A summary of the South African sardine (and anchovy) fishery

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Summary

Sardine is an important target of the South African purse-seine fishery, the largest commercial fishery in South Africa (by landed mass). This fishery, initially established on the West Coast, but with some subsequent infrastructure development on the South Coast, is currently under pressure because of recent low biomass levels, reduced Total Allowable Catches (TACs) and frequent changes in the spatial distribution of the resource. The current low biomass followed from prolonged poor recruitment, whereas the distributional changes are plausibly linked to processes related to spatial structuring of the population. The population had been hypothesized to consist of three components (previously termed western, southern and eastern components), but is now considered to comprise two components, one cool temperate (Atlantic Ocean ancestry) and the other warm temperate (Indian Ocean ancestry), with interchange amongst them. Given the predominantly west-coast-based location of sardine processing infrastructure, exploitation levels on the previously modelled western component have been high relative to other components, particularly when most of the biomass is located on the south coast. This has necessitated the implementation of a form of spatial management to promote both a healthy ecosystem and a more soundly managed resource. Research is currently underway to model a revised spatial structuring of the population. This document summarises the history of the fishery, the current status of the resource and data used in its assessment and management.

Distribution, Life History and Stock Structure

South African Sardine *Sardinops sagax* are found in continental shelf waters between Hondeklip Bay (~30°S) off the West Coast and Durban off the East Coast (Figure 1). Sardine found northwards along the Namibian coast as far as Southern Angola (~15 °S) are considered a separate stock, separated from the South African stock by a semi-permanent intense upwelling cell off Luderitz (27°S). Current understanding is that South African sardine comprises a single "stock" (in the sense of a reproductively isolated biological unit), but there is spatial structure within this stock, which has been hypothesized to comprise multiple components.

Ichthyoplankton samples collected during summer biomass surveys (see below) have indicated two distinct and separated sardine spawning areas, with eggs collected from mid-shelf to shelf-edge waters between Hondeklip Bay and Cape Agulhas off the West Coast and between Mossel Bay (22°E) and Port Alfred (27°E) off the South Coast (Figure 1a). Sardine can spawn year-round but the gonadosomatic index (GSI) of fish caught in commercial catches off the West Coast is highest, indicating peak spawning, between September and February (spring-summer; Figure 1b) whereas that for fish caught in commercial catches off the South Coast is highest between June and November (winter-spring; Figure 1c). Sardine also spawn off the East Coast during the winter sardine run, which had been considered the seasonal spawning migration of a genetically distinct subpopulation (Fréon et al., 2010), with eggs common between June and

November (Figure 1d). The environmental characteristics of these spawning habitats vary markedly; the average sea surface temperature of selected spawning habitat off the West Coast (17.0°C) is lower than off the South Coast (19.5°C; Mhlongo et al., 2015), and sardine eggs are found in water of up to 22°C off the East Coast.

Sardine larvae occur off the West (van der Lingen and Huggett, 2003), South (Costalago et al., 2018), and East (Beckley and Naidoo, 2003) coasts. Juveniles (<14 cm CL) are found off the West and South Coasts during autumn recruit and summer biomass surveys, but only rarely off the KZN Coast during the sardine run (van der Lingen et al., 2010) although juveniles are seen further south (Coetzee et al., 2010). Whilst a substantial number of sardine recruits have been observed at times off the South Coast, particularly during the recent period of high biomass (Figure 2), West Coast recruitment remains dominant at the time of the recruit survey. The thermal differences in sardine natal habitats around the South African coast are reflected by higher $\delta^{18}O$ levels in the cores of their otoliths (indicating lower natal temperatures) and lower early growth rates of sardines collected from the West and Central regions compared to those from the South and East regions (Figure 1d).

In addition to these three apparently distinct life history strategies, spatial (regional) differences in a variety of biological traits of South African sardine have been documented, including differences in meristic and morphometric characteristics, parasite biotag prevalence and infection levels, and others (see van der Lingen, 2022). These results, together with observations that marine species around South Africa tend to be subdivided into regional subpopulations associated with distinct biogeographic provinces, had suggested the existence of three sardine components: namely western (distributed off the West Coast; i.e. to the west of Cape Agulhas), southern (distributed off the South Coast from Cape Agulhas to Port Alfred) and eastern (distributed off the South Coast in spring/summer and the East Coast in autumn/winter when they undertake the annual sardine run) sardine components (or sub-stocks). Because the South African purse-seine fishery only targets sardine off the West and South Coasts (sardine off the East coast are harvested via a small beach-seine fishery), only the putative western and southern components had been considered in a commercial management sense. The conceptual model showing the spawning grounds and passive and active movement between western and southern components used to inform the sardine two-component assessment model from 2016[1] onwards is shown in Figure 3.

Previous genetic studies that examined sardine microsatellite and mitochondrial DNA did not support a multi-stock hypothesis. However, a recent study (Teske et al., 2021) that analysed thousands of genetic markers from across the genomes of hundreds of sardines captured around the SA coast reported that a suite of genetic markers with a signal of adaptation to water temperature showed regional genetic differences within the species' temperate core range and only two stocks, one associated with South Africa's cool-temperate West Coast and the other with the warm-temperate South Coast. The strong affiliation with water temperature suggests that thermal adaