Prerecruits` (80+ to 120mm) and `Recruits` (120mm+). We refer to these as three *stages* in the analysis.

After the initial inspection and counts, a further set of animals is collected from the same site and measured, giving a sample of lengths representative of abalone at that site.

1.1 The 'quota year'

In the analysis below we use the term `quota year` to refer to the annual period in which the FIS observations were made. This is sometimes in line with the WZ fishing year, which begins on 1 April and ends on 31 March of the following year, (and is labelled by the calendar year as at 31 March), but at other times it deviates. The actual time ranges over which the FIS observations were made for each nominated `QuotaYear` are given in the table in the final addendum section below.

1.2 Data input

The primary data (as supplied to me) comes in two related data sets.

- The first relates to the transects and gives the count data,
- The second relates to the sites and gives the length samples in length-frequency form.

Abalone lengths may be converted into weights using a morphometric relationship of the form

$$W = \alpha L^\beta$$

where L is the length in mm, W is the weight in gm and the two constants are $\alpha = 3.34 \times 10^{-4}$ and $\beta = 2.857$.

The following code chunk reads in the data and performs a few elementary manipulations, mainly to classify the length-frequency data into the same three *stages* corresponding to the three sub-counts, and adding in the *weight* for each length.

```
####################################################################
##                     Transect data (counts)                   ##
####################################################################
Transects <- read_csv("data/FIS transects - all.csv", na = c("", "NA", "NULL"),
                   col_types = cols(.default = col_skip(),
                                      Date = col_date(format = "%d/%m/%Y"),
                                      QuotaYear = col_integer(),
                                      Site = col_integer(),
                                      Latitude = col_double(),
                                      Longitude = col_double(),
                                      ReefCode = col_character(),
                                      SMU = col_character(),
                                      Zone = col_character(),
                                      Diver = col_character(),
                                      Direction = col_double(),
                                      SwimLength = col_double(),
                                      Juveniles = col_double(),
                                      Prerecruits = col_double(),
                                      Recruits = col_double(),
                                      TotalCount = col_double(),
                                      Methodology = col_integer(),
                                      Depth = col_double())) %>%
  within({
    ReefCode <- format(as.numeric(ReefCode))
    SMU <- sub("Julia Percy Island", "Lady Julia Percy", SMU)
  }) %>%
  select(Date, Longitude, Latitude, QuotaYear, Site, ReefCode, SMU, Diver,
         SwimLength:Methodology) %>%
  arrange(QuotaYear, ReefCode, Site, Date)


####################################################################
##                     Length-frequency data                    ##
```

```
##################################################################

Lengths <- read_csv("data/FIS length frequency - all.csv",
                    col_types = cols(.default = col_skip(),
                                     ReefCode = col_character(),
                                     Site = col_double(),
                                     QuotaYear = col_double(),
                                     Length = col_double(),
                                     Frequency = col_double(),
                                     ReefSet = col_character(),
                                     Zone = col_character())) %>%
  select(-ReefSet, -Zone) %>%
  within({
    ReefCode <- format(as.numeric(ReefCode))
    Weight <- exp(log(3.34e-04) + 2.857*log(Length))
    Stage <- case_when(               Length <  80 ~ "Juvenile",
                       80 <= Length & Length < 120 ~ "Prerecruit",
                       120 <= Length                ~ "Recruit")
  }) %>% filter(Length>=80) %>%
  arrange(QuotaYear, Site, Length)
```

2 Biomass indicators from raw FIS data

Two sets of data are analysed, a 2002-2020 data set with a mostly consistent set of sites that continued to be sampled until 2020, and a 1992-2020 data set containing all sites sampled. Estimates of biomass and its density for the 2002-2020 data are calculated by averaging the raw FIS data across a mostly consistent set of sites (in this section), and after standardisation (in a later section). Estimates of biomass and density for the 1992-2020 data set are calculated after standardisation (also in a later section).

In this section, we only present calculations from 2002-2020 from a consistent set of sites that were selected by VFA and continued to be sampled 2017-2020. The approach described to calculation of the indicators is also used in subsequent calculations with standardised data.

Two biomass indicators are produced from this data, firstly at the *Site* level. These are estimates of *weight* densities, in Kg/Ha, for three overlapping classes of animals, namely

- Legal sized animals, 130mm and up,
- Mature animals, 102mm and up,
- Under legal size, 100 mm and up and below 130 mm

The method used to arrive at estimates of these indicators is as follows

- Aggregate the counted abalone in the `Transects` data to the `QuotaYear`/`Site` level to match the recorded level for the `Lengths` data. This produces three counts for the three *stages*, which add to the `TotalCount` for that `QuotaYear` and `Site`:

$$C_1 + C_2 + C_3 = N_T$$

where C_1 = juveniles, C_2 = prerecruits and C_3 = recruits, and N_T is the total count as well as an `Area_m2` measure of total swim area, by adding over transects.

```
Transects_site <- Transects %>%
  group_by(QuotaYear, SMU, Site) %>%
  summarise(Area_m2    = sum(SwimLength),
            Juveniles  = sum(Juveniles),
            Prerecruit = sum(Prerecruits),
```

```
            Recruit    = sum(Recruits), .groups = "drop") %>%
  arrange(QuotaYear, Site) %>%
  pivot_longer(cols = c(Juveniles, Prerecruit, Recruit),
               names_to = "Stage", values_to = "Cs")
```

- For the `Lengths` data, which provides the counts of abalone per 1mm length classes, compute the corresponding count within the three *stages*, for each `QuotaYear` by `Site` class, as well as the total count. This leads to a corresponding set of counts:

$$D_1 + D_2 + D_3 = N_L$$

for each class, where again
  - D_1 is the count of lengths for juveniles, *i.e.* with length < 80mm,
  - D_2 is the count of lengths for prerecruits, *i.e.* with length $80 - 120$mm,
  - D_3 is the cound of lengths for recruits, *i.e.* with length > 120mm, making
  - N_L the total count of lengths.

We note that only prerecruits and recruits are used below; juveniles have not as yet been used in the analysis of FIS data.

- For a given year and site, let F_i be the frequency, (*i.e.* the count), for length class i in the in the `Lengths` data set. To produce an *adjusted* frequency, $\tilde{F}_i$ we multiply it by a magnification factor:

$$\tilde{F}_i = \frac{C_s}{D_s} \times F_i$$

Here s is the *stage* of the animals in that `QuotaYear` by `Site`, *i.e.* $s = 1$ for juveniles, $s = 2$ for prerecruits and $s = 3$ for recruits. In this sense the stage, s, is a function of the particular length class i.

Another way to view the process could be to note that the ratios F_i/D_s, for the i in a particular stage s, are the *relative frequencies* of length classes for that stage, and the factor C_s then scales up these so that they now total to the known count, C_s, for the transects data.

The adjusted frequencies now sum to N_T, the total count, for that `QuotaYear` and `Site`, and do so while also adding to their *stage* counts, C_s, separately.

```
Lengths_site <- Lengths %>%
  within({
    Ds <- ave(Frequency, QuotaYear, Site, Stage, FUN = sum)
  }) %>%
  left_join(Transects_site, by = c("Site", "QuotaYear", "Stage")) %>%
  within({
    Fadj <- Cs/Ds*Frequency
  })
```

- Using the *adjusted* frequencies, $\tilde{F}_i$, calculate the estimated total weight for the site for each indicator class as defined above, by adding across all length-classes within each class, namely `Under_sized`, `Mature` and `Legal_sized`.

  Divide these by the `Area_m2` figure to produce a *weight density estimate* (and multiply by 10 to convert from gm/m² to Kg/Ha).

```
Indicators_site <- Lengths_site %>%
  filter(Stage != "Juvenile") %>%
  group_by(QuotaYear, SMU, Site, Area_m2) %>%
  summarise(
    Legal_sized = sum(Fadj*Weight*(Length >= 130))        /Area_m2 * 10,
    Mature      = sum(Fadj*Weight*(Length >= 102))        /Area_m2 * 10,
```

```
    Under_sized = sum(Fadj*Weight*(Length >= 100 & Length < 130))/Area_m2 * 10,
    .groups = "drop") %>%
arrange(QuotaYear, Site) %>%
select(QuotaYear, SMU, Site, everything())
```

The first few entries appear as follows:

Table 1: Biomass indicators, first 10 records

QuotaYear	SMU	Site	Area_m2	Legal_sized	Mature	Under_sized
1992	Warrnambool	124	180	134	3463	3359
1992	Warrnambool	124	180	134	3463	3359
1992	Warrnambool	124	180	134	3463	3359
1992	Warrnambool	124	180	134	3463	3359
1992	Warrnambool	124	180	134	3463	3359
1992	Warrnambool	124	180	134	3463	3359
1992	Warrnambool	124	180	134	3463	3359
1992	Warrnambool	124	180	134	3463	3359
1992	Warrnambool	124	180	134	3463	3359
1992	Warrnambool	124	180	134	3463	3359

2.1   Biomass indicators at the SMU level

To produce the indicators we need first to average the mature and legal biomass at 'recent sampled' sites only since 2002 for each SMU (note, 'recent sampled' means only those sites sampled in the most recent year).

Filter out the indicators needed and do weighted averages (as swept area is not constant):

```
Indicators_smu <- Indicators_site %>%
  within(year <- as.numeric(as.character(QuotaYear))) %>%
  filter(year > 2002, Site %in% Site[year == max(year)]) %>%
  group_by(year, SMU) %>%
  summarise(Mature      = weighted.mean(Mature,      Area_m2),
            Legal_sized = weighted.mean(Legal_sized, Area_m2),
            Under_sized = weighted.mean(Under_sized, Area_m2),
            .groups = "drop")
```

The results are given in the following display:
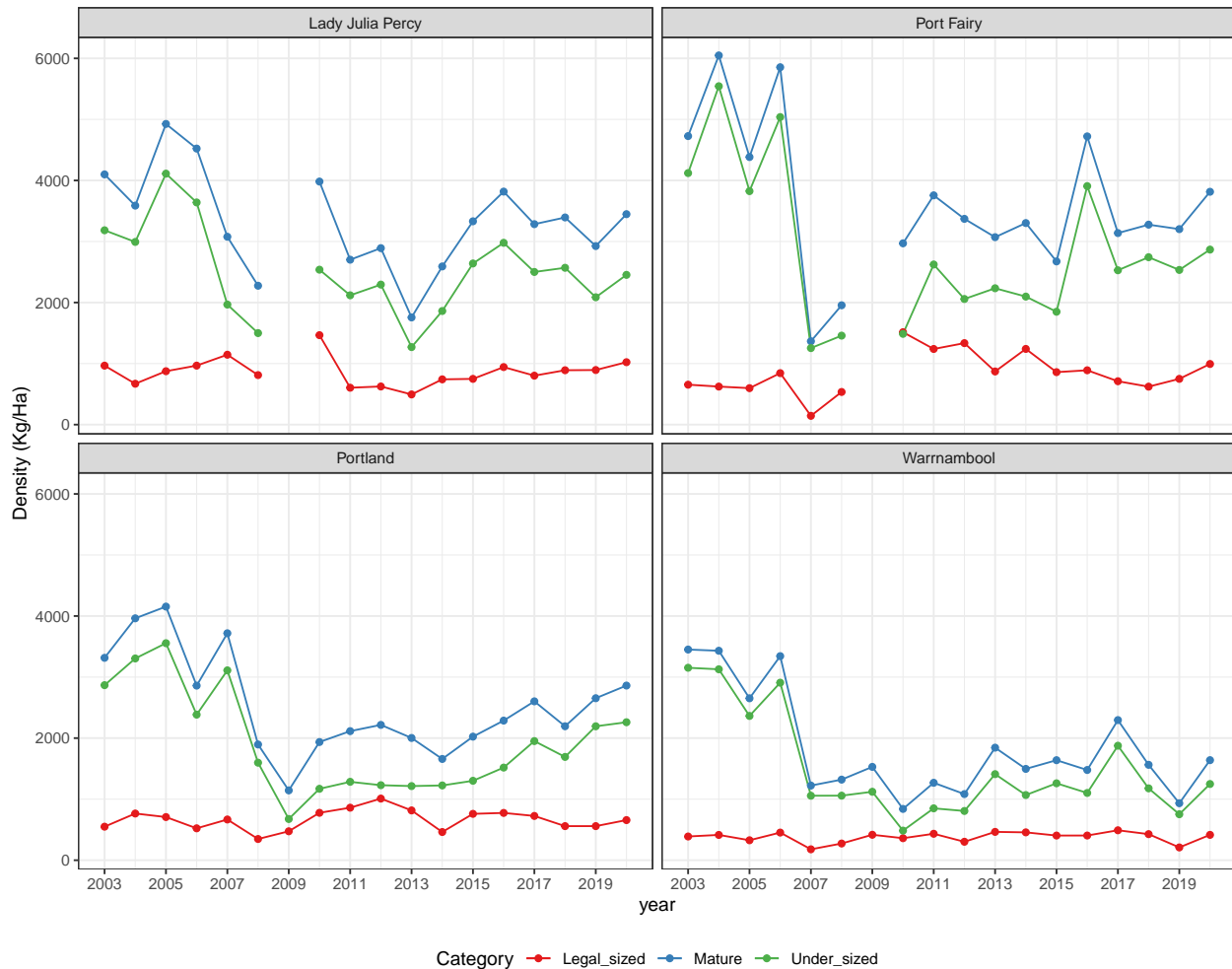
2.2 Conversion to total biomass estimates per SMU

The total fished area for each SMU, as estimated separately, are as in the following Table:

Table 2: SMU Fishery area estimates in Ha.

SMU	Area (Ha)
Lady Julia Percy	59
Port Fairy	215
Portland	376
Warrnambool	343

We can now match this estimate with the density estimates, convert to t/Ha, and arrive at estimates of total available biomass for each SMU.
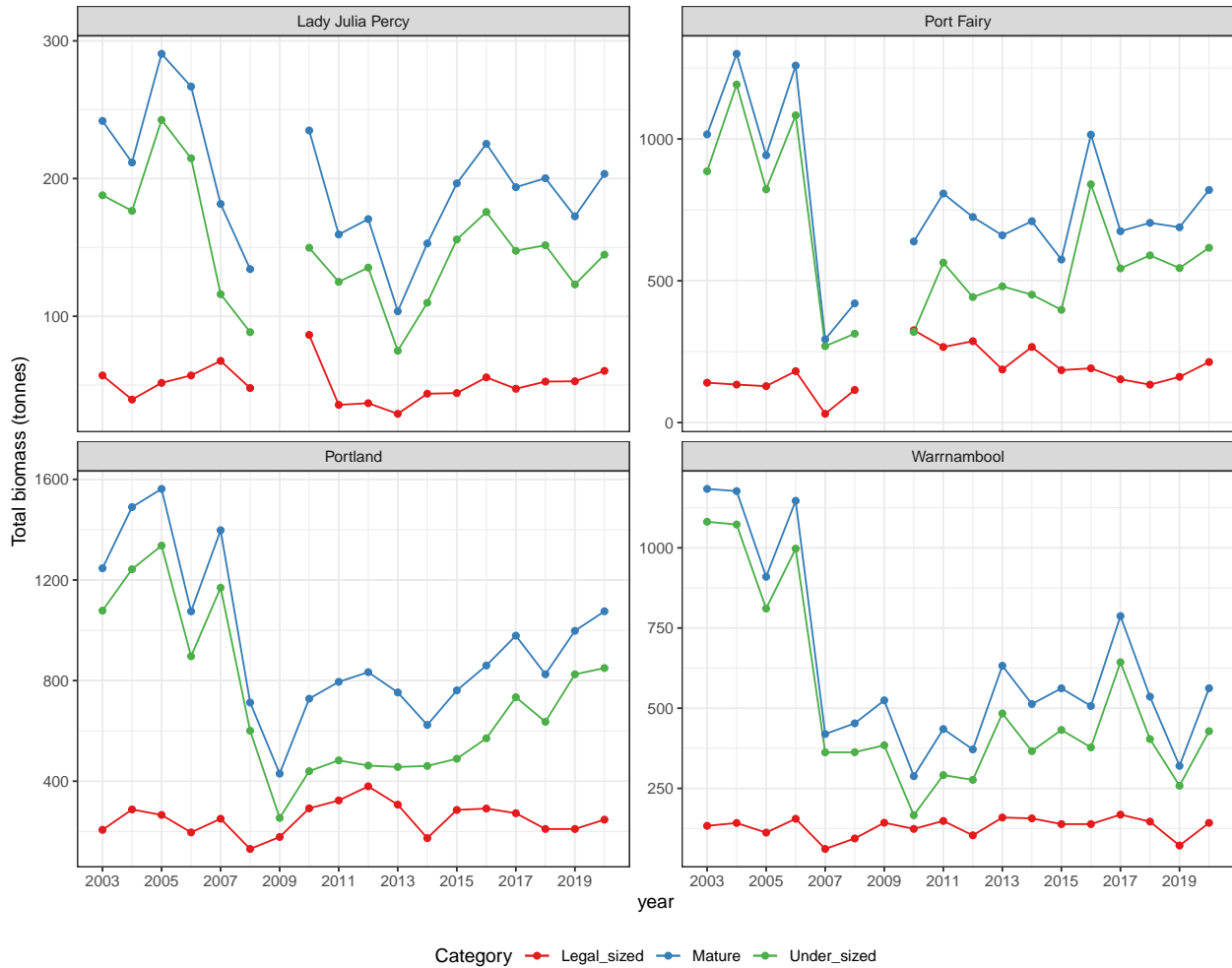
```
Indicators_smu_long <- Indicators_smu %>%
  pivot_longer(c(Mature, Legal_sized, Under_sized),
               names_to = "Category", values_to = "Density") %>%
  left_join(area, by = "SMU") %>%
  within({
    Total_biomass <- Density/1000*`Area (Ha)`
```

```
}) %>%
select(-Density, -`Area (Ha)`)
```

The results are shown in the following display:

For reference, the results are now given in table form

Table 3: Legal sized biomass estimates, (tonnes)

Year	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2003	57.0	140.7	206.5	133.3
2004	39.5	134.0	287.5	142.1
2005	51.6	128.5	265.8	112.1
2006	57.0	181.4	196.4	155.3
2007	67.6	31.0	250.7	61.2
2008	47.9	115.1	130.7	93.8
2009			178.2	143.0
2010	86.5	325.6	291.9	123.7
2011	35.7	266.5	323.5	148.5
2012	36.9	287.0	379.6	103.6
2013	29.2	187.2	306.7	159.1
2014	43.8	266.6	173.6	156.5

Year	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2015	44.2	184.8	285.6	138.6
2016	55.6	191.4	291.3	138.7
2017	47.3	152.8	272.6	168.2
2018	52.6	133.7	209.9	146.5
2019	52.8	161.2	209.9	71.8
2020	60.3	213.6	247.1	142.5

Table 4: Mature biomass estimates, (tonnes)

Year	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2003	241.9	1016.2	1246.6	1183.7
2004	211.7	1300.3	1489.8	1176.9
2005	290.6	942.5	1562.1	909.8
2006	266.8	1258.7	1075.3	1146.7
2007	181.6	293.6	1397.8	419.5
2008	134.2	420.3	712.7	452.8
2009			430.0	524.5
2010	234.9	638.6	728.0	288.2
2011	159.4	807.5	795.0	435.1
2012	170.6	724.8	833.5	371.6
2013	103.6	660.2	752.9	632.4
2014	152.9	709.9	623.7	513.1
2015	196.5	574.8	761.1	562.0
2016	225.2	1015.1	860.0	506.9
2017	193.7	674.7	978.5	787.3
2018	200.2	704.3	825.0	535.9
2019	172.6	688.6	997.8	320.2
2020	203.4	820.1	1075.7	562.1

Table 5: Under sized biomass estimates, (tonnes)

Year	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2003	187.8	886.0	1078.2	1081.3
2004	176.6	1191.9	1242.7	1072.8
2005	242.6	822.4	1336.7	810.6
2006	214.7	1083.2	896.6	997.5
2007	116.0	269.6	1169.3	362.3
2008	88.5	313.4	600.7	362.7
2009			253.7	384.6
2010	149.8	319.7	439.9	166.3
2011	125.0	564.0	482.8	291.4
2012	135.3	442.5	462.1	276.6
2013	74.9	480.3	456.6	483.6
2014	109.8	451.0	460.5	366.2
2015	155.8	397.5	489.2	432.2
2016	175.7	840.1	570.5	377.9
2017	147.5	543.7	733.8	643.3
2018	151.6	589.6	636.2	403.7
2019	123.1	544.8	824.9	258.2

Year	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2020	144.8	616.5	849.8	428.2

3 Indicators based on prerecruits

To product the prerecruit indicators we need to average the prerecruits at 'recent sampled' sites only since 2002 for each SMU, and calculate - year running average.

```
Prerecruit_data <- Transects %>%
  within(year <- as.numeric(as.character(QuotaYear))) %>%
  filter(year > 2002, Site %in% Site[year == max(year)]) %>%
  select(Date, year, QuotaYear, Site, SMU, Area = SwimLength, Prerecruits) %>%
  untibble()
```

A check on the replication of site visits per year is as in the following table:

Table 6: Site by year transect frequency

	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
121	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
122	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
123	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
124	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
126	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
129	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
130	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
131	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
132	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
133	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
134	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
135	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
136	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
137	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
143	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
144	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
145	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
152	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
153	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
154	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
155	6	6	7	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
157												6	6	6	6	6	6	6
158			6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6

The average prerecruit counts per SMU are given below

```
p_average <- Prerecruit_data %>%
  group_by(year, SMU) %>%
  summarise(mean_count = mean(Prerecruits),
            .groups = "drop") %>%
  pivot_wider(names_from = SMU, values_from = mean_count) %>%
  untibble()
```

Table 7: Mean prerecruits per transect

Year	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2003	33.04	40.63	35.83	37.40
2004	25.79	52.63	39.36	35.20
2005	34.15	36.67	41.25	23.43
2006	33.25	51.10	29.48	25.40
2007	16.62	12.60	38.44	9.67
2008	14.29	8.73	17.19	5.97
2009	17.17	8.47	5.38	6.30
2010	11.71	10.83	7.90	3.37
2011	13.67	22.90	11.50	6.07
2012	9.54	10.13	8.62	6.00
2013	6.42	13.97	9.60	10.80
2014	10.21	12.89	9.75	6.90
2015	15.50	10.58	11.33	10.87
2016	18.92	27.08	10.73	8.07
2017	13.38	25.81	19.94	17.10
2018	21.96	23.25	16.73	11.63
2019	17.00	21.14	24.02	8.20
2020	15.33	20.53	20.88	9.63

The 2-year moving averages are shown in the following table.

```
X <- p_average %>% select(-year) %>% as.matrix()
p_average_2 <- data.frame(mav(nrow(X), 2) %*% X,
                          check.names = FALSE) %>%
  within({
    year <- p_average$year
    years <- paste(year[-length(year)], substring(year[-1], 3, 4), sep = "-")
    year <- year[-1]
  }) %>% select(year, years, everything())
```

Table 8: Mean prerecruits, 2 year running average

Years	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2003-04	29.42	46.63	37.60	36.30
2004-05	29.97	44.65	40.31	29.31
2005-06	33.70	43.88	35.37	24.41
2006-07	24.94	31.85	33.96	17.53
2007-08	15.46	10.67	27.81	7.82
2008-09	15.73	8.60	11.28	6.13
2009-10	14.44	9.65	6.64	4.83
2010-11	12.69	16.87	9.70	4.72
2011-12	11.60	16.52	10.06	6.03
2012-13	7.98	12.05	9.11	8.40
2013-14	8.31	13.43	9.68	8.85
2014-15	12.85	11.74	10.54	8.88
2015-16	17.21	18.83	11.03	9.47
2016-17	16.15	26.44	15.33	12.58
2017-18	17.67	24.53	18.33	14.37
2018-19	19.48	22.19	20.38	9.92

Years	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2019-20	16.17	20.83	22.45	8.92

These are shown in the following graphical display.
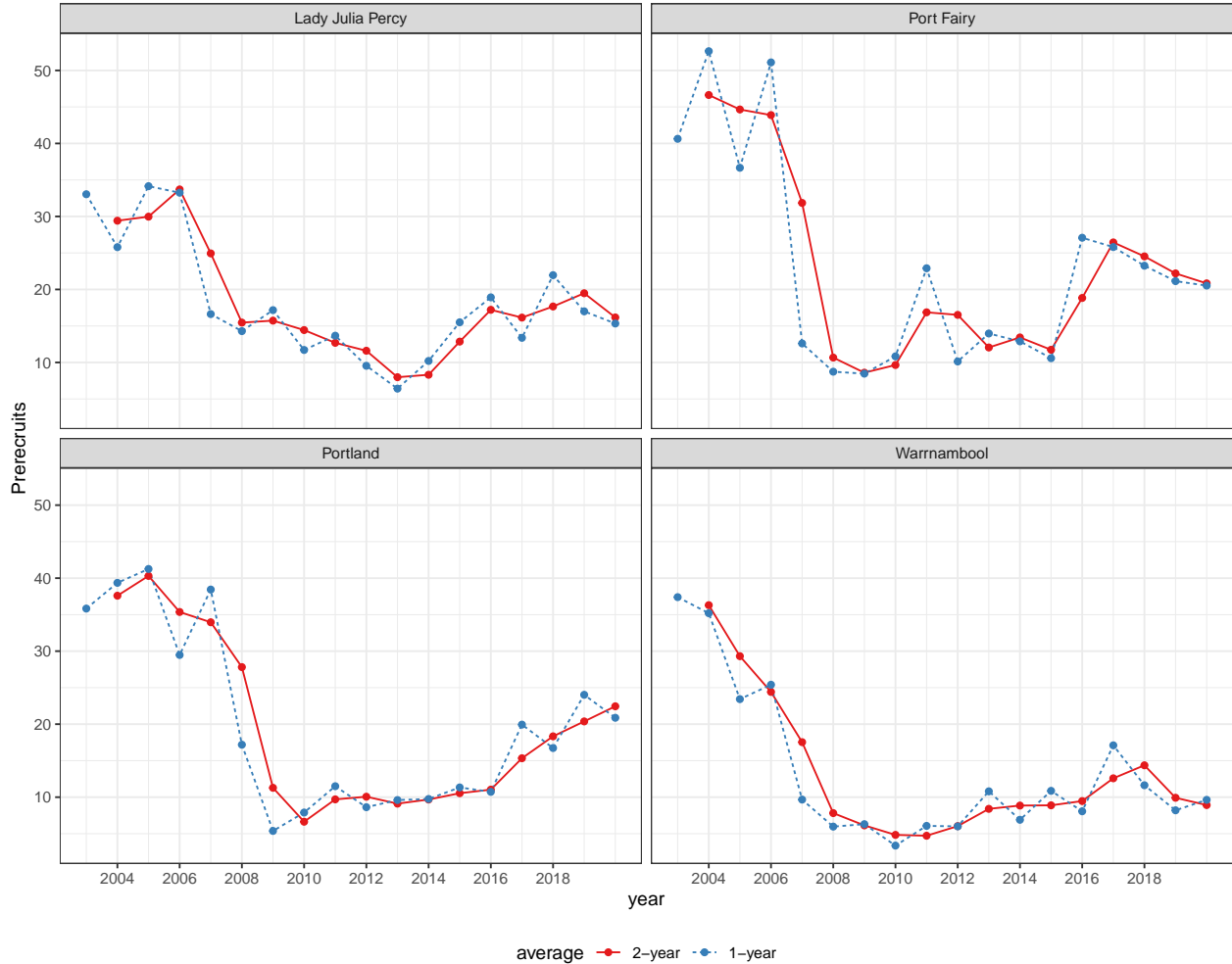
3.1 Indicators and standardisation processes

There are three indicators obtained using a standardisation process and we calculate each of these separately for both prerecruit and recruit numbers per transect. These indicators are:

a) *Raw*, which uses all sites, (not just 'recent sampled') and all years, and averages numbers across sites for each SMU.

b) *All standardised*, which again uses all sites and all years, standardised by simple GLM of the form `glm(prerecruits ~ year/smu + site + diver, family = quasipoisson, data)` and in the graph the predictions are *normalised* to match the raw value in the most recent year.

c) *Current standardised*, which uses only 'recent sampled' sites only years since 2002 and uses a standardisation GLM as in b).

3.1.1 Raw indicator

We turn first to the *Raw* indicator, i.e. a) above.

Noting that not all transects have the same swept area ($\propto$ `SwimLength`) some form of area-weighted averaging is needed, which we achieve by a simple adjustment to the GLM.

```
Prerecruits <- Transects %>%
  select(Date, QuotaYear, Site, SMU, Area_m2 = SwimLength, Prerecruits) %>%
  within({
    year <- as.numeric(as.character(QuotaYear))
    QuotaYear <- factor(QuotaYear)
  }) %>% untibble()

Raw <- Prerecruits %>%
  group_by(year, SMU, Site) %>%
  summarise(raw = sum(Prerecruits),
            Area = sum(Area_m2), .groups = "drop") %>%
  group_by(year, SMU) %>%
  summarise(raw = mean(raw/Area)*30, .groups = "drop") %>%
  untibble()
```

The results are shown in the following display.

3.1.2 All standardised

Turning to the *All standardised* indicator, i.e. b) above, we first fit the standardisation model.

```
b_data <- Transects %>%
  within({
    Year <- factor(QuotaYear)
    Site <- factor(Site)
    SMU <- factor(SMU)
    Diver <- factor(Diver)
  })

smod_b <- glm(Prerecruits ~ offset(log(SwimLength)) +
                Year/SMU + Site + Diver, family = quasipoisson, data = b_data)
```

The model is now used to produce standardised prerecruit numbers by isolating relevant components of the fitted model and removing irrelevant components. The final result is *normalised* by scaling it so that it agrees with the raw figure at the end of the time sequence. This is done independently for each SMU.

```
pB_data <- b_data %>%
  within({
    year <- QuotaYear
    SwimLength <- 30
  })
pB_data$pred <- rowSums(predict(smod_b, pB_data,
                           type = "terms")[, c("Year", "Year:SMU")])
Stand_b <- pB_data %>%
  group_by(year, SMU) %>%
  summarise(stand_b = exp(mean(pred)), .groups = "drop") %>% untibble()

RB <- merge(Raw, Stand_b, by = c("year", "SMU"))
scale_factor <- RB %>%
  filter(year == max(year)) %>%
  select(SMU, raw, stand_b) %>%
  within({
    sf <- raw/stand_b
  }) %>% select(SMU, sf)
RB <- merge(RB, scale_factor) %>%
  within({
    stand_b <- stand_b*sf
    sf <- NULL
  })

RBPrerecruits <- RB  ## needed for later in the document
```
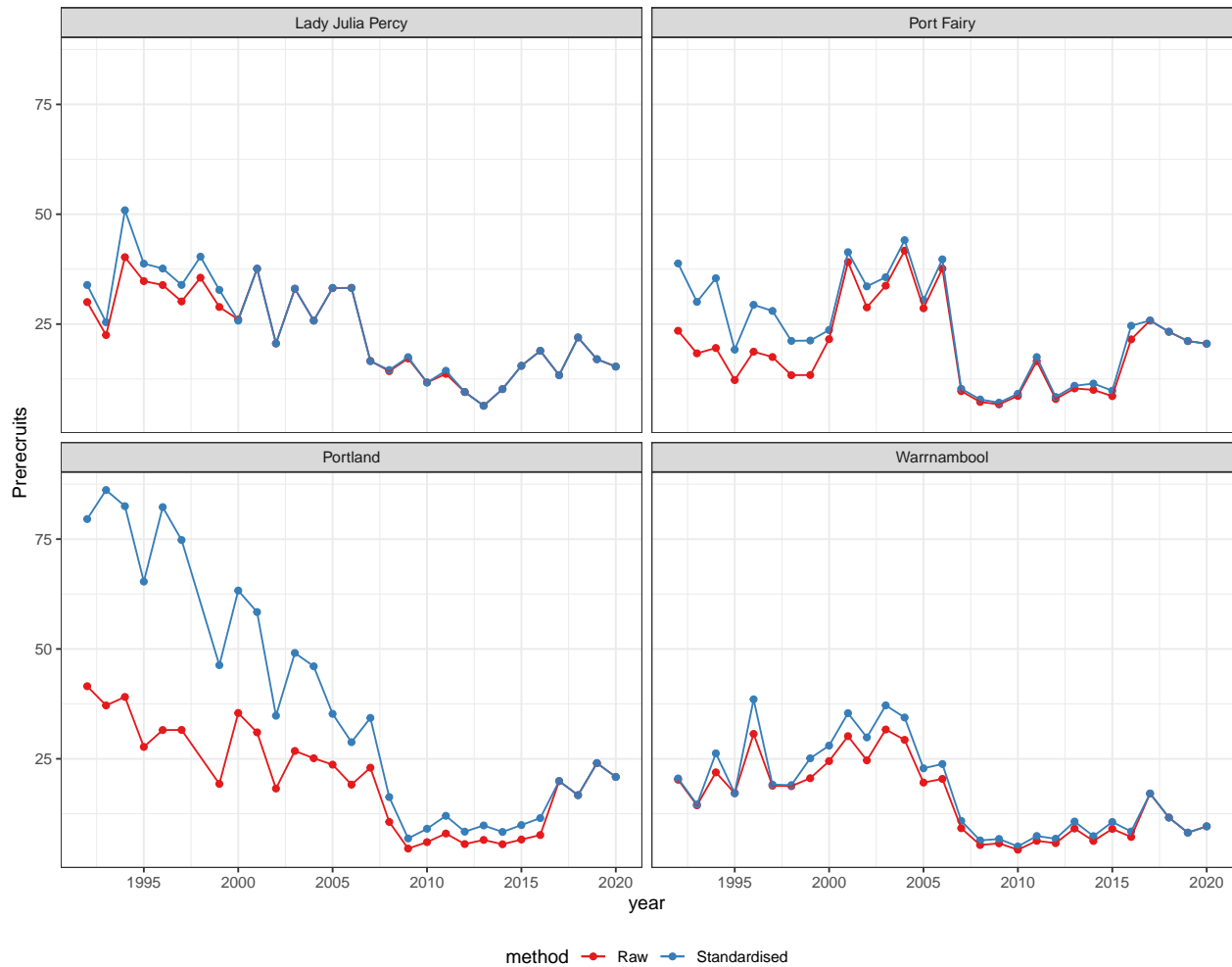
The results are shown in the following display.
```

### 3.1.3 Current standardisd

The *Current standardised* indicator, i.e. c) in the list, uses the same standardisation process as the above, but with a restricted data to fit the standardisation model, and similarly restricted outputs.

Note that this requires a restricted 'Raw' indicator as well, in order to achieve the apporpriate normalisation.

```
c_data <- b_data %>% rename(year = QuotaYear) %>%
  filter(year > 2001,
         Site %in% Site[year == max(year)]) %>%
  droplevels()
Raw_c <- c_data %>%
  group_by(year, SMU, Site) %>%
  summarise(raw_c = sum(Prerecruits),
            Area = sum(SwimLength), .groups = "drop") %>%
  group_by(year, SMU) %>%
  summarise(raw_c = mean(raw_c/Area)*30, .groups = "drop")

smod_c <- update(smod_b, data = c_data)
```

The standardisation proceeds as follows.

```
pC_data <- c_data %>%
  within({
```

```
    SwimLength <- 30
  })
pC_data$pred <- rowSums(predict(smod_c, pC_data,
                        type = "terms")[, c("Year", "Year:SMU")])
Stand_c <- pC_data %>%
  group_by(year, SMU) %>%
  summarise(stand_c = exp(mean(pred)), .groups = "drop") %>% untibble()
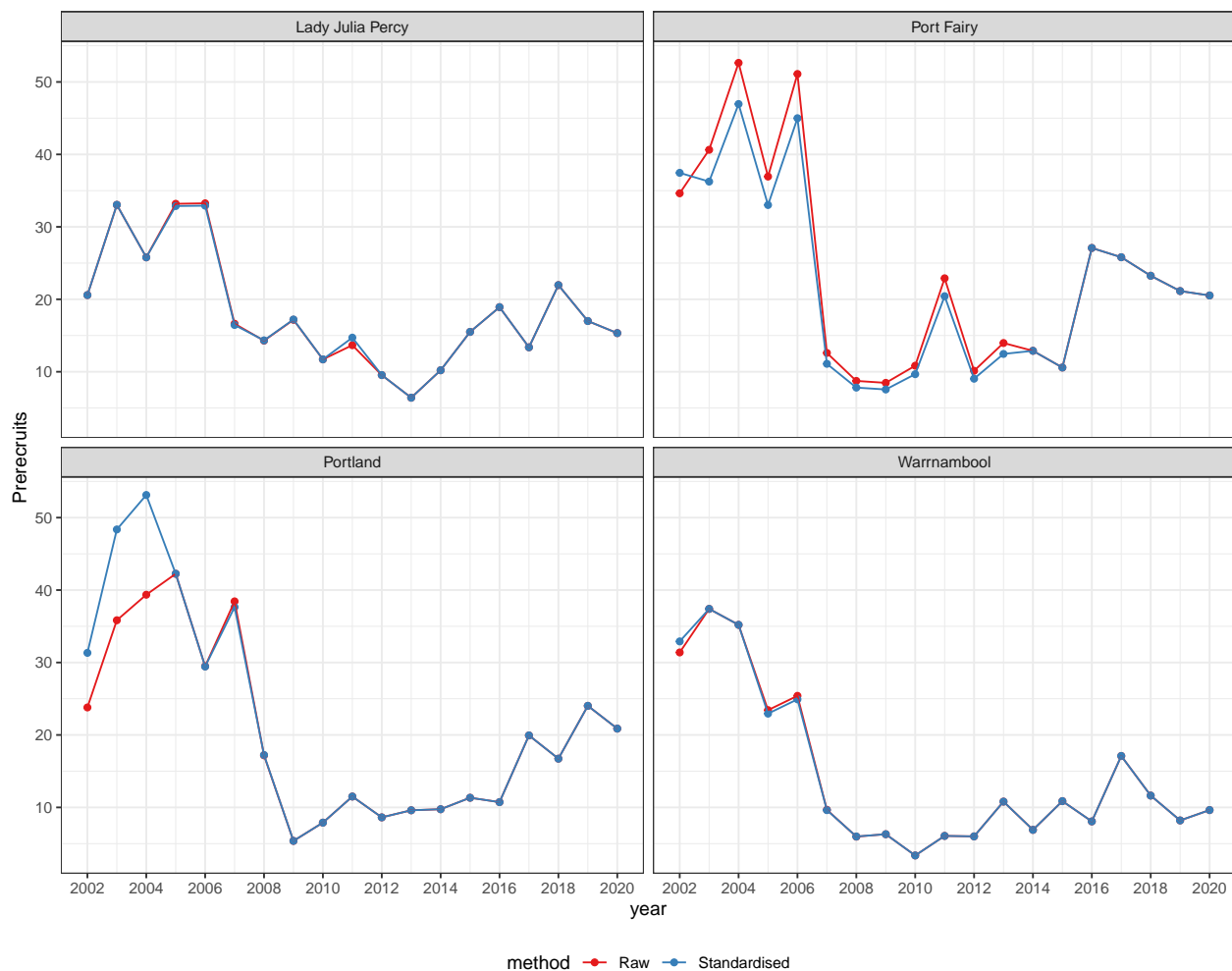
RC <- merge(Raw_c, Stand_c, by = c("year", "SMU"))
scale_factor <- RC %>%
  filter(year == max(year)) %>%
  select(SMU, raw_c, stand_c) %>%
  within({
    sf <- raw_c/stand_c
  }) %>% select(SMU, sf)
RC <- merge(RC, scale_factor) %>%
  within({
    stand_c <- stand_c*sf
    sf <- NULL
  })
```

The results are shown in the following display.

4 Indicators based on recruits

In this section we repeat the analsysi as shown above for the prerecruit indicators, but basing the computations on the *recruits* rather than the prerecruit numbers.

To recap, the three indicators are as follows:

a) *Raw*, which uses all sites, (not just 'recent sampled') and all years, and averages numbers across sites for each SMU.

b) *All standardised*, which again uses all sites and all years, standardised by simple GLM of the form `glm(recruits ~ year/smu + site + diver, family = quasipoisson, data)` and in the graph the predictions are *normalised* to match the raw value in the most recent year.

c) *Current standardised*, which uses only 'recent sampled' sites only years since 2002 and uses a standardisation GLM as in b).

4.1 Indicators and standardisation processes

4.1.1 Raw indicator

We begin, as before with the *Raw* indicator, which does not involve any model-based standardisation. The details are completely analogous to the process used for prerecruits, as shown in the code chunks to follow.

