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ESTIMATING SPECIES-SPECIFIC CATCH RATES IN A MIXED-SPECIES DIVE FISHERY

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ABSTRACT Catch-per-unit-effort (CPUE) is frequently used as a measure of relative abundance in fisheries stock assessment. Determining reliable estimates of species-specific CPUE is more challenging in multispecies, rather than single-species, fisheries because identification of appropriate effort data for each species is often difficult. Divers in the South Australian abalone fishery can harvest blacklip (*Haliotis rubra*) and greenlip (*Haliotis laevigata*) abalone simultaneously, but report only a single value for daily fishing effort. This is problematic because total allowable commercial catches are set for each species following species-specific stock assessments in which CPUE is a key index of relative abalone abundance. To provide an evidence-based approach to the identification of the most appropriate CPUE estimation method for ongoing assessment of the fishery, we assessed six diverse CPUE estimation methods for estimating annual, species-specific CPUEs using 30 y of data. The candidate CPUE estimation methods yielded relative CPUE time series with similar temporal trends throughout the 30-y period. These relative CPUE estimates each had low coefficients of variation and were highly correlated with one another, requiring consideration of other factors to determine a preferred method. Using a catch-weighted estimate of CPUE ($CPUE_{Wt}$) overcomes many of the problems associated with using the other five methods tested. Specifically, $CPUE_{Wt}$ (1) weights each daily catch and effort objectively; (2) removes the need to ''subset'' the data subjectively, which ensures that data availability and representation are not reduced by arbitrary rules; and (3) is relatively simple to explain to stakeholders and can be applied consistently to greenlip and blacklip abalone at multiple spatial scales across the fishery. Although the requirement to estimate species-specific catch rates in mixed-species dive fisheries is rare, our analyses demonstrate that $CPUE_{Wt}$ could provide a robust measure of species-specific CPUEs across other diverse multispecies fisheries.

KEY WORDS: CPUE, abalone, fishery assessment, spatial management

INTRODUCTION

The difficulty and expense associated with managing fisheries primarily on the basis of fishery-independent data has resulted in many stock assessments relying predominantly on indirect measures of abundance, such as the size or age frequency of the catch and catch-per-unit-effort (CPUE) (Quinn & Deriso 1999, Bordalo-Machado 2006). CPUE, derived from commercial logbook data, is the most commonly used abundance index because it is generally the cheapest and easiest to obtain (Maunder & Punt 2004, Cotter & Pilling 2007). The shortcomings of CPUE as a relative index of abundance are well documented (Cooke & Beddington 1984, Richards & Schnute 1986, Harley et al. 2001, Walters 2003, Kleiber & Maunder 2008), including in abalone fisheries (e.g., Breen 1992, Officer et al. 2001). However, this measure remains in widespread use for stock assessment because it is a primary data source that, when assessed in context with complementary data, can provide a meaningful measure of stock status (Dowling et al. 2008, Smith et al. 2010, Tarbath & Gardner 2010).

Despite recent moves toward whole ecosystem management, most fish stocks are managed on an individual basis (Pitcher et al. 2009). For single-species fisheries, estimating CPUE is straightforward when catch and effort are known (Low 1976, Schnute 1985), although several different methods have been proposed (Petrere Jr. et al. 2010). In multispecies fisheries, especially those where harvesting is undertaken by nonselective fishing gear, a common difficulty is the identification of an appropriate subset of catch and effort records to estimate species-specific CPUE (Westrheim 1983, Biseau 1998, Stephens & MacCall 2004, Lauridsen et al. 2008).

Dive fisheries, in contrast, are highly selective, and typically target inshore invertebrate species (Ye et al. 2005, Miller & Nolan 2008) with fine-scale population structures (Swearer et al. 2002, Orensanz et al. 2005), termed ''metapopulations'' (Morgan & Shepherd 2006). These metapopulations frequently exhibit a high variability in biology and morphology (Saunders et al. 2008, Saunders et al. 2009). Abalone (Family: Haliotidae) are a good example because rates of growth, maximum length, fecundity, size at sexual maturity, recruitment, and genetic structure all vary at spatial scales from several hundred meters to a few kilometers (Shepherd & Hearn 1983, McShane et al. 1988, Worthington et al. 1995, Prince 2003, Prince 2005, Saunders & Mayfield 2008, Miller et al. 2009). Increasing spatial management to overcome biological differences among metapopulations requires information on stock status at relevant spatial scales that, in part, has been made possible through development of new approaches (Prince et al. 2008, Saunders et al. 2008, Saunders et al. 2009). Nevertheless, assessment and management of these stocks remain challenging, especially in multispecies fisheries. Mixed-species dive fisheries include those for lobster and conch (Béné & Tewfik 2001), scallop (Basurto 2006), sea cucumber (Kinch 2002, Uthicke & Conand 2005), and abalone (Hart et al. 2009, Tarbath & Gardner 2010, Mayfield et al. 2011). For most of these fisheries, species-specific CPUE is either not estimated (Béné & Tewfik 2001, Basurto 2006, Kinch 2002, Uthicke & Conand 2005) or is estimated only for that species comprising the highest proportion of the total allowable commercial catch (TACC) (Hart et al. 2009, Tarbath & Gardner 2010).

Divers in the South Australian abalone fishery harvest blacklip (*Haliotis rubra* Leach 1814) and greenlip abalone (*Haliotis*

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laevigata Donovan 1808). Existing regulations permit simultaneous harvest of both species, but require fishers to provide only a single measure of daily fishing effort (Chick et al. 2009). This makes estimation of species-specific CPUE difficult. However, these measures need to be calculated because each species has a separate TACC, which is reviewed annually following species-specific stock assessments (e.g., Chick et al. 2009, Stobart et al. 2010, Mayfield et al. 2011), for which CPUE is used as a primary measure of relative abalone abundance. This approach is consistent with that in Tasmania (Tarbath & Gardner 2010), Victoria (Gorfine et al. 2002), and western Australia (Hart et al. 2009). CPUE is also a key performance indicator in the existing management plan for the fishery (Nobes et al. 2004). Although that management plan is currently under review, CPUE is being retained as an indicator of fishery performance. As in other abalone fisheries (e.g., Prince et al. 2008), scales of assessment are being reduced to that of individual metapopulations.

The objective of this study was to evaluate the performance of six species-specific CPUE estimation methods, including the method currently used, so that the most appropriate method for ongoing assessment of the fishery could be identified. Although this study focused on the western zone of the fishery, where daily catches of both greenlip and blacklip abalone occur most commonly, the outcomes are of direct benefit to the broader South Australian abalone fishery and to mixed-species fisheries elsewhere.

METHODS

Description of the Fishery

The South Australian abalone fishery began in the early 1960s, with management arrangements evolving since its inception (Nobes et al. 2004). Fishers dive using a surface-supplied breathing apparatus from trailing vessels, and remove abalone from the reef using an "abalone iron." In 1971, the fishery was subdivided into three zones: western, central, and southern. This study focused on the western zone. The fishing season for the western zone extends from January 1 to December 31. The western zone is geographically extensive (129° E to 136°30′ E) and was subdivided into regions A (133°50.8′ E to 136°30′E; Fig. 1) and B (129° E to 133°50.8′ E) in 1985. Region A of the western zone is subdivided into 18 fishing areas (FAs; numbered 3–20; Fig. 1). Each FA is further subdivided into a series of map codes (e.g., 9A, 18F), which are the spatial scale at which commercial catch and effort data are recorded. Total catches from region B are small and were not included in this study.

Annual TACCs were introduced to region A from 1985. In 2009, the TACCs for greenlip abalone (hereafter termed "greenlip") and blacklip abalone (hereafter termed "blacklip") were 227 t and 293 t (whole weight), respectively. Catches of both species are usually shucked (separation of the abalone meat from the shell and viscera) at sea so quotas are issued in meat weight. The minimum legal sizes for greenlip and blacklip are 145 mm and 130 mm in shell length, respectively. There are 23 license holders in the western zone.