```
Recruits <- Transects %>%
  select(Date, QuotaYear, Site, SMU, Area_m2 = SwimLength, Recruits) %>%
  within({
    year <- as.numeric(as.character(QuotaYear))
    QuotaYear <- factor(QuotaYear)
  }) %>% untibble()

Raw <- Recruits %>%
  group_by(year, SMU, Site) %>%
  summarise(raw = sum(Recruits),
            Area = sum(Area_m2), .groups = "drop") %>%
  group_by(year, SMU) %>%
  summarise(raw = mean(raw/Area)*30, .groups = "drop") %>%
  untibble()
```

The results are shown in the following display.

4.1.2 All standardised

The second and third indicators are obtained via a standardisation process, as outlined above.

```
b_data <- Transects %>%
  within({
    Year <- factor(QuotaYear)
    Site <- factor(Site)
    SMU <- factor(SMU)
    Diver <- factor(Diver)
  })
smod_b <- glm(Recruits ~ offset(log(SwimLength)) +
                Year/SMU + Site + Diver, family = quasipoisson, data = b_data)
```

The model is now used to produce standardised recruit numbers by removing irrelevant components. The standardisation is scaled so that it agrees with the raw figure at the end of the time sequence, independently in each SMU.

```
pB_data <- b_data %>%
  within({
    year <- QuotaYear
    SwimLength <- 30
  })
```

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```
pB_data$pred <- rowSums(predict(smod_b, pB_data,
                                type = "terms")[, c("Year", "Year:SMU")])
Stand_b <- pB_data %>%
  group_by(year, SMU) %>%
  summarise(stand_b = exp(mean(pred)), .groups = "drop") %>% untibble()

RB <- merge(Raw, Stand_b, by = c("year", "SMU"))
scale_factor <- RB %>%
  filter(year == max(year)) %>%
  select(SMU, raw, stand_b) %>%
  within({
    sf <- raw/stand_b
  }) %>% select(SMU, sf)
RB <- merge(RB, scale_factor) %>%
  within({
    stand_b <- stand_b*sf
    sf <- NULL
  })


RBRecruits <- RB   ## needed later in the documnet
```

The results are shown in the following display.

4.1.3 Current standardisation

We now turn to the third indicator, c) in the list, where we use only those sites while are 'recently sampled', i.e. were surveyed in the most recent year of the time sequence.

```
c_data <- b_data %>% rename(year = QuotaYear) %>%
  filter(year > 2001, Site %in% Site[year == max(year)]) %>%
  droplevels()
Raw_c <- c_data %>%
  group_by(year, SMU, Site) %>%
  summarise(raw_c = sum(Prerecruits),
            Area = sum(SwimLength), .groups = "drop") %>%
  group_by(year, SMU) %>%
  summarise(raw_c = mean(raw_c/Area)*30, .groups = "drop")

smod_c <- update(smod_b, data = c_data)
```

The standardisation proceeds along similar lines to the above.

```
pC_data <- c_data %>%
  within({
    SwimLength <- 30
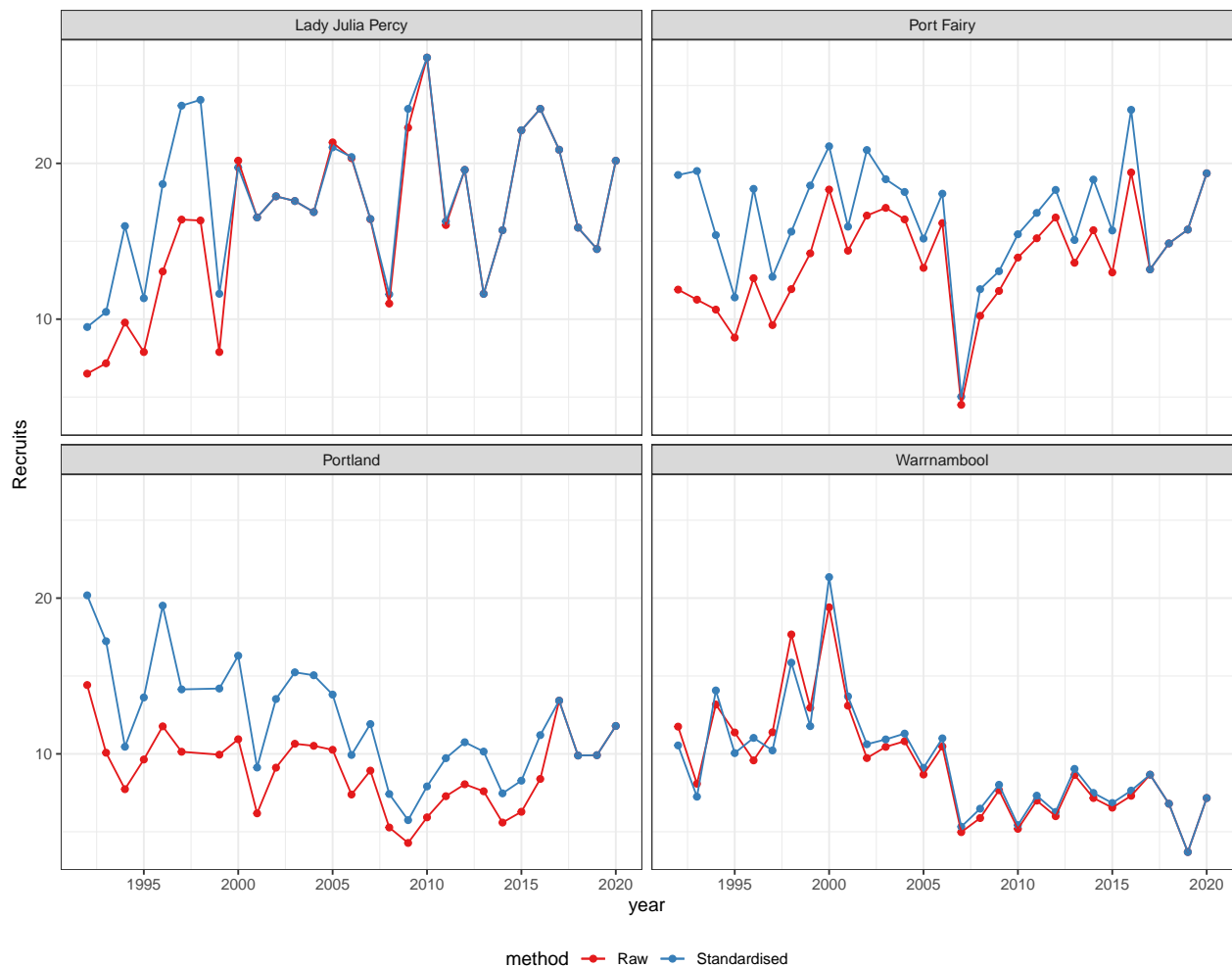  })
pC_data$pred <- rowSums(predict(smod_c, pC_data,
                                type = "terms")[, c("Year", "Year:SMU")])
Stand_c <- pC_data %>%
  group_by(year, SMU) %>%
  summarise(stand_c = exp(mean(pred)), .groups = "drop") %>% untibble()
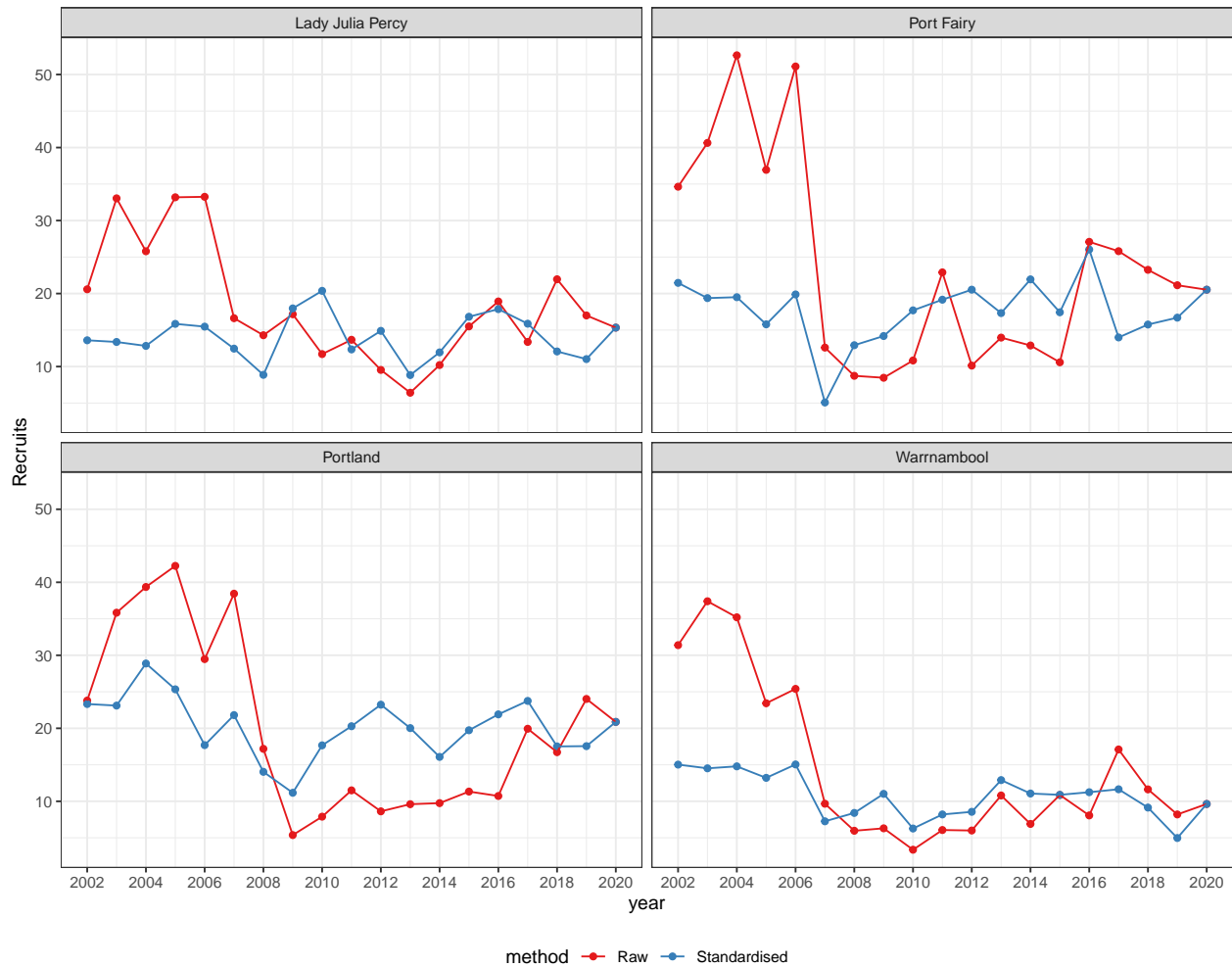
RC <- merge(Raw_c, Stand_c, by = c("year", "SMU"))
scale_factor <- RC %>%
  filter(year == max(year)) %>%
  select(SMU, raw_c, stand_c) %>%
  within({
    sf <- raw_c/stand_c
  }) %>% select(SMU, sf)
RC <- merge(RC, scale_factor) %>%
  within({
    stand_c <- stand_c*sf
    sf <- NULL
  })
```

The results are shown in the following display.

5 Biomass indicators from standardised prerecruits and recruits

Biomass calculations earlier in this document were completed with raw prerecruit and recruit counts from the data file. Here we repeat the same calculations of biomass density and total biomass with the standardised prerecruit and recruit estimates. Note that we use a normalisation to the final year.

```
RBPrerecruits <- RBPrerecruits %>%
  rename(QuotaYear = year)
RBRecruits <- RBRecruits %>%
  rename(QuotaYear = year)
Transects <- Transects %>%
  left_join(RBPrerecruits, by = c("SMU", "QuotaYear")) %>%
  left_join(RBRecruits, by = c("SMU", "QuotaYear"))


Transects_site <- Transects %>%
  group_by(QuotaYear, SMU, Site) %>%
  summarise(Area_m2   = sum(SwimLength),
            Prerecruit = sum(stand_b.x),
            Recruit    = sum(stand_b.y), .groups = "drop") %>%
  arrange(QuotaYear, Site) %>%
  pivot_longer(cols = c(Prerecruit, Recruit), names_to = "Stage", values_to = "Cs")
```

The following code chunk does the frequency adjustment, as described in general above.

```
Lengths_site <- Lengths %>%
  within({
    Ds <- ave(Frequency, QuotaYear, Site, Stage, FUN = sum)
  }) %>%
  left_join(Transects_site, by = c("Site", "QuotaYear", "Stage")) %>%
  within({
    Fadj <- Cs/Ds*Frequency
  })
```

```
Indicators_site <- Lengths_site %>%
  group_by(QuotaYear, SMU, Site, Area_m2) %>%
  summarise(
    Legal_sized = sum(Fadj*Weight*(Length >= 130))            /Area_m2 * 10,
    Mature      = sum(Fadj*Weight*(Length >= 102))            /Area_m2 * 10,
    Under_sized = sum(Fadj*Weight*(Length >= 100 & Length < 120))/Area_m2 * 10,
    .groups = "drop") %>%
  arrange(QuotaYear, Site) %>%
  select(QuotaYear, SMU, Site, everything())
```

The following table shows the first 10 entries in the combined data set.

Table 9: Biomass indicators, first 10 records

Year	SMU	Site	Area_m2	Legal_sized	Mature	Under_sized
1992	Warrnambool	124	180	132	2630	1510
1992	Warrnambool	124	180	132	2630	1510
1992	Warrnambool	124	180	132	2630	1510
1992	Warrnambool	124	180	132	2630	1510
1992	Warrnambool	124	180	132	2630	1510
1992	Warrnambool	124	180	132	2630	1510
1992	Warrnambool	124	180	132	2630	1510
1992	Warrnambool	124	180	132	2630	1510
1992	Warrnambool	124	180	132	2630	1510
1992	Warrnambool	124	180	132	2630	1510

5.1 Biomass indicators at the SMU level

```
Indicators_smu <- Indicators_site %>%
  within(year <- as.numeric(as.character(QuotaYear))) %>%
  filter(Site %in% Site[year == max(year)]) %>%
  group_by(year, SMU) %>%
  summarise(Mature      = weighted.mean(Mature,      Area_m2),
            Legal_sized = weighted.mean(Legal_sized, Area_m2),
            Under_sized = weighted.mean(Under_sized, Area_m2),
            .groups = "drop")
```

```
tmp <- Indicators_smu %>%
  pivot_longer(-c(SMU, year), names_to = "Category", values_to = "Density")
ggplot(tmp) + aes(x = year, y = Density, colour = Category) +
  geom_line(data = tmp %>% filter(year <= 2009)) +
  geom_line(data = tmp %>% filter(year >= 2009)) +
  geom_point() + facet_wrap(~ SMU, ncol = 2) + labs(y = "Density (Kg/Ha)") +
```

```
scale_colour_brewer(palette = "Set1") +
scale_x_continuous(breaks = with(Indicators_smu, seq(min(year), max(year), by = 2)))
```


5.2 Conversion to total biomass estimates per SMU

This is a repeat of a previous computation but now based on both prerecruit and recruit numbers.

For reference we repeat here the fished area table for each SMU, as used for the biomass estimates.

Table 10: SMU Fishery area estimates in Ha.

SMU	Area (Ha)
Lady Julia Percy	59
Port Fairy	215

SMU	Area (Ha)
Portland	376
Warrnambool	343

The computation is shown in the chunk below.

```
Indicators_smu_long <- Indicators_smu %>%
  pivot_longer(c(Mature, Legal_sized, Under_sized),
               names_to = "Category", values_to = "Density") %>%
  left_join(area, by = "SMU") %>%
  within({
    Total_biomass <- Density/1000*`Area (Ha)`
  }) %>%
  select(-Density, -`Area (Ha)`)
```

The biomass indicators are shown in the display below.

Finally, the following tables show the information in numerical form.

Table 11: Legal sized biomass estimates, (tonnes)

Year	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2002	32.8	160.0	195.6	112.9
2003	53.3	147.2	275.9	135.4
2004	42.7	129.3	286.7	148.0
2005	51.8	126.6	279.6	116.0
2006	67.0	152.1	212.1	158.1
2007	77.7	36.0	250.8	65.7
2008	49.5	127.2	132.1	99.2
2009			167.4	146.4
2010	99.3	262.5	207.4	119.4
2011	41.9	245.9	267.8	143.4
2012	45.9	239.1	260.6	94.6
2013	35.9	152.1	247.1	154.1
2014	48.5	246.2	155.0	125.1
2015	58.6	176.9	189.6	120.5
2016	64.1	185.3	227.6	122.0
2017	57.4	145.9	292.2	151.9
2018	53.7	119.7	208.1	133.2
2019	54.2	151.1	204.6	71.2
2020	67.0	201.7	277.7	136.6

Table 12: Mature biomass estimates, (tonnes)

Year	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2002	201.9	1009.9	1411.5	1119.0
2003	238.8	948.0	1771.7	1187.0
2004	212.2	1104.4	1641.9	1191.9
2005	284.7	840.4	1400.6	860.8
2006	270.8	1036.7	1089.3	1031.1
2007	192.9	259.8	1321.1	458.5
2008	140.3	402.3	678.9	394.2
2009			430.9	458.5
2010	239.8	518.2	585.8	331.4
2011	170.3	663.3	707.3	439.3
2012	172.6	598.3	668.9	374.0
2013	108.8	537.9	691.7	593.2
2014	153.5	647.9	520.4	446.8
2015	203.4	534.9	592.4	494.4
2016	232.8	954.9	768.7	483.4
2017	202.1	660.6	1002.1	691.0
2018	203.4	681.5	784.5	495.8
2019	173.6	671.5	973.5	331.5
2020	209.1	786.5	1023.7	522.4

Table 13: Under sized biomass estimates, (tonnes)

Year	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2002	84.3	505.2	853.7	715.6
2003	119.4	492.1	1144.9	798.1
2004	101.2	680.1	1010.6	782.8
2005	143.4	478.7	802.6	518.6
2006	130.2	602.9	664.5	602.2
2007	63.4	141.3	816.1	254.9
2008	56.8	106.4	371.6	137.4
2009			157.3	133.0
2010	47.4	105.1	224.4	107.8
2011	58.8	236.1	258.7	145.5
2012	40.0	128.6	186.1	134.6
2013	27.7	164.9	229.0	234.7
2014	43.7	164.1	193.1	155.8
2015	55.3	139.6	224.1	224.7
2016	76.9	389.3	266.6	186.4
2017	58.2	347.5	413.9	364.4
2018	94.0	332.5	361.1	232.0
2019	72.4	290.0	564.4	186.2
2020	66.7	310.8	508.3	240.9

6 Addendum: Observation date ranges for each listed Quota year

The following table gives the recorded FIS `QuotaYear`, and the starting and ending dates for the period over which the FIS observations were actually made.

Table 14: FIS observation date ranges for each quota year

Quota year	Start date	End date
1992	1992-04-28	1992-05-24
1993	1993-02-16	1993-05-19
1994	1994-02-08	1994-10-04
1995	1995-03-21	1995-05-09
1996	1996-02-07	1996-06-19
1997	1997-04-29	1997-11-11
1998	1998-05-14	1998-06-15
1999	1999-06-26	1999-06-30
2000	2000-04-19	2000-07-05
2001	2001-02-01	2001-02-09
2002	2002-01-17	2002-02-15
2003	2002-12-21	2003-01-14
2004	2004-01-27	2004-02-26
2005	2005-02-11	2005-02-28
2006	2006-02-04	2006-02-27
2007	2007-01-03	2007-02-04
2008	2007-09-06	2007-11-28
2009	2008-11-18	2009-03-13
2010	2010-02-09	2010-03-16
2011	2011-01-05	2011-03-09
2012	2012-02-14	2012-02-19

Quota year	Start date	End date
2013	2013-01-02	2013-02-16
2014	2014-01-26	2014-02-12
2015	2014-11-12	2015-01-20
2016	2015-11-16	2015-12-16
2017	2017-02-28	2017-05-21
2018	2018-01-27	2018-01-29
2019	2019-02-24	2019-03-01
2020	2020-01-30	2020-02-18

Appendix 3: VMS and Depth Data Summarised as Dive Events

2022-09-13

Contents

1 Introduction

Here we summarise the VMS (i.e. Vessel Monitoring System, GPS points of boat) and depth logger data (i.e depth of diver) collected by WADA from 2009-10 to the end March in the 2020-21 Quota Year (i.e. presented here for blacklip abalone only).

The GPS data was collected with Scielex and Succorfish GPS loggers and Scielex Measuring Boards (i.e. with regular logging enabled) on diver's boats, and Sensus depth loggers on divers. GPS loggers initially recorded at 10 second intervals, but were later adjusted to 1 minute, while Sensus depth loggers always logged at 10 second intervals.

The two data streams include the GPS location of the boat with date and time, and depth of the diver with date and time, which is adjusted (i.e. to account for decay of the depth logger time) and linked to the date and time of GPS points, to identify where the diver was in the water with depth > 0.5m (i.e. < -0.5m).

Only VMS and linked depth data from the same diver and date-time are used here, although a large amount of additional data with GPS points only (i.e. no depth data, and depth data with no GPS) is also available, and such data has been analysed in other fishery (e.g. NSW, Tas) using boat movements and/or GPS point density to identify when the diver was in the water (e.g. not diving when boat moving straight ahead at fast speed with low GPS point density, and diving when slow speed and greater turning with higher point density).

A regulated requirement for VMS reporting every 15 minutes was implemented from July 2020, and WADA have facilitated additional 1 minute logging and a new Scielex depth logger from March 2021.

2 Analysis

2.1 Data input

Data are read from a csv file containing linked VMS and depth logger data. Data are currently held in separate VMS and Depth logger SQL databases, and can also be read directly from the database or processed in SQL prior to connection and reading by R. Here, data are filtered to Depth > -0.5m, Speed < 4kn and then with > 7 GPS points to enable appropriate analysis.

```r
XYprefilt_all <- vroom("Data/VMS data/kuds/0853_August11_XYprefilt_MGA94z54_all.csv",
                       na = c("", "NA", "NULL"),
                       col_types = cols(ID = col_double(),
                                        CODE = col_character(),
                                        LASTNAME = col_character(),
                                        FIRSTNAME = col_character(),
                                        DATE_LOCAL = col_datetime(format = ""),
                                        EASTING = col_double(),
                                        NORTHING = col_double(),
                                        SPEED = col_double(),
                                        DROP_NUMBER = col_double(),
                                        DEPTH = col_double(),
                                        TEMPERATURE = col_double(),
                                        FP = col_double(),
                                        DiveID = col_character())) %>%
  filter(DEPTH > 0.5, SPEED < 4) %>%
  select(Id = ID, Code = CODE, lastname = LASTNAME, firstname = FIRSTNAME, date = DATE_LOCAL,
         easting = EASTING, northing = NORTHING, speed = SPEED, drop_number = DROP_NUMBER,
         depth = DEPTH, temperature = TEMPERATURE, QuotaYear = FP, DiveID) %>%
  within({
    QuotaYear <- QuotaYear + 1                # Year modified
    Diver <- paste(firstname, lastname)
    Diver <- sub("^Phil ", "Phillip ", Diver)
    Diver <- sub("^Rob ", "Robert ", Diver)
    Diver <- str_trim(Diver)
  }) %>%
  select(Id, Code, Diver, date, everything(), -lastname, -firstname) %>%
  untibble()

OKdives <- with(XYprefilt_all, table(DiveID)) %>%
  as.data.frame(responseName = "n") %>%
  filter(n > 7) %>%
  pull(DiveID) %>%
  as.character()

XYdat <- XYprefilt_all %>%
  filter(DiveID %in% OKdives) %>%
  arrange(date, DiveID)
```

2.2 Dive events

GPS points and depth data are grouped into Dive events. A Dive event is defined by the depth logger as a group of GPS points separated by a period of 2.5 minutes above a depth of 0.5m.