Greenlip and blacklip catches are not evenly distributed among the FAs comprising region A. FAs can be classified into 1 of 4 categories (Fig. 1): (1) low-catch FAs (3, 7, 10, 15, 16, 17, and 20), which collectively comprised less than 10% of the total catch from 2005 to 2009; (2) blacklip FAs (4, 6, 11, 12, and 13), where catches are dominated (>70%) by blacklip; (3) greenlip FAs (18 and 19), where catches are dominated (>70%) by greenlip; and (4) mixed-catch FAs (5, 8, 9, and 14), where catches are not dominated (<70%) by either species.

Data Sources and Validation

Daily commercial logbook data from 1980 to 2009 were used to evaluate 6 candidate methods of estimating CPUE. The logbook includes information on the fishing license number, diver, date of fishing, fishing location (FA and map code), species-specific catch (i.e., weight of greenlip and blacklip harvested in kilograms), and total daily fishing effort (i.e., dive time in hours). Consistent with other similar studies (Worthington et al. 1998, Maunder & Punt 2004), a series of data validation rules were applied to the daily logbook data to reduce the influence of outliers and to ensure calculations were based on an appropriate data set. First, records with obvious data recording or entry errors (i.e., unrealistic catch, effort, and CPUE levels) were removed. Thus, daily records in which (1) total catch was more than 900 kg, (2) fishing effort was longer than 8 h, and (3) CPUE (total catch per total effort) was greater than 150 kg/h were excluded to account for the physical limits of vessels and divers. Second, records with less than 3 h of fishing effort were excluded because they likely represent incomplete fishing days (e.g., equipment failure). Last, records in which the reported catch of both species was 0 were omitted.

CPUE Estimation Methods

A time series of species-specific CPUEs for the western zone and each FA were estimated from the catch of each species and the total fishing effort using six CPUE estimation methods: the simple ratio estimator (CPUE_{SR}; Eq. 1 (Cochran 1977)), the extended (or bias-corrected) ratio estimator (CPUE_{ER}; Eq. 2 (Cochran 1977)), arithmetic mean of daily CPUE (CPUE_{AM}; Eq. 3), the geometric mean of daily CPUE (CPUE_{GM}; Eq. 4), the proportion CPUE ($\text{CPUE}_{\text{Prop}}$; Eq. 5), and the catch-weighted mean of daily CPUE (CPUE_{Wt}; Eq. 6).

Four of these CPUE estimation methods—simple ratio extended ratio, arithmetic mean, and geometric mean—were calculated from different subsets of the available data based on the percentage of greenlip and blacklip in the catch, to identify those records likely to inform best the species-specific catch rates. These subsets comprised those records: (1) with only greenlip or blacklip in the catch (termed "100%"), (2) when greenlip or blacklip comprised ≥75% of the total catch (termed "75%"), and (3) when greenlip or blacklip comprised ≥50% of the total catch (termed "50%"), which is the method currently used for western zone assessments. CPUE_{Wt} and $\text{CPUE}_{\text{Prop}}$ were calculated from all daily records when the catch of that species was greater than 0 kg (termed "All").

With the $\text{CPUE}_{\text{Prop}}$ method, the fishing effort was allocated between the two harvested species in proportion to their contribution to total catch, and the resulting CPUE was calculated using the simple ratio estimator. This method assumes (or implies) that the catch rates for both species are identical. For CPUE_{Wt}, the percentages of each species in the catch for each daily record were used as weighting factors in an arithmetic mean (Kutner et al. 2005), and was similar to the approach used by Pons and Domingo (2009). Thus, for a day when 300 kg blacklip and 200 kg greenlip were harvested, the weightings would be 0.6 and 0.4 for blacklip and greenlip, respectively.

The formulae for estimating CPUE, from species-specific catch (C_{Si}), effort (E_i), and total catch (C_{Ti}) from the i^{th} record from the n daily fishing records were

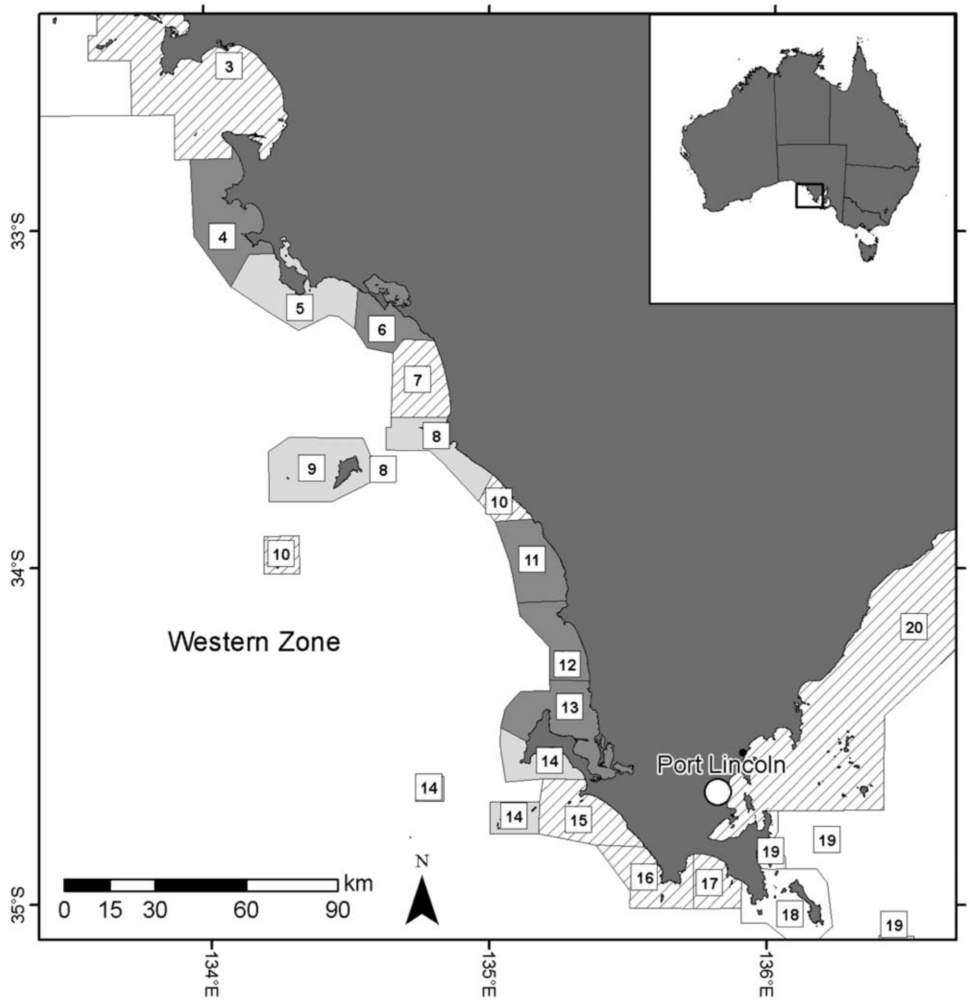

Figure 1. Map showing the western zone of the South Australian abalone fishery. Fishing areas (FAs) are categorized based on the mean catch of each species between 2005 and 2009: low-catch FAs (collectively, less than 10% of the total catch from 2005 to 2009, hashed shading), blacklip FAs (catches are dominated (>70%) by blacklip, dark-gray shading), greenlip FAs (catches are dominated (>70%) by greenlip, no shading), and mixed-catch FAs (catches are not dominated (<70%) by either species, light-gray shading).

$$\mathrm{CPUE_{SR}} = \frac{\sum_{i=1}^{n} C_{Si}}{\sum_{i=1}^{n} E_i} \tag{1}$$

$$\mathrm{CPUE_{ER}} = \frac{\overline{C}_S}{\overline{E}} + \left(\frac{1}{\overline{E}^2}\frac{\overline{C}_S}{\overline{E}}\sigma_E^2 - \mathrm{cov}(E, C_S)\sigma_E\right) \tag{2}$$

where $\bar{C}_S$ and $\bar{E}$ are mean daily species-specific catch and total effort, respectively; σ_E is the standard deviation of the effort E; and $cov(E,C_S)$ is the covariance of E_i and C_{Si}.

$$\mathrm{CPUE_{AM}} = \frac{1}{n}\left(\sum_{i=1}^{n} \frac{C_{Si}}{E_i}\right) \tag{3}$$

$$\mathrm{CPUE_{GM}} = \exp\left(\frac{1}{n}\sum_{i=1}^{n} \ln\frac{C_{Si}}{E_i}\right) \tag{4}$$

$$\mathrm{CPUE_{Prop}} = \frac{\sum_{i=1}^{n} C_{Si}}{\sum_{i=1}^{n} E_i \frac{C_{Si}}{C_{Ti}}} \tag{5}$$

$$\mathrm{CPUE_{Wt}} = \frac{\sum_{i=1}^{n} wi \frac{C_{Si}}{E_i}}{\sum_{i=1}^{n} wi}, \tag{6}$$

where w_i is the weight of the proportion of each species in the total catch.