A spatial grid (i.e. resolution = 5m) is created for each Dive event, covering the GPS points and a 25m buffer. The spatial grid and GPS points are then used to fit a bivariate normal Kernel Density model that estimates the density of the GPS points (i.e. KDE = Kernel Density Estimate with a fixed bandwidth of 7m).

Contours enclosing 50% and 90% of the volume of points estimated by the KDE are then calculated to represent the extent of the Dive event, and associated with other data (e.g. average depth per Dive event).

```r
dive_info <- XYdat %>%
  group_by(DiveID, drop_number) %>%
  summarise(DvStart = min(date),
            DvEnd   = max(date),
```

```
            AvgDpth = mean(depth),
            AvgTemp = mean(temperature),
            bbox_x1 = min(easting),
            bbox_x2 = max(easting),
            bbox_y1 = min(northing),
            bbox_y2 = max(northing),
            maxdist = diameter(easting, northing),
            .groups = "drop") %>%
  within({
    DvStart <- as.POSIXlt(DvStart, origin = "1970-01-01", tz = "Australia/Sydney")
    DvEnd <- as.POSIXlt(DvEnd, origin = "1970-01-01", tz = "Australia/Sydney")
    duration <- difftime(DvEnd, DvStart, units = "mins") %>%
      as.numeric()
  }) %>% untibble()

grids <- dive_info %>%
  select(idcd = DiveID,
         MinE = bbox_x1, MaxE = bbox_x2,
         MinN = bbox_y1, MaxN = bbox_y2)

oldOpt <- options(warn = -1) ## expect a warning here
SXYdat <- with(XYdat,
               SpatialPointsDataFrame(coords = cbind(easting, northing),
                                      data = data.frame(DiveID),
                                      # proj4string = CRS("+init=epsg:28354"),
                                      proj4string = coord_ref,
                                      match.ID = TRUE))
options(oldOpt)

###  Start of grid computations

buffer <- 25
resolution <- 5

oldOpt <- options(warn = -1) ## expect a warning here
ascgrid <- grids %>%
  split(., .$idcd) %>%
  lapply(function(data) {
    with(data, {
      extent <- SpatialPoints(data.frame(x = c(MinE - buffer, MaxE + buffer),
                                         y = c(MinN - buffer, MaxN + buffer)))
      # proj4string(extent) <- CRS("+init=epsg:28354")
      proj4string(extent) <- coord_ref
      ascgen(extent, cellsize = resolution)
    })
  })

hrkde <- kernelUD(SXYdat, h = 7, grid = ascgrid, same4all = FALSE)
sp_hrver90 <- getverticeshr(hrkde, 90)

slot(sp_hrver90, "polygons") <- lapply(slot(sp_hrver90, "polygons"),
                                       checkPolygonsHoles)
# proj4string(sp_hrver90) <- CRS("+init=epsg:28354")
```

```r
proj4string(sp_hrver90) <- coord_ref

##### new code #####

sp_hrver50 <- getverticeshr(hrkde, 50)

slot(sp_hrver50, "polygons") <- lapply(slot(sp_hrver50, "polygons"),
                                       checkPolygonsHoles)
# proj4string(sp_hrver50) <- CRS("+init=epsg:28354")
proj4string(sp_hrver50) <- coord_ref

##### end new code #####

options(oldOpt)  ### end of warnings due to faulty CRS


names <- sapply(slot(sp_hrver90, "polygons"), slot, "ID")
sp_hrver90df <- SpatialPolygonsDataFrame(
  sp_hrver90,
  data = structure(data.frame(names = names),
                   row.names = names),
  match.ID = TRUE)

polyunion90df <- SpatialPolygonsDataFrame(
  unionSpatialPolygons(SpP = sp_hrver90df, sp_hrver90df$names),
  data = data.frame(names = names,
                    row.names = names),
  match.ID = TRUE)

##### new code #####

names <- sapply(slot(sp_hrver50, "polygons"), slot, "ID")
sp_hrver50df <- SpatialPolygonsDataFrame(
  sp_hrver50,
  data = structure(data.frame(names = names),
                   row.names = names),
  match.ID = TRUE)

polyunion50df <- SpatialPolygonsDataFrame(
  unionSpatialPolygons(SpP = sp_hrver50df, sp_hrver50df$names),
  data = data.frame(names = names,
                    row.names = names),
  match.ID = TRUE)

##### end new code #####

##Join with other Dive event data
Diver <- with(XYdat, data.frame(DiveID, Diver)) %>%
  unique() %>% remove_rownames()

HR_kud50 <- as(sp_hrver50, "data.frame") %>%
  remove_rownames() %>%
  within({
```

```
    area <- area * 10000 ## convert to m^2
  }) %>%
  rename(DiveID = id) %>%
  merge(dive_info, by = "DiveID") %>%
  within({
    DvStart <- as.Date(DvStart)
    DvEnd <- as.Date(DvEnd)
    drop_number <- as.character(drop_number)
  }) %>%
  rename(MaxDist = maxdist) %>%
  select(DiveID, drop_number, DvStart, DvEnd, AvgDpth, AvgTemp,
         duration, MaxDist, area) %>%
  left_join(Diver, by = "DiveID") %>%
  arrange(DiveID)

HR_kud90 <- as(sp_hrver90, "data.frame") %>%
  remove_rownames() %>%
  within({
    area <- area * 10000 ## convert to m^2
  }) %>%
  rename(DiveID = id) %>%
  merge(dive_info, by = "DiveID") %>%
  within({
    DvStart <- as.Date(DvStart)
    DvEnd <- as.Date(DvEnd)
    drop_number <- as.character(drop_number)
  }) %>%
  rename(MaxDist = maxdist) %>%
  select(DiveID, drop_number, DvStart, DvEnd, AvgDpth, AvgTemp,
         duration, MaxDist, area) %>%
  left_join(Diver, by = "DiveID") %>%
  arrange(DiveID)
```

2.3 Linking Catch to Dive events

Catch data are read from a csv file containing a Diver ID to link with the Diver ID in the VMS and depth logger data. Data are currently held in a separate SQL database, and can also be read directly from the database or processed in SQL prior to connection and reading by R.

As Catch data are validated and reported each day, Catch and VMS data are aggregated to the daily-scale, and associated with the Reefcode of highest catch each day (e.g and the Reefcode of highest estimated GPS point density). Daily reporting includes Catch per Reefcode, and could also be linked to VMS data by Reefcode, but is not validated.

Estimates of daily fishing effort (i.e. h) are available from Catch reporting and the duration of Dive events from the depth logger. Data are filtered where the Depth logger estimate of fishing effort is $< 50\%$ or $> 200\%$ of the reported fishing effort. This filter is used as operational issues during the diver's day, such as flat logger battery or diving while not fishing, can impact estimates of fishing effort from the depth logger.

An area-based estimate of daily fishing effort can also calculated from the total area of Dive events each day (i.e. Ha), and is calculated from the area enclosing 50% of the estimated density of GPS points of the boat during each Dive event (i.e. and assumed to estimate the area covered and fished by the diver), and summed across Dive events.

A simple linear model is used to standardise the daily catch rate calculated from the three different estimates

of fishing effort (i.e. fishing effort from catch reporting in h, Dive event duration in h, Dive event area in Ha).

```r
### Aggregate catch

modal <- function(Catch, SMU) {
  if(length(u <- unique(SMU)) == 1) return(u)
  tab <- tapply(Catch, SMU, sum)
  names(tab)[which.max(tab)]
}


SMU_Table <- vroom("Data/VMS data/SMU_Table.csv",
                   col_types = cols(
                     SMU = col_character(),
                     ReefCode = col_character()
                   )) %>% untibble()


WADA_CE_all <- vroom("Data/VMS data/WADA_CE_all_2.csv",       ### changed rcode column format
                     na = c("", "NA", "NULL"),
                     col_types = cols(dat = col_date(format = ""),
                                      Diver = col_character(),
                                      pfn = col_double(),
                                      rcode = col_character(),
                                      reef_name = col_character(),
                                      Cat = col_double(),
                                      est_weight_greenlip = col_double(),
                                      est_dive_hours = col_double(),
                                      est_dive_minutes = col_double(),
                                      Eff = col_double(),
                                      FP = col_double(),
                                      CODE = col_character(),
                                      DPFN = col_character(),
                                      Lastname = col_character(),
                                      gEff = col_double())) %>%
  filter(Eff > 0, est_weight_greenlip == 0, dat < as.Date("2021-04-01")) %>%    ### new code
  within({
    FP <- FP + 1                                       # Year modified
    Diver[is.na(Diver)] <- "Mystery Diver"
    Diver <- str_trim(Diver)
    Diver <- sub("^Phil ", "Phillip ", Diver)
    Diver <- sub("^Rob ", "Robert ", Diver)
  }) %>%
  select(date = dat, Diver, PFN = pfn, ReefCode = rcode, Catch = Cat,
         QuotaYear = FP, Eff_hrs = Eff) %>%
  left_join(SMU_Table, by = "ReefCode") %>%
  filter(SMU %in% c("Lady Julia Percy", "Port Fairy", "Portland",  ### new code
                    "Warrnambool")) %>%                            ### new code
  untibble()


Catch <- WADA_CE_all %>%
  group_by(QuotaYear, date, Diver, PFN) %>%
  summarise(
    ReefCode = modal(Catch, ReefCode),
```

```
    SMU = modal(Catch, SMU),
    Catch = sum(Catch),
    Eff_hrs = sum(Eff_hrs),                              ### new code
    .groups = "drop") %>%
  filter(Catch > 0) %>%                                  ### new code
  untibble()

HR_kud50 <- HR_kud90 %>%select(DiveID,area90=area) %>%
  right_join(HR_kud50, by = 'DiveID')

Effort <- HR_kud50 %>%
  select(date = DvStart, duration, area, area90, Diver) %>%
  group_by(date, Diver) %>%
  summarise(area_m2 = sum(area),
            area_90 = sum(area90),
            duration = sum(duration)/60,
            .groups = "drop")          ### changed code

CE <- full_join(Catch, Effort, by = c("date", "Diver")) %>% untibble()

vtab <- CE %>%
  group_by(SMU, QuotaYear) %>%
  summarise(Effort = sum(Eff_hrs),
            Duration = sum(duration, na.rm = TRUE),
            Area_50 = sum(area_m2/10000, na.rm = TRUE),
            Area_90 = sum(area_90/10000, na.rm = TRUE),
            .groups = "drop")
```

Table 1: Fishing Effort measured by Catch reporting Effort (h), Dive event Duration from depth logger (h) and Dive event Area from 50% and 90% contours (Ha). Note, GPS data with no depth, depth with no GPS, and new depth logger data in 2020 are not included here, and if logger data is not linked to a reported catch it is included as '-'.