Although all computations were undertaken, results presented are constrained to both species for the western zone (all estimation methods) and 10 FAs ($\mathrm{CPUE_{ER}}$ 50%, $\mathrm{CPUE_{GM}}$ 50%, and $\mathrm{CPUE_{Wt}}$). CPUE time series are shown relative to the first year of the study (1980) to permit their direct comparison. Limited data (i.e., $n < 10$ daily records (Fox & Starr 1996, Chernick 2008)) prevented estimation of CPUE in some years in some FAs. All calculations were undertaken using the statistical programming environment R 2.11.1.

Comparison Among Estimation Methods

The six candidate estimation methods were compared using two approaches. First, relationships among candidate CPUE estimation methods were evaluated across the western zone and

FAs using Pearson correlations. Second, rates of change during recent periods of increasing and decreasing CPUE in the western zone were compared among CPUEs using analysis of covariance (ANCOVA). For blacklip, these periods were 1999 to 2006 (increasing) and 2006 to 2009 (decreasing); for greenlip, they were 1999 to 2003 (increasing) and 2003 to 2009 (decreasing). Heterogeneity was assessed using residual plots, and α was set at 0.05 in all cases.

The precision of CPUE estimates among CPUE_{ER} (50%), CPUE_{GM} (50%), and CPUE_{Wt} for each FA was compared using coefficients of variation (CV) obtained from 10,000 bootstrap iterations applying the percentile method (Efron & Tibshirani 1993). The CVs are presented using notched box-and-whisker plots, in which nonoverlapping notches provide strong evidence of a difference between the two medians (McGill et al. 1978).

For each FA, we also determined the number of years in which CPUE_{ER} (50%), CPUE_{GM} (50%), and CPUE_{Wt} were estimable (i.e., $n \geq 10$ daily records), and the mean number of annual daily records from which these measures were determined.

RESULTS

Data Validation

After data validation, 10.5% of total daily records were excluded from the analyses. The majority (8.9%) were omitted by the restriction on effort. CPUE and catch restrictions removed 1.8% and 0.8% of records, respectively (Fig. 2). Some records were excluded by more than one of the constraints applied.

Whole Western Zone

Estimates of CPUE on greenlip and blacklip in the western zone showed few differences in yearly temporal trend among methods throughout the 30-y period from 1980 to 2009 (Fig. 3A, B). CPUE_{Wt} had the highest relative values in most years for blacklip, whereas CPUE_{ER} (100%) had the lowest relative values. For greenlip, although there was more overlap among CPUE estimation methods, since the mid 1990s $\text{CPUE}_{\text{Prop}}$ generally had the highest, and CPUE_{Wt} the lowest, relative values. Median CVs were low (~0.015) and similar for both species for most estimation methods. The exception was CPUE_{ER} (100%), when they were about twice as large: ~0.033 for blacklip and ~0.038 for greenlip.

For blacklip, CPUE was stable between 1980 and 1988, and from 1991 to 1999. Increases to local maxima occurred from 1988 to 1991 and between 1999 and 2006. For all CPUE estimation methods, CPUE declined rapidly between 2006 and 2009. The 8 CPUE series were highly and positively correlated with one another ($r > 0.95$) with the exception of CPUE_{ER} (100%), which had the lowest correlation with the remaining series at between 0.78 and 0.89 (Table 1). Recent rates of increasing (1999 to 2006) and decreasing (2006 to 2009) CPUE did not vary significantly among estimation methods (ANCOVA, $P = 0.869$ and $P = 0.978$, respectively).

Similar results were evident for greenlip where, for all estimation methods, CPUE was variable between 1980 and 1990, increased rapidly from 1999 to 2003, and declined sharply again thereafter. Annual estimates of CPUE from the different methods were also highly correlated with one another ($r > 0.95$), with CPUE_{ER} (100%) again the least correlated with the other CPUE estimates (range, 0.84–0.89; Table 1). Rates of change during recent years did not differ significantly among methods (ANCOVA, 1999 to 2003, $P = 0.462$; ANCOVA, 2003 to 2009, $P = 0.905$).

The proportion of available records for estimating CPUE was similar for both species and declined from 1, when all daily records were used, to ~58% of available daily records when greenlip or blacklip were required to comprise ≥50% of the total catch (Fig. 3C). When the percentage of greenlip or blacklip in the catch was required to exceed 75% or to be 100%, the proportion of daily records available for estimating CPUE was reduced to ~40% and ~15%, respectively.

Individual Fishing Areas

Results obtained for the individual FAs broadly reflect those observed for the entire western zone. Overall, the yearly temporal trends in CPUE showed few differences among methods throughout the 30-y period from 1980 to 2009 (Figs. 4 and 5), which was also reflected in the high, positive correlations among CPUE estimation methods (Table 2).

Blacklip

Blacklip were the dominant species harvested from FAs 4, 11, 12, and 13. In FAs 11 and 12, the relative values from the 3 CPUE estimation methods were almost identical (Fig. 4) and, consequently, highly correlated with one another ($r > 0.98$). Relative values in FAs 4 and 13 differed among estimation methods. In both FAs, CPUE_{Wt} was generally higher than estimates from the other methods. Despite these differences, and the correlations among methods being slightly lower than those in FAs 11 and 12 (range, 0.96–0.99; Table 2), the temporal patterns were consistent (Fig. 4). For all 4 blacklip FAs, there were sufficient data to estimate CPUE in all years for both CPUE_{Wt} and when blacklip were required to comprise ≥50% of the total catch (i.e., CPUE_{ER} (50%), CPUE_{GM} (50%); Fig. 4). However, the mean number of annual daily records for the latter was typically 20% fewer (range, 3–25%) than for the former.

Temporal patterns in the relative values of blacklip CPUE were also similar, among methods in those FAs from which greenlip and blacklip were harvested in approximately equal quantities (i.e., mixed FAs; Fig. 4). Thus, in FAs 5, 8, 9, and 14, the 3 CPUE estimation methods were strongly correlated with each other (range, 0.86–0.99; Table 2), despite CPUE_{Wt} providing estimates generally higher than those from the other methods. There were sufficient data to estimate CPUE_{ER} (50%), CPUE_{GM} (50%), and CPUE_{Wt} in all years in FAs 5 and 8 (Fig. 4). However, although data were adequate to estimate CPUE_{Wt} in all years in FAs 9 and 14, CPUE_{ER} (50%) and CPUE_{GM} (50%) were only estimable in 90% and 97% of years, respectively. Notably, in these 4 mixed FAs, the mean number of annual daily records for estimating CPUE_{Wt} was usually double (range, 40–63%; Fig. 4) that available for estimating CPUE_{ER} (50%) and CPUE_{GM} (50%).

In the 2 FAs where blacklip catches were small (i.e., FAs 15 and 18), it was still possible to estimate the CPUE on blacklip using all three methods in most years (Fig. 4). There were, however, two noticeable differences from the other FAs. First, interannual variation in CPUE_{Wt} was considerably greater than that observed for CPUE_{ER} (50%) and CPUE_{GM} (50%). This also resulted in the correlations among methods being considerably lower than in the blacklip or mixed FAs (range, 0.75–0.98; Table 2). Second, the mean number of annual daily records for

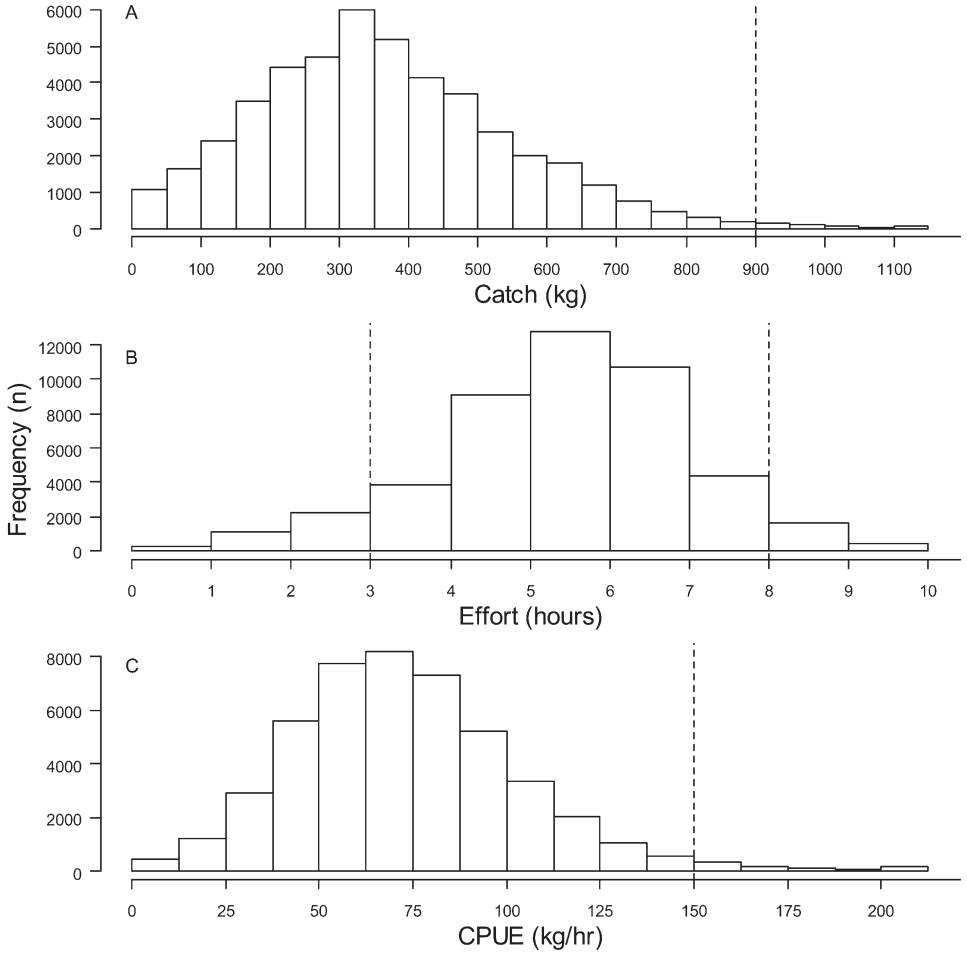

Figure 2. (A–C) Histograms of daily total catch (A), effort (B) and CPUE (C) from commercial logbooks between 1980 and 2009. Catches greater than 1,100 kg, effort longer than 10 h, and CPUE greater than 200 kg/h were aggregated.

estimating CPUE_{ER} (50%) and CPUE_{GM} (50%) was typically 70% fewer (range, 63–75%) than for estimating CPUE_{Wt} (Fig. 4).

The medians of the annual CVs for CPUE_{ER} (50%), CPUE_{GM} (50%), and CPUE_{Wt} in the blacklip and mixed FAs, obtained from the 10,000 bootstrap iterations, were not significantly different (Fig. 6).

Greenlip

The FAs within which greenlip dominate the catch were FAs 18 and 19. In FA 18, relative values from the 3 CPUE estimation methods were very similar (Fig. 5) and, consequently, were highly correlated ($r > 0.98$; Table 2). Relative CPUE values in FA 19 differed among estimation methods, with CPUE_{GM} generally higher than estimates from the others considered (Fig. 5). Nevertheless, the correlations among methods remained high ($r > 0.98$; Table 2) as the temporal patterns were consistent (Fig. 5). For both greenlip FAs, there were sufficient data to estimate CPUE in all years for both CPUE_{Wt} and when greenlip were required to comprise ≥50% of the total catch (i.e., CPUE_{ER} (50%), CPUE_{GM} (50%); Fig. 5). However, the mean number of annual daily records for estimating CPUE_{Wt} was ~15% greater (range, 10–18%) than those available for estimating CPUE_{ER} (50%) and CPUE_{GM} (50%).

For the mixed FAs, temporal patterns in the relative values of greenlip CPUE were also similar among methods (Fig. 5). Thus, the 3 CPUE estimation methods in FAs 5, 8, 9, and 14 were strongly correlated with each other (range, 0.78–0.99; Table 2), despite CPUE_{GM} providing estimates generally higher than those from the other methods. There were sufficient data to estimate CPUE_{ER} (50%), CPUE_{GM} (50%), and CPUE_{Wt} in all years in all mixed FAs (Fig. 5). Nevertheless, the mean number of annual daily records for estimating CPUE_{Wt} in these 4 mixed FAs was ~40% greater (range, 30–54%; Fig. 5) than that available for estimating either CPUE_{ER} (50%) or CPUE_{GM} (50%).

Although it was still possible to estimate the CPUE on greenlip using all three methods in the four FAs where greenlip catches were small (i.e., FAs 4, 13, 15, and 16; Fig. 5), in FAs 13 and 15, CPUE_{ER} (50%) and CPUE_{GM} (50%) were only estimable in 53% and 70% of years, respectively. Furthermore, the mean number of annual daily records for estimating CPUE_{ER} (50%) and CPUE_{GM} (50%) was approximately half that available for estimating CPUE_{Wt} (range, 37–69%; Fig. 5). Despite this difficulty, the CPUE estimates in FA 4 were strongly correlated (Table 2).

As with blacklip, the medians of the annual CVs for CPUE_{ER} (50%), CPUE_{GM} (50%), and CPUE_{Wt} in the greenlip and mixed FAs were not significantly different (Fig. 6).