SMU	QuotaYear	Effort	Duration	Area_50	Area_90
Lady Julia Percy	2010	203	0	0	0
Lady Julia Percy	2011	260	0	0	0
Lady Julia Percy	2012	269	0	0	0
Lady Julia Percy	2013	82	18	1	4
Lady Julia Percy	2015	36	15	2	6
Lady Julia Percy	2016	56	18	1	4
Lady Julia Percy	2017	33	0	0	0
Lady Julia Percy	2018	55	11	1	3
Lady Julia Percy	2019	65	6	1	5
Lady Julia Percy	2020	41	0	0	0
Lady Julia Percy	2021	45	4	1	3
Port Fairy	2010	134	56	5	17
Port Fairy	2011	210	78	9	32
Port Fairy	2012	256	48	4	14
Port Fairy	2013	436	81	7	24
Port Fairy	2014	219	93	7	24
Port Fairy	2015	253	132	9	32
Port Fairy	2016	318	210	21	71
Port Fairy	2017	265	100	12	43
Port Fairy	2018	289	159	17	57
Port Fairy	2019	316	155	19	64
Port Fairy	2020	316	56	9	31
Port Fairy	2021	183	14	4	12
Portland	2013	129	79	9	34
Portland	2014	267	168	16	58
Portland	2015	354	218	23	82
Portland	2016	400	177	22	75
Portland	2017	311	200	26	92
Portland	2018	328	166	22	78
Portland	2019	318	135	19	69
Portland	2020	306	180	34	124
Portland	2021	238	107	21	71
Warrnambool	2012	69	31	4	14
Warrnambool	2013	45	30	3	10
Warrnambool	2014	92	28	3	9
Warrnambool	2015	82	64	6	21
Warrnambool	2016	82	98	9	31
Warrnambool	2017	133	89	11	37
Warrnambool	2018	88	70	8	26
Warrnambool	2019	131	84	10	35
Warrnambool	2020	125	9	1	3
Warrnambool	2021	75	4	1	3
-	-	-	537	58	204

2.4 Standardisation

This section provides detail of three standardisations each for a reduced data set including logbook and logger data on only days where both GPS and depth data are available. These include raw and standardised catch rate determined by reported logbook effort from the reduced data set where both GPS and depth data were available, raw and standardised catch rate with effort determined by the duration of daily Dive events from the depth logger, and raw and standardised catch rate with effort determined by the area of daily Dive events from the GPS and depth logger.

```r
CE <- inner_join(Catch, Effort, by = c("date", "Diver")) %>%
  within({                                                    ### new code
    T_ratio <- Eff_hrs/duration
  }) %>%
  filter(0.5 < T_ratio, T_ratio < 2.0) %>%
  untibble()                                                  ### end new code
```

```r
### base standardisation

Catch <- Catch %>%
  within({
    Year <- as.numeric(QuotaYear)
    QuotaYear <- as.character(QuotaYear)
    CPUE <- Catch/Eff_hrs
  })

Crude <- Catch %>%
  group_by(Year, QuotaYear, SMU) %>%
  summarise(N = n(),
            tot_catch = sum(Catch),
            tot_effort = sum(Eff_hrs),
            raw_cpue = sum(Catch)/sum(Eff_hrs),
            .groups = "drop") %>% untibble()

s_model <- lm(terms(log(CPUE) ~ 0 + SMU:QuotaYear + ReefCode + Diver,
                    keep.order = TRUE), data = Catch)

Stand <- cbind(
  Catch %>% select(Year, QuotaYear, SMU),
  stand_cpue = exp(predict(s_model, type = "terms")[, "SMU:QuotaYear"] +
                    deviance(s_model)/df.residual(s_model)/2) ## bias necessary??
) %>% unique() %>% left_join(Crude, by = c("Year", "QuotaYear", "SMU"))

norm <- Stand %>%
  group_by(SMU) %>%
  summarise(sf = mean(stand_cpue)/mean(raw_cpue),
            .groups = "drop") %>%
  select(SMU, sf)

Stand <- Stand %>%
  left_join(norm, by = "SMU") %>%
  within(raw_cpue <- raw_cpue * sf) %>%
  select(-sf) %>% arrange(Year, SMU)

theme_set(theme_bw() + theme(legend.position = "bottom",
                             plot.title = element_text(hjust = 0.5)))
```

```
redish <- palette()[2]
blueish <- palette()[4]
Stand_long <- Stand %>%
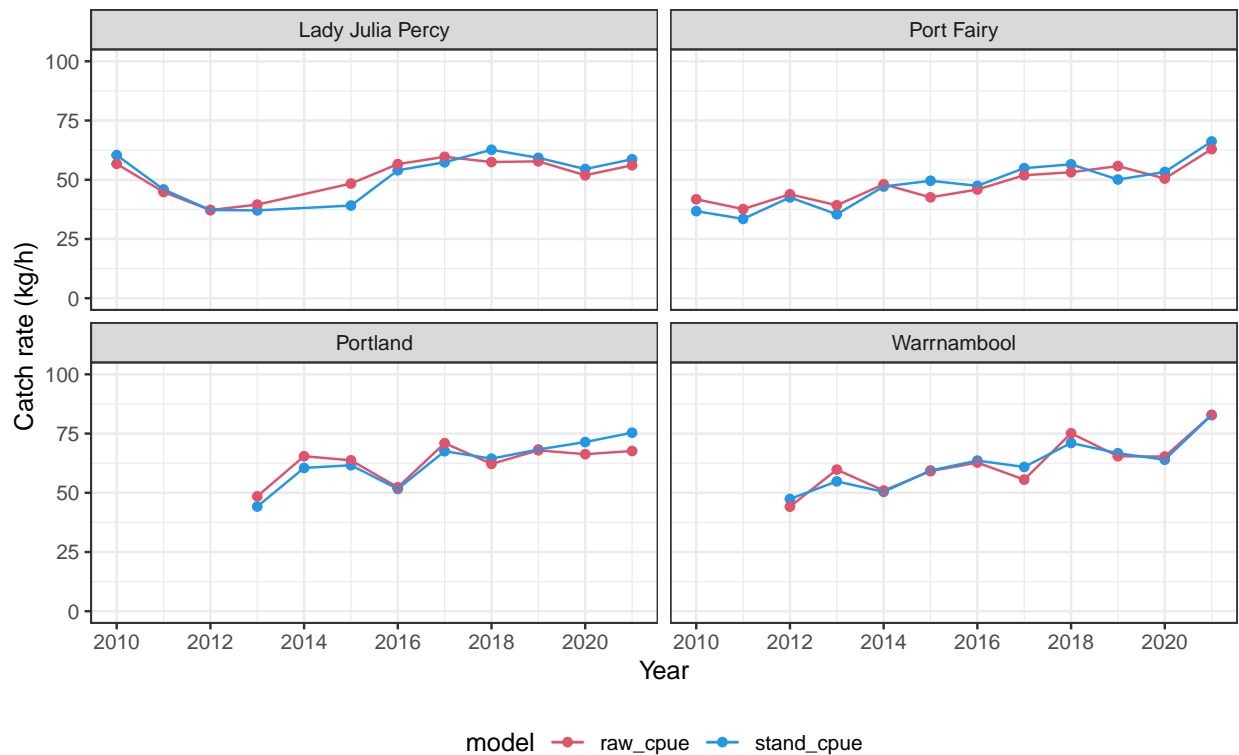  pivot_longer(c(stand_cpue, raw_cpue), names_to = "model", values_to = "CPUE")
```


Figure 1: Raw catch rate normalised to the average standardised catch rate from reported effort within each SMU, for all days where both GPS and depth data are available.

```
### dive event duration standardisation

CE <- CE %>%
  within({
    Ha <- area_m2 / 10000
    Year <- as.numeric(QuotaYear)
    QuotaYear <- as.character(QuotaYear)
    CPUE_d <- Catch/duration
    CPUE_h <- Catch/1000/Ha
    Tdiff <- Eff_hrs/duration
  })

s_model_d <- lm(terms(log(CPUE_d) ~ 0 + SMU:QuotaYear + ReefCode + Diver,
                  keep.order = TRUE), data = CE)

Stand_d <- cbind(
  CE %>% select(Year, QuotaYear, SMU),
```

```
    stand_cpue_d = exp(predict(s_model_d, type = "terms")[, "SMU:QuotaYear"] +
                       deviance(s_model_d)/df.residual(s_model_d)/2) ## bias necessary??
) %>% unique() %>% left_join(Crude, by = c("Year", "QuotaYear", "SMU"))

norm <- Stand_d %>%
  group_by(SMU) %>%
  summarise(sf = mean(stand_cpue_d)/mean(raw_cpue),
            .groups = "drop") %>%
  select(SMU, sf)

Stand_d <- Stand_d %>%
  left_join(norm, by = "SMU") %>%
  within(raw_cpue <- raw_cpue * sf) %>%
  select(-sf) %>% arrange(Year, SMU)

Stand_d_long <- Stand_d %>%
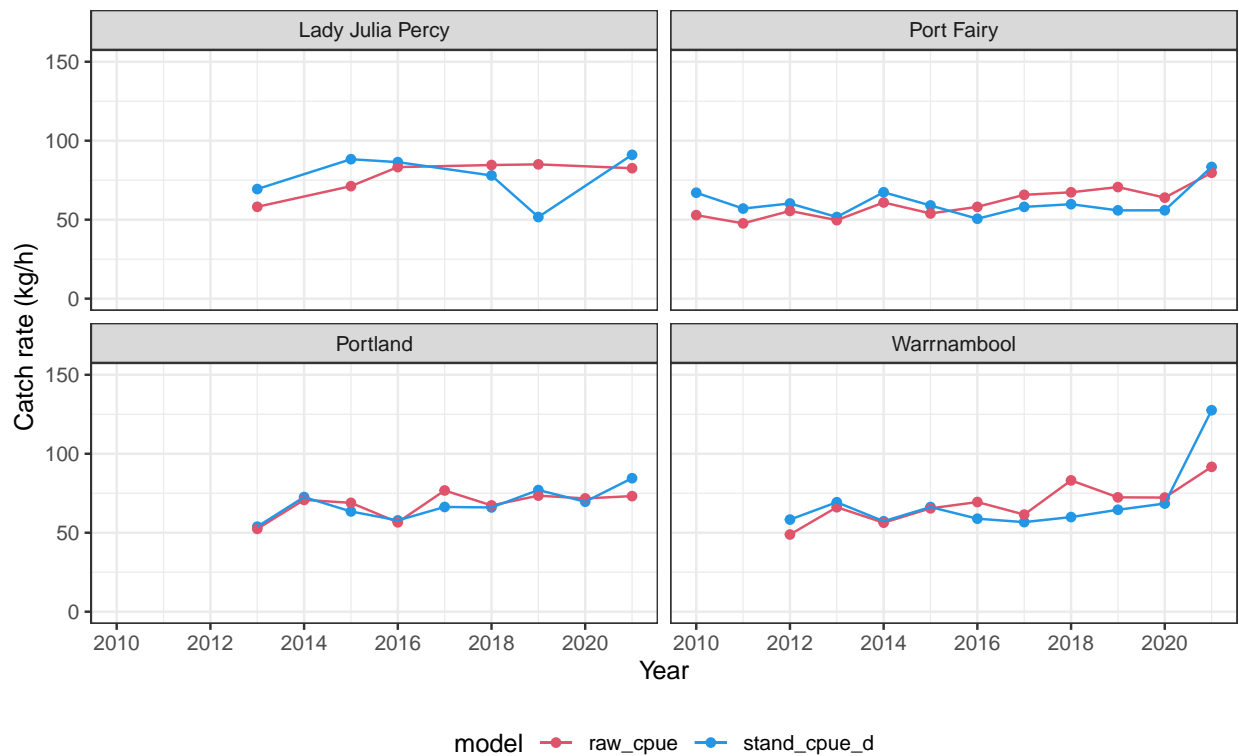  pivot_longer(c(stand_cpue_d, raw_cpue), names_to = "model", values_to = "CPUE")
```


Figure 2: Raw catch rate normalised to average standardised catch rate from the daily duration of Dive events (i.e. depth logger) within each SMU for all days where both GPS and depth logger data is available.

dive event area standardisation

```
s_model_h <- lm(terms(log(CPUE_h) ~ 0 + SMU:QuotaYear + ReefCode + Diver,
                      keep.order = TRUE), data = CE)
```

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```
Stand_h <- cbind(
  CE %>% select(Year, QuotaYear, SMU, CPUE_h),
  stand_cpue_h = exp(predict(s_model_h, type = "terms")[, "SMU:QuotaYear"] +
                        deviance(s_model_h)/df.residual(s_model_h)/2) ## bias necessary??
) %>% unique() %>% left_join(Crude, by = c("Year", "QuotaYear", "SMU"))

norm <- Stand_h %>%
  group_by(SMU) %>%
  summarise(sf = mean(CPUE_h)/mean(raw_cpue),
            sf1 = mean(CPUE_h)/mean(stand_cpue_h),
            .groups = "drop") %>%
  select(SMU, sf, sf1)

Stand_h <- Stand_h %>%
  left_join(norm, by = "SMU") %>%
  within({
    raw_cpue <- raw_cpue * sf
    stand_cpue_h <- stand_cpue_h * sf1}) %>%
  select(-sf,-sf1) %>%
  arrange(Year, SMU)