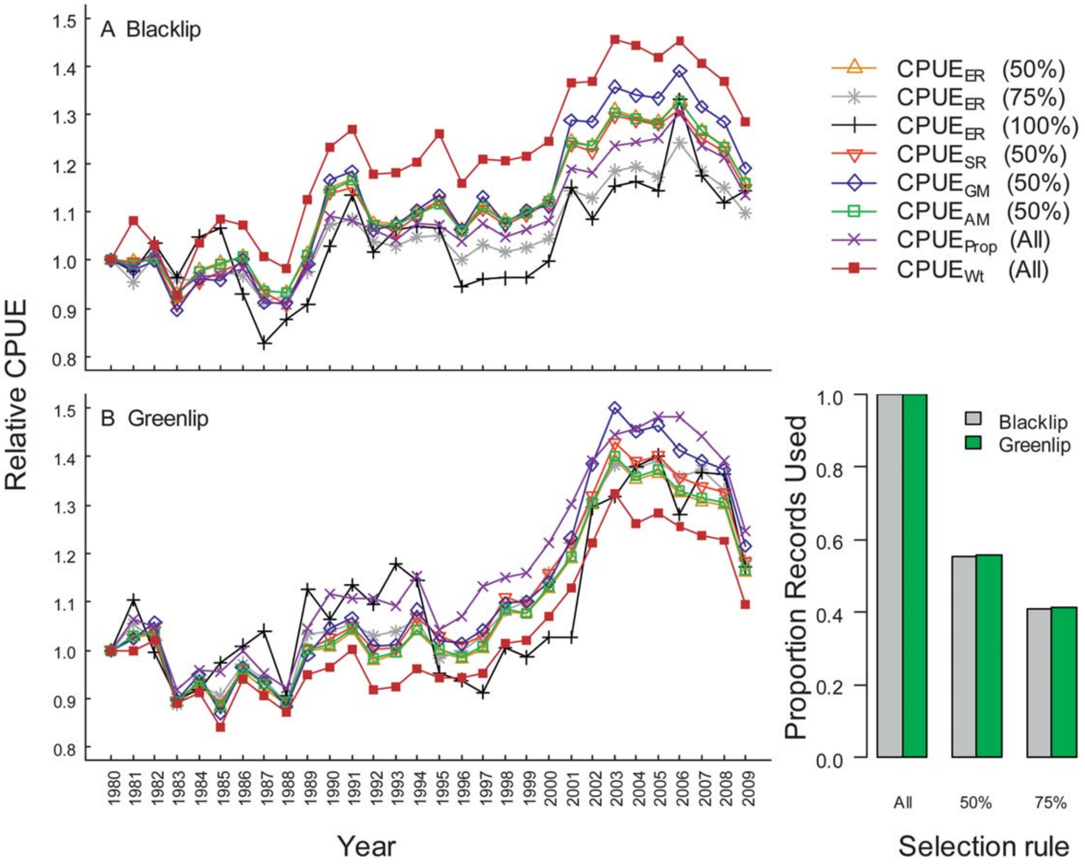

Figure 3. (A, B) Relative (to 1980) estimates of CPUE on blacklip (A) and greenlip (B) between 1980 and 2009 obtained from the 6 candidate CPUE estimation and data subset methods tested. (C) The proportion of total records retained by the data subset methods are also shown for each species.

DISCUSSION

This study compared candidate, species-specific CPUE estimation methods for assessing abalone stock status in the western zone of the South Australian fishery. This was to underpin an evidence-based approach to selection and implementation of a CPUE estimation method suitable for ongoing assessment of the fishery. These analyses were required because divers in the fishery harvest blacklip and greenlip simultaneously, but provide only a single measure of daily fishing effort. This complicates the estimation of species-specific CPUEs that are required for stock assessment of these species (Chick et al. 2009, Stobart et al. 2010, Mayfield et al. 2011) and for evaluation of the performance of the fishery against one of the key performance indicators in the fishery management plan (Nobes et al. 2004). This study also facilitates consideration of a CPUE estimation method that provides reliable CPUE measures at small spatial scales, which

TABLE 1.

Pearson correlations among relative, annual CPUE estimates obtained from the 6 candidate CPUE estimation and data subset methods tested across the Western Zone.

		Blacklip							
	Method	CPUE$_{ER}$ 50%	CPUE$_{ER}$ 75%	CPUE$_{ER}$ 100%	CPUE$_{SR}$ 50%	CPUE$_{GM}$ 50%	CPUE$_{AM}$ 50%	CPUE$_{Prop}$	CPUE$_{Wt}$
Greenlip	CPUE$_{ER}$ 50%	—	0.982	0.829	0.998	0.998	1.000	0.987	0.987
	CPUE$_{ER}$ 75%	0.993	—	0.888	0.978	0.982	0.982	0.990	0.949
	CPUE$_{ER}$ 100%	0.866	0.887	—	0.816	0.828	0.830	0.851	0.783
	CPUE$_{SR}$ 50%	0.999	0.993	0.856	—	0.996	0.998	0.987	0.986
	CPUE$_{GM}$ 50%	0.997	0.990	0.867	0.997	—	0.998	0.989	0.980
	CPUE$_{AM}$ 50%	1.000	0.993	0.866	0.999	0.998	—	0.987	0.986
	CPUE$_{Prop}$	0.981	0.991	0.860	0.986	0.984	0.982	—	0.964
	CPUE$_{Wt}$	0.992	0.980	0.844	0.988	0.988	0.993	0.959	—

Values in the upper right triangle represent blacklip; those in the lower left triangle represent greenlip.

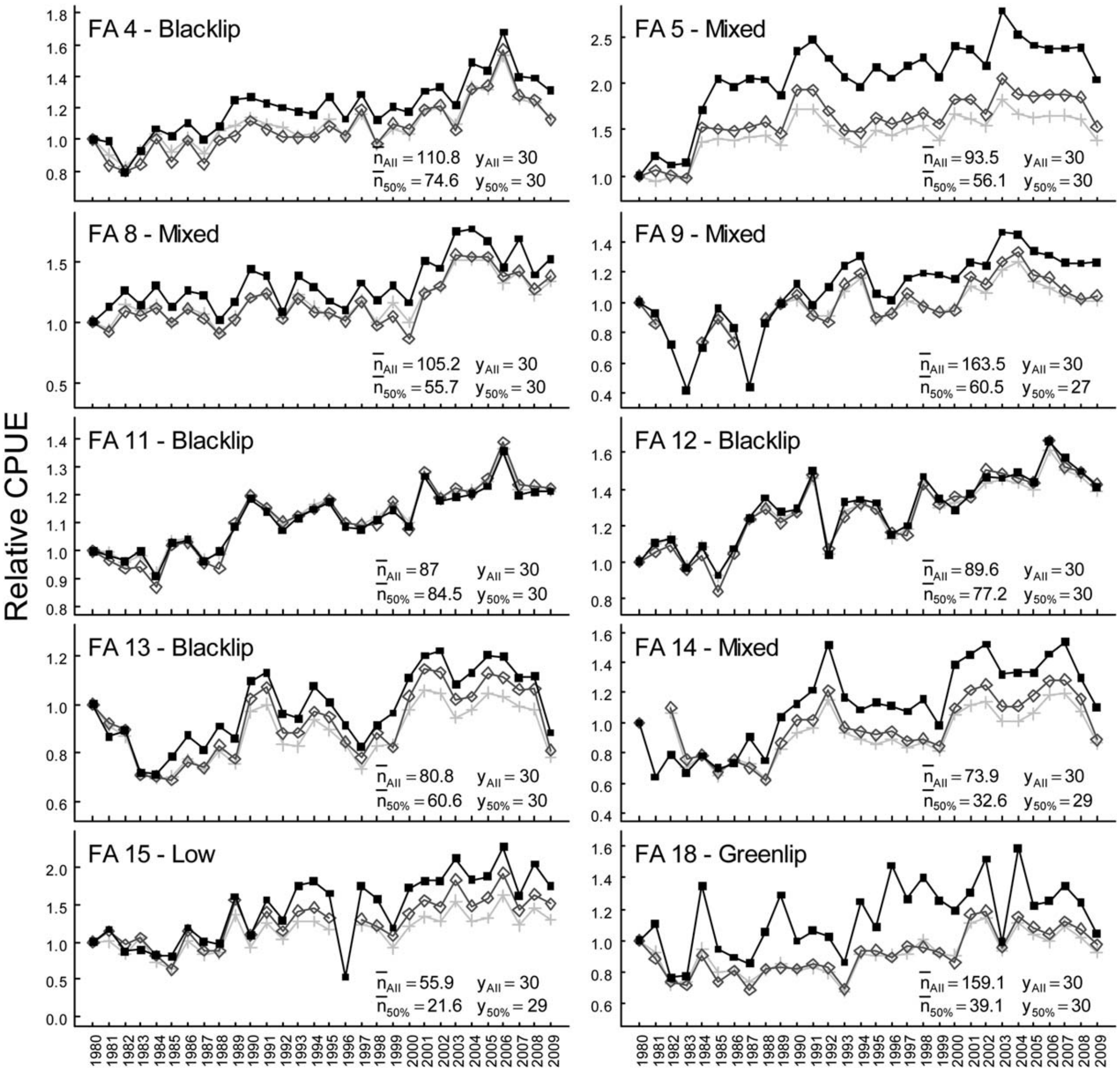

Figure 4. Estimated CPUE on blacklip in selected fishing areas (FAs) between 1980 and 2009. CPUE$_{ER}$ (50%, light-gray line and cross) and CPUE$_{GM}$ (50%, dark-gray line and open diamonds) were derived from daily records in which blacklip comprised ≥50% of the total catch. $\bar{n}_{50\%}$ and $y_{50\%}$ show the mean number of annual records and the number of years when there were sufficient data to estimate CPUE using the 50% data subset rule, respectively. CPUE$_{Wt}$ (All, black line and closed squares) was calculated from all daily records in which the catch of blacklip was more than 0 kg. $\bar{n}_{All}$ and y_{All} show the mean number of annual records and the number of years when there were sufficient data to estimate CPUE using the All data subset rule, respectively.

reflects the increasing trend toward finer scale assessment and management of these fisheries (Prince et al. 2008, Saunders & Mayfield 2008, Saunders et al. 2008, Saunders et al. 2009).

The 2 key strengths of our analyses were: (1) the use of 30 y of catch and effort data to compare among candidate CPUE methods at different spatial scales and (2) the selection of diverse CPUE estimation methods. The availability of 30 y of detailed fishery-dependent data, which included information on fishing location, species-specific catch, and fishing effort provided a substantial data set for undertaking these comparative analyses. More important, these data ensured that the comparisons could be made over an extended time period, which substantially reduces the likelihood of individual years strongly biasing the outcomes. Similarly, evaluating the CPUE methods across the western zone and within numerous FAs reduced the likelihood of spatial bias. The six CPUE estimation methods selected encompassed simple approaches such as CPUE$_{SR}$, which is widely used (Richards & Schnute 1992); those currently used for assessing abalone fisheries (i.e., CPUE$_{GM}$ (Tarbath & Gardner 2010) and CPUE$_{ER}$ (Chick et al. 2009)); and two novel methods: CPUE$_{Wt}$ and CPUE$_{Prop}$. An obvious approach that we excluded was generalized linear models (GLM), which, in other studies, have been used to standardize CPUE by accounting for the presence of other species (Glazer & Butterworth 2002, Tascheri et al. 2010). We did not use GLMs because (1) this approach has limited application at small spatial scales in which large data sets consistent across time and space are unavailable (Maunder & Punt 2004), such as individual FAs; and (2) CPUE standardizations

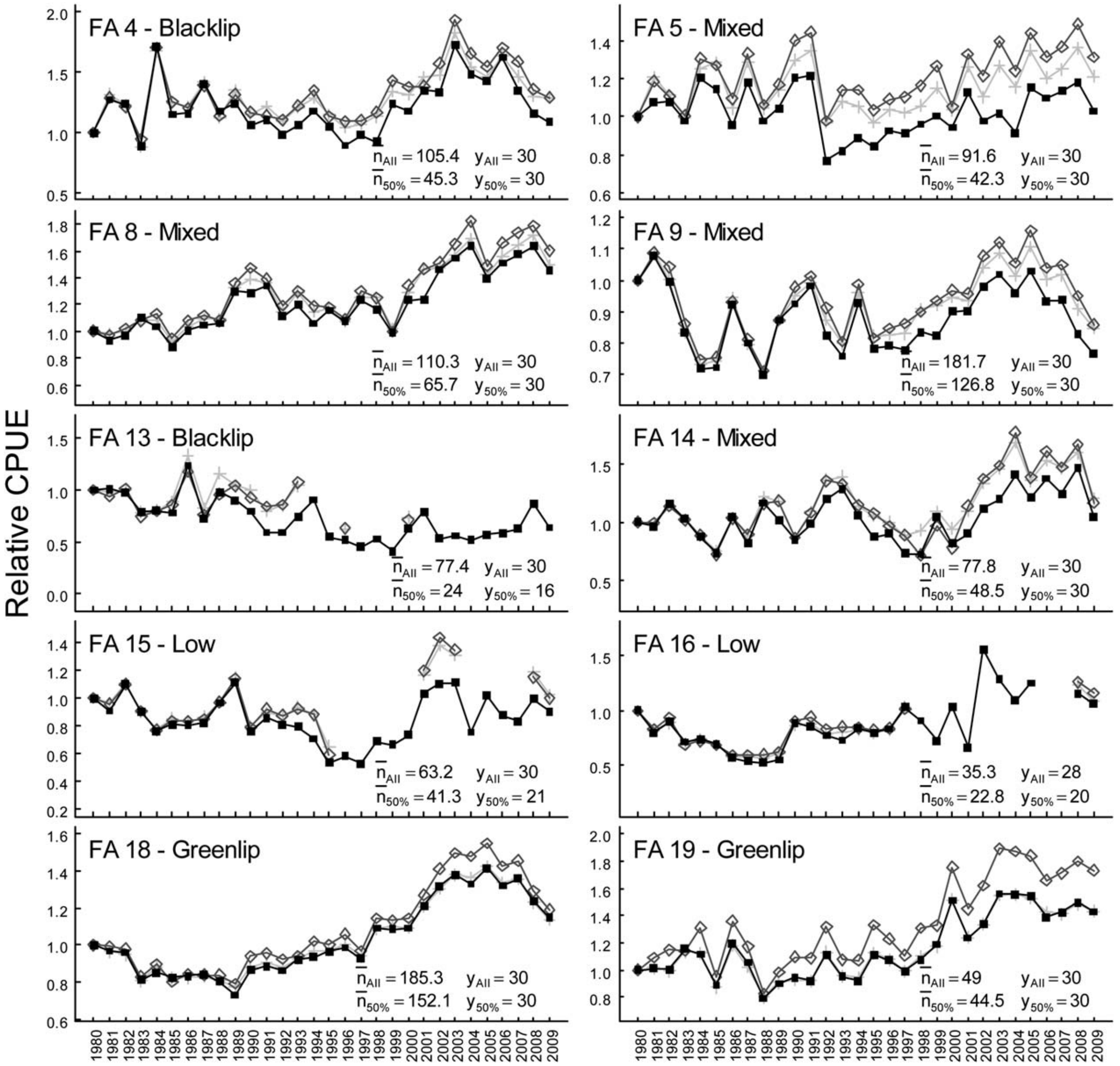

Figure 5. Estimated CPUE on greenlip in selected fishing areas (FAs) between 1980 and 2009. $CPUE_{ER}$ (50%, light gray line and cross) and $CPUE_{GM}$ (50%, dark gray line and open diamonds) were derived from daily records in which greenlip comprised ≥50% of the total catch. $\bar{n}_{50\%}$ and $y_{50\%}$ show the mean number of annual records and the number of years when there were sufficient data to estimate CPUE using the 50% data subset rule, respectively. $CPUE_{Wt}$ (All, black line and closed squares) was calculated from all daily records in which the catch of greenlip was greater than 0 kg. $\bar{n}_{All}$ and y_{All} show the mean number of annual records and the number of years when there were sufficient data to estimate CPUE using the All data subset rule, respectively.

in the Tasmanian abalone fishery did not differ substantially from $CPUE_{GM}$ (Tarbath & Gardner 2010).

Our main finding was that there were almost no differences in the relative, temporal trends in CPUE on greenlip and blacklip among methods across the western zone, and in individual FAs, throughout the 30-y period between 1980 and 2009. Thus, despite the magnitude of estimates varying among methods, relative CPUE estimates were highly correlated with one another. This was clearly evident by the lack of significant differences in the rates of change among CPUE estimation methods throughout recent periods of increasing and declining CPUE in the western zone.

The similarity in the temporal trends of all CPUE estimates makes selection of a CPUE estimation method for ongoing assessment of stock status in this fishery more challenging, and requires consideration of other information. For robustness, the method used to estimate CPUE should be (1) derived from appropriate data, (2) unbiased, (3) representative of the fishery and maximizing use of the available data, (4) a reliable index of relative abundance for each species, and (5) consistent and applicable to both species across the western zone and in each FA.

In this study, selection of appropriate data for estimating CPUE was undertaken using a series of validation rules applied to the daily logbook data. Although this approach was consistent with previous studies (Worthington et al. 1998, Maunder & Punt 2004), the catch, effort, and CPUE validation rules applied here led to the removal of more than 10% of the available data. Most of the data were excluded by the restriction on fishing effort that was designed to remove daily records in which fishing effort

TABLE 2.