Stand_h_long <- Stand_h %>%
  pivot_longer(c(stand_cpue_h, raw_cpue), names_to = "model", values_to = "CPUE")
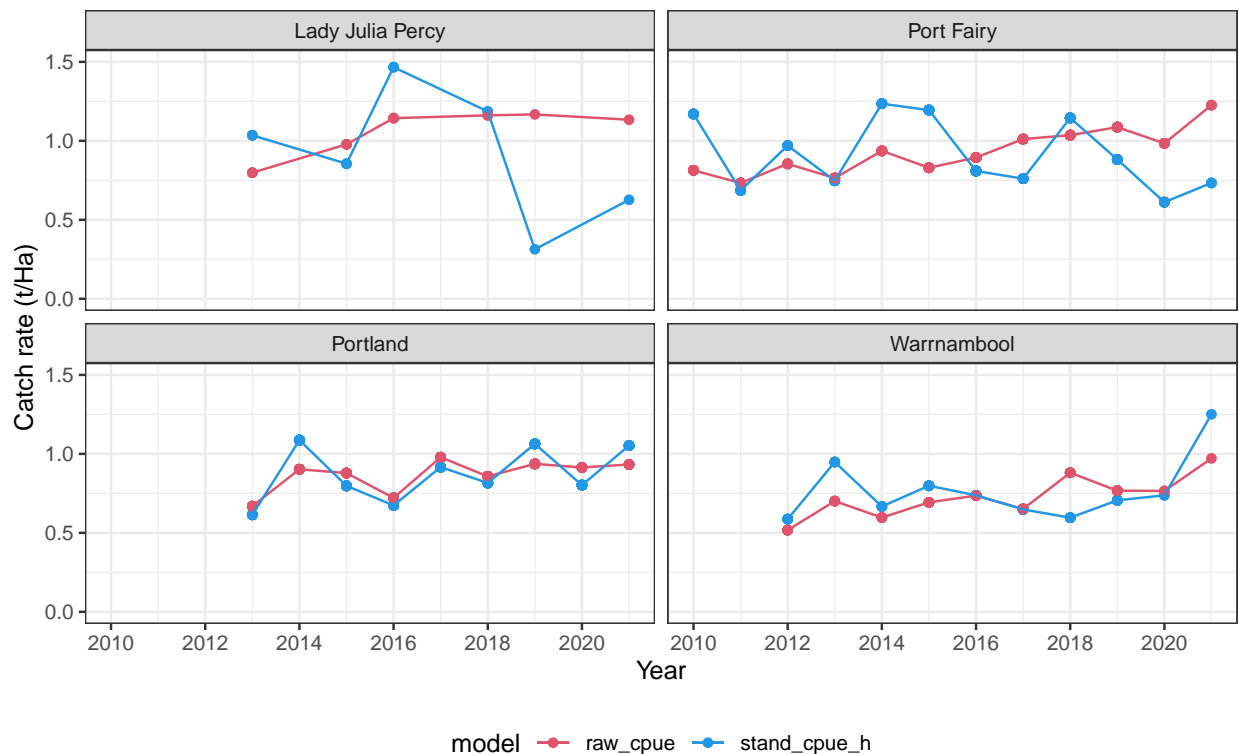```



Figure 3: Raw catch rate (in kg per h) normalised to the average standardised catch rate from the daily area of Dive events (in t per Ha) within each SMU, for days where both GPS and Depth logger data is available.

## 2.5 Conversion to total biomass estimates per SMU

The total fished area for each SMU, as estimated separately, are as in the following Table:

Table 2: SMU Fishery area estimates in Ha.

| SMU | Area (Ha) |
|---|---|
| Portland | 376 |
| Lady Julia Percy | 59 |
| Port Fairy | 215 |
| Warrnambool | 343 |

We can now match this estimate with the standardised area-based catch rate (t/Ha, from Figure 3) and assume this can be used as an indicator of legal-sized abalone density (t/Ha), extrapolate to the total fished area, and arrive at estimates of total legal biomass.

```
Indicators_smu_long <- Stand_h %>%
  group_by(Year,SMU) %>%
  summarise(avCPUE_h = mean(stand_cpue_h, na.rm = TRUE),
            .groups = "drop") %>%
  left_join(area, by = "SMU") %>%
  within({
    Total_biomass <- avCPUE_h*`Area (Ha)`
  }) %>%
  select(Year, SMU, Total_biomass) %>%
  arrange(SMU)

Indi_tot <- Indicators_smu_long %>%
  pivot_wider(names_from = SMU, values_from = Total_biomass) %>%
  arrange(Year)
  kable(Indi_tot, booktabs = TRUE, row.names = FALSE, digits = 0,
        caption = "Legal sized biomass estimates in t")
```

Table 3: Legal sized biomass estimates in t

Year	Lady Julia Percy	Port Fairy	Portland	Warrnambool
2010	-	252	-	-
2011	-	148	-	-
2012	-	209	-	201
2013	61	161	231	325
2014	-	266	409	229
2015	50	257	300	274
2016	87	174	253	253
2017	-	164	345	222
2018	70	246	307	204
2019	18	190	400	242
2020	-	132	302	253
2021	37	158	396	429

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Figure 4: Total Legal-sized biomass (in t) estimated from loggers with standardised catch rate from the daily area of Dive events (in t per Ha, with density shown Figure 3) extrapolated to the area of the fishery within each SMU.

Appendix 4: FRDC project 2020-065 "Indicators for density and biomass of exploitable abalone – developing and applying a new approach"

Key project objectives:

- Replicate past calculations of exploitable density and biomass from catch, GPS logger and fixed site surveys
- develop a new approach to calculate density and biomass of exploitable abalone
- calibrate logger-derived local density from local observations of loggers and surveys

Approach:

- Have replicated past calculations of exploitable density and biomass from reported catch, GPS logger and from fixed site surveys (undersize, mature biomass, exploitable biomass)
- Have developed a standardised history of CPUE
- New method to calculate estimates of exploitable density and biomass needs to calibrate estimates from GPS loggers with fixed site surveys

➢ This calibration is why we are meeting

Fishery dependent and fishery independent monitoring

- Fishery Independent Surveys
  - standardised methods
  - independent of commercial issues (i.e. fish value, fish size, area fished, swimming speed etc)
  - can cover legal and undersized fish
  - expensive
  - covers small areas and numbers of samples (i.e. area and abalone seen on each FIS site)
  - density estimates can be biased up or down from truth, depending on survey design

- Catch, effort and GPS logger surveys
  - unstandardised methods (i.e. diver preferences)
  - influenced by commercial issues (i.e. fish price, fish size, area fished, swimming speed etc)
  - covers just legal sized fish
  - relatively cheap
  - covers large areas with many samples (e.g. area and catch in a day)
  - density estimates can be biased down from truth because of commercial interest, but usually unknown

➢ There can be big differences in the interpretations that are made
➢ There are big differences in the areas and times covered by the estimates

Both monitoring approaches have problems
- change in abalone abundance as population changes

Fishery Independent Survey (FIS) sites

FIS Site 1   FIS Site 2   FIS Site 3
  *   *   *

High abalone abundance

Abalone catch rate or density

Medium abalone abundance

Low abalone abundance

Location on seabed

Abalone catch rate or density

FIS Site 1

FIS Site 2

FIS Site 3

High   Medium   Low
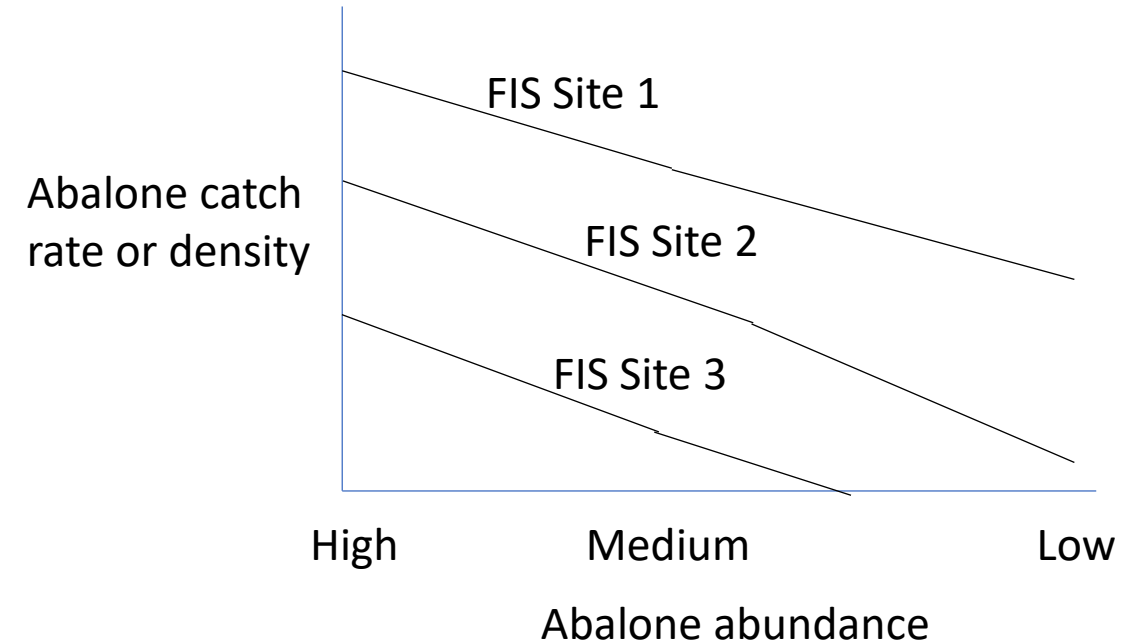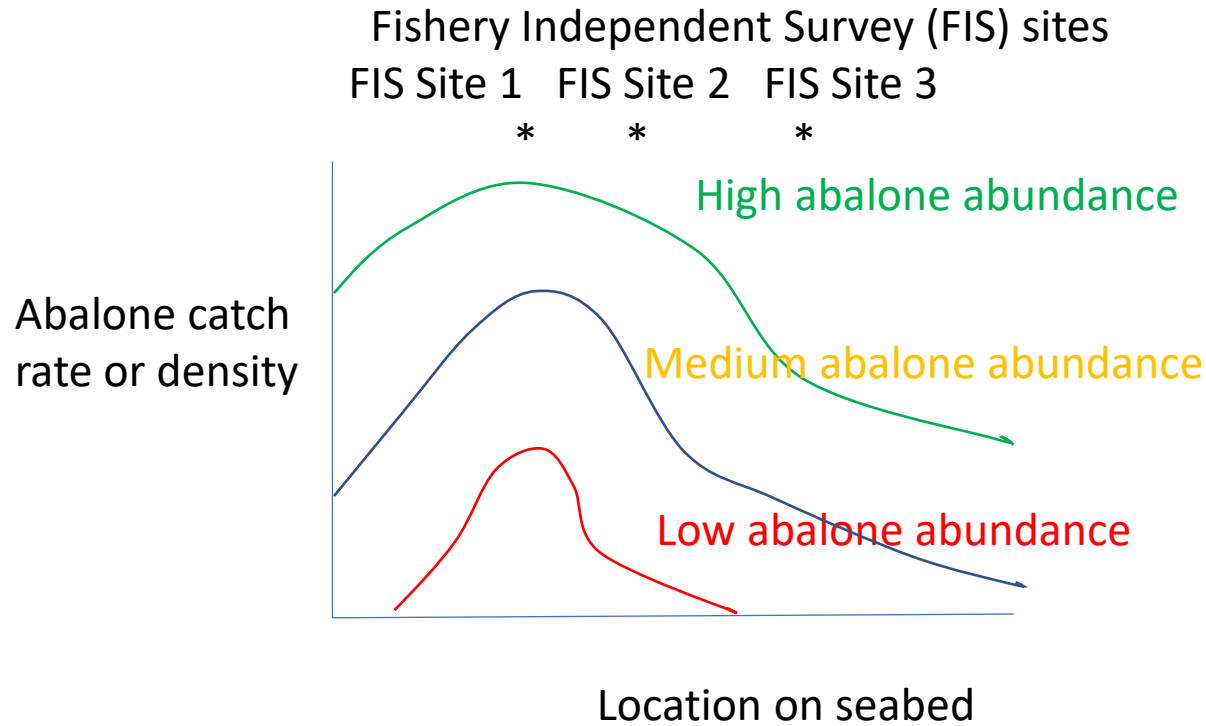
Abalone abundance

At high abundance abalone density is greatest in areas of high local productivity

As population decreases abalone decrease in proportion to local productivity

The change in local density from FIS or fishery need not follow the population trend

- FIS sites can give bias above or below total population trends
- Fishery can follow the high density areas and show positive bias

Combining fishery independent and fishery dependent approaches

- Calibrate the GPS logger density with the FIS density
  - For main categories of abalone density and habitat complexity
  - ➤ for a given GPS logger density what is the expected FIS density ?

- Calibration requires specific sampling of both methods for similar areas and times

- Commercial fishing at FIS calibration sites should record
  - Catch weight, number and effort by bag lift
  - GPS logger data by bag lifts, recording individual weight, length and number of catch

- Fishery independent fishing at FIS calibration sites should record
  - the area searched and abalone numbers and length

- There is need to be clear on
  - how close to a FIS site the commercial fishing must be
  - how similar the density of abalone or the seabed habitat must be between the commercially fished and the FIS site

- This calibration need only be done occasionally, and not all the time or all at the same time

Calibration of FIS and GPS logger densities

- Should this calibration be done?

- How many calibration comparisons?
  - Represent the densities, seabed complexity, other issues
  - 10-20 comparisons?

- Where should the calibration sites be?
  - VFA FIS, WADA FIS sites?
  - What SMUs and reef codes?
  - See sites for VFA FIS and WADA April 2022 Strategic Plan

- When should calibration be done?
  - FRDC has already agreed on Sept-Dec 2022
  - 2022, 2023, combination?

Commercial fishing

FIS site