Pearson correlations among relative, annual CPUE estimates obtained from $\mathrm{CPUE_{ER}}$ (50%, ER), $\mathrm{CPUE_{GM}}$ (50%, GM), and $\mathrm{CPUE_{Wt}}$ (Wt) for the fishing areas presented in Figure 4.

		Blacklip						
	FA 4	**$\mathrm{CPUE_{ER}}$ 50%**	**$\mathrm{CPUE_{GM}}$ 50%**	**$\mathrm{CPUE_{Wt}}$**	**FA 5**	**$\mathrm{CPUE_{ER}}$ 50%**	**$\mathrm{CPUE_{GM}}$ 50%**	**$\mathrm{CPUE_{Wt}}$**
Greenlip	$\mathrm{CPUE_{ER}}$ 50%	—	0.985	0.970	$\mathrm{CPUE_{ER}}$ 50%	—	0.992	0.976
	$\mathrm{CPUE_{GM}}$ 50%	0.978	—	0.961	$\mathrm{CPUE_{GM}}$ 50%	0.958	—	0.975
	$\mathrm{CPUE_{Wt}}$	0.957	0.927	—	$\mathrm{CPUE_{Wt}}$	0.868	0.779	—
	FA 8				**FA 9**			
	$\mathrm{CPUE_{ER}}$ 50%	—	0.981	0.970	$\mathrm{CPUE_{ER}}$ 50%	—	0.990	0.913
	$\mathrm{CPUE_{GM}}$ 50%	0.995	—	0.947	$\mathrm{CPUE_{GM}}$ 50%	0.991	—	0.909
	$\mathrm{CPUE_{Wt}}$	0.982	0.983	—	$\mathrm{CPUE_{Wt}}$	0.961	0.942	—
	FA 11				**FA 12**			
	$\mathrm{CPUE_{ER}}$ 50%	—	0.994	0.997	$\mathrm{CPUE_{ER}}$ 50%	—	0.992	0.996
	$\mathrm{CPUE_{GM}}$ 50%	—	—	0.990	$\mathrm{CPUE_{GM}}$ 50%	—	—	0.984
	$\mathrm{CPUE_{Wt}}$	—	—	—	$\mathrm{CPUE_{Wt}}$	—	—	—
	FA 13				**FA 14**			
	$\mathrm{CPUE_{ER}}$ 50%	—	0.988	0.951	$\mathrm{CPUE_{ER}}$ 50%	—	0.990	0.864
	$\mathrm{CPUE_{GM}}$ 50%	0.933	—	0.964	$\mathrm{CPUE_{GM}}$ 50%	0.979	—	0.885
	$\mathrm{CPUE_{Wt}}$	0.863	0.773	—	$\mathrm{CPUE_{Wt}}$	0.940	0.932	—
	FA 15				**FA 16**			
	$\mathrm{CPUE_{ER}}$ 50%	—	0.983	0.950	$\mathrm{CPUE_{ER}}$ 50%	—	—	—
	$\mathrm{CPUE_{GM}}$ 50%	0.994	—	0.954	$\mathrm{CPUE_{GM}}$ 50%	0.990	—	—
	$\mathrm{CPUE_{Wt}}$	0.904	0.904	—	$\mathrm{CPUE_{Wt}}$	0.985	0.971	—
	FA 18				**FA 19**			
	$\mathrm{CPUE_{ER}}$ 50%	—	0.974	0.804	$\mathrm{CPUE_{ER}}$ 50%	—	—	—
	$\mathrm{CPUE_{GM}}$ 50%	0.997	—	0.754	$\mathrm{CPUE_{GM}}$ 50%	0.987	—	—
	$\mathrm{CPUE_{Wt}}$	0.997	0.993	—	$\mathrm{CPUE_{Wt}}$	0.998	0.984	—

Values in the upper right triangles (dark gray shading) represent blacklip; those in the lower left triangles (unshaded) represent greenlip.

either exceeded that reasonably expected from diving decompression schedules or was considered to represent incomplete fishing days caused by equipment failure or unpredicted weather changes resulting in a cessation of fishing. The high proportion of daily records removed by these effort restrictions could be reduced by reviewing the decision rules applied. For example, if daily records in which fishing effort ranged between 2 h and 9 h (as opposed to between 3 h and 8 h), then less than 5% of the daily records would be eliminated. Decisions regarding future implementation of data validation rules should be well informed through direct conversations with relevant stakeholders in the fishery (i.e., divers, license holders, managers, and researchers).

It is also important that any CPUE estimation method is not known to be biased. $\mathrm{CPUE_{AM}}$, $\mathrm{CPUE_{GM}}$, and $\mathrm{CPUE_{SR}}$ have each been shown to provide biased CPUE estimates. For example, previous studies have shown $\mathrm{CPUE_{AM}}$ and $\mathrm{CPUE_{SR}}$ are biased when the underlying data are not normally distributed (Cochran 1977, Pennington 1996, Walters 2003). For $\mathrm{CPUE_{SR}}$, the bias-corrected version is $\mathrm{CPUE_{ER}}$ (Cochran 1977). Similarly, lognormal-based estimators, including $\mathrm{CPUE_{GM}}$, are biased when the data are not distributed in a lognormal manner (Myers & Pepin 1990, Longford 2009). Our observation that $\mathrm{CPUE_{AM}}$, $\mathrm{CPUE_{GM}}$, and $\mathrm{CPUE_{SR}}$ did not provide biased estimates of CPUE in our analyses may be a result of the exclusion of a large number of daily records that eliminated skew and kurtosis from the CPUE distributions. Nevertheless, planned reductions in the spatial scale of assessment in this fishery to those of individual metapopulations will likely result in fewer skewed data for calculating CPUE. Under these circumstances, $\mathrm{CPUE_{AM}}$, $\mathrm{CPUE_{GM}}$, and $\mathrm{CPUE_{SR}}$ may not provide unbiased CPUE estimates.

Data processing can also cause bias in CPUE estimates (Quirijns et al. 2008). For example, in calculating $\mathrm{CPUE_{Prop}}$, fishing effort was allocated between greenlip and blacklip in direct proportion to their contribution to total catch, which relies on the assumption that catch rates for both species are similar. Although this assumption is difficult to justify, because the catch rates are almost certainly different, there is little evidence to determine a more reasonable approach to apportion effort between the 2 species. This problem may be overcome through more complex analyses, possibly by using catch rates on single-species fishing days to inform relative species-specific catch rates for distributing fishing effort between the species. However, this relies on a range of additional assumptions, including constant catch rates and fisher behavior across mixed- and single-species fishing days.

CPUE estimates can also be influenced by data selection and data quality (Chen et al. 2003). In this study $\mathrm{CPUE_{ER}}$, $\mathrm{CPUE_{GM}}$, $\mathrm{CPUE_{SR}}$, and $\mathrm{CPUE_{AM}}$ were determined from 3 subsets of the available data based on the proportions of greenlip and blacklip in the catch (i.e., 100%, 75%, and 50%). These rules were applied to remove daily records that were considered inappropriate for use in calculating species-specific CPUEs. There are three obvious problems with this approach. First, application of the 100%, 75%, and 50% rules requires a subjective decision around which dataset to use (Westrheim 1983, Biseau 1998), and it complicates data selection, which increases the probability of process error. Second, increasing the data selection rule above 50% substantially diminished the number of

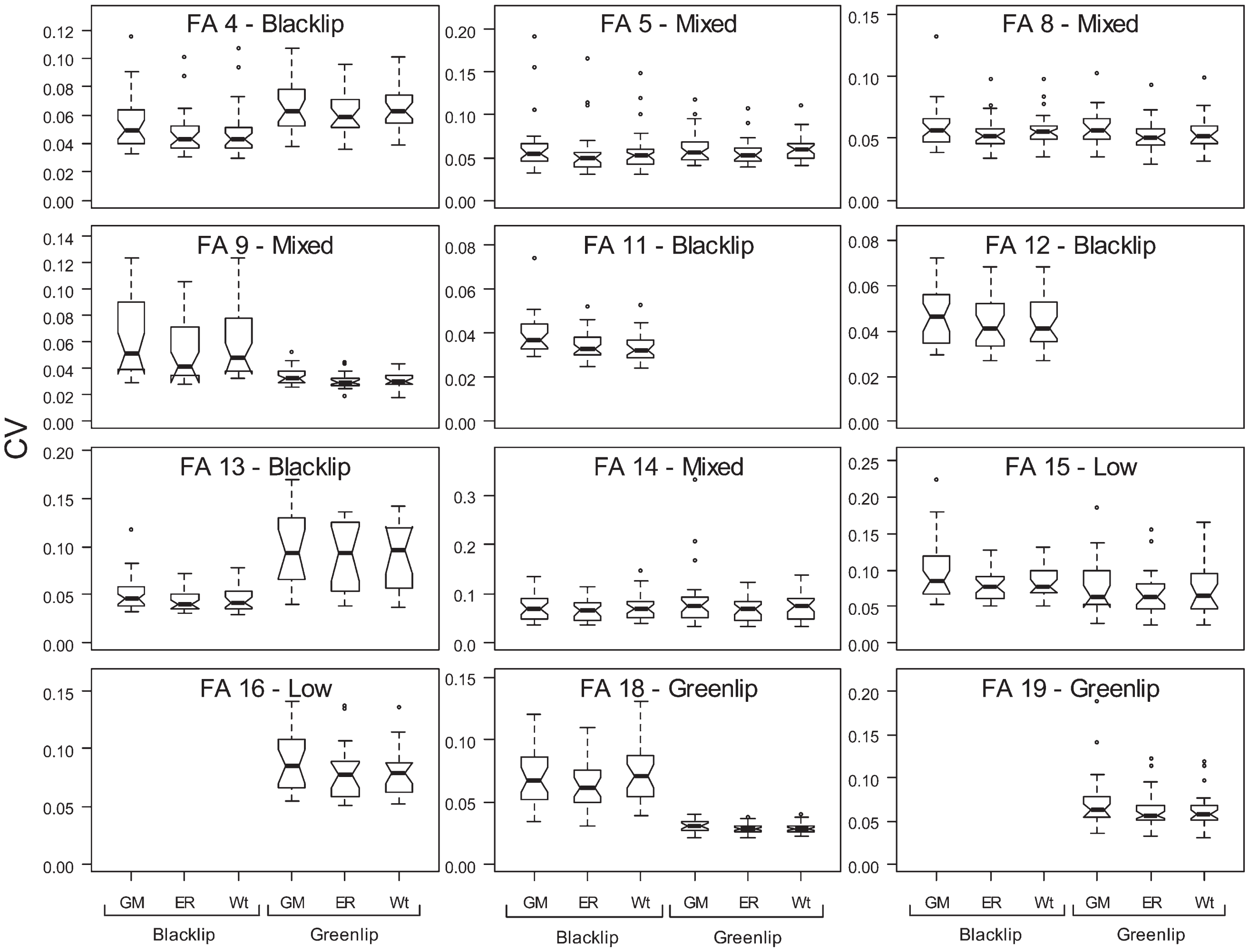

Figure 6. Notched box-and-whisker plots of annual CVs obtained from 10,000 bootstrap iterations for 3 CPUE estimation methods between 1980 and 2009. CVs for CPUE_{ER} (50%, ER) and CPUE_{GM} (50%, GM) were derived from daily records in which greenlip (or blacklip) comprised ≥50% of the total catch. The CVs for CPUE_{Wt} (Wt) were calculated from all daily records in which the catch of greenlip (or blacklip) was greater than 0 kg. Years when CPUE was not estimated for all series resulting from insufficient data were excluded.

daily records for estimating CPUE and, hence, the number of years in which adequate data are available. For example, in the western zone, the proportion of daily records for determining CPUE_{ER} (50%) was four times that for determining CPUE_{ER} (100%). This indicates that application of subjective data selection rules may result in CPUE being determined from data that do not adequately represent the catch or the fishery. Third, for the 75% and 50% subsets, these CPUE estimation methods weight each record equally. Thus, for example, daily records for which greenlip comprised 100%, 75%, or 50% of the total catch make an equal contribution to the estimate of CPUE_{ER} (50%) for greenlip. This biases these CPUE estimates downward, and future CPUE time series could be impacted by changes in fishing practices (e.g., one species preferentially targeted).

Many of the problems associated with using $\text{CPUE}_{\text{Prop}}$, CPUE_{ER}, CPUE_{GM}, CPUE_{SR}, and CPUE_{AM} to estimate CPUE in this fishery (described earlier), can be overcome by using CPUE_{Wt}. Perhaps most important, CPUE_{Wt} weights each daily catch and effort record objectively. Thus, days when greenlip dominate the catch have a larger influence on the estimate of greenlip CPUE when compared with days when either equal amounts of greenlip and blacklip are harvested, or blacklip dominates the catch. Use of CPUE_{Wt} also removes the need to distribute effort between species, as is required for $\text{CPUE}_{\text{Prop}}$, and to divide the data subjectively for estimating CPUE using CPUE_{ER}, CPUE_{GM}, CPUE_{SR}, or CPUE_{AM}. Avoiding the need to create subsets of data (Stephens & MacCall 2004) ensures that data availability is not reduced by arbitrary rules, and that CPUE estimates obtained from CPUE_{Wt} can be derived from all available data. This ensures that the data used are as representative of the catch and fishery as possible. Retention of data also facilitates application of this method in the maximum possible number of years and FAs. Thus, CPUE_{Wt}, in comparison with CPUE_{ER}, CPUE_{GM}, CPUE_{SR}, and CPUE_{AM}, would be expected to remain robust to the planned shift to the assessment of individual metapopulations, where data availability is likely to be a key issue. In some cases (e.g., blacklip in FA 18) this led to CPUE_{Wt} estimates showing considerable interannual variation. Create subsets of the data by using a "lower bound" to exclude small catches (e.g., less than 20% of total catch) of the species for which

CPUE is being estimated—although subjectively removing some data and increasing analytical complexity—will moderate the interannual variation in the CPUE estimates that result from data limitations (Chen et al. 2003). This will increase the robustness of assessing stock status in those FAs that are lightly fished.

There are two other advantages of using CPUE_{Wt}. First, it is a reliable index of relative abalone abundance because the temporal patterns in CPUE_{Wt} observed since the mid 1990s, which imply increases and subsequent reductions in the harvestable biomass of both species across the western zone, are consistent with other fishery-dependent and fishery-independent information for these fish stocks (Mayfield et al. 2011, Stobart et al. 2011). Second, this method remains relatively simple and it can be applied consistently to greenlip and blacklip across the western zone and in each FA. This reduces the likelihood of process error, makes it possible to compare CPUE estimates among FAs, and facilitates easier explanations to industry stakeholders, who actively engage in the research and management of this fishery (Mayfield et al. 2011). Consequently, CPUE_{Wt} meets all 5 criteria identified as important for confirming the robustness of a future CPUE estimation method.

In summary, there are several reasons why $\text{CPUE}_{\text{Prop}}$, CPUE_{ER}, CPUE_{GM}, CPUE_{SR}, and CPUE_{AM} are less suitable than CPUE_{Wt} for estimating CPUE in this fishery. These reasons include potential biases, the need to create data subsets subjectively, and the resulting reduction in data availability, which diminishes the degree to which the remaining data are representative of the fishery. CPUE_{Wt} reduces the likelihood of these problems and, consequently, should be used for future estimation of species-specific CPUE in the South Australian abalone fishery. Although the problems of estimating species-specific CPUEs in mixed-species dive fishery are unusual, our analyses suggest that CPUE_{Wt} could provide a robust measure of species-specific CPUEs in other fisheries, particularly those using nonselective fishing gears (Westrheim 1983, Welcomme 1999, Lauridsen et al. 2008). However, because this method may also be sensitive to CPUE distribution, comparison against other methods should be undertaken before adoption and implementation.

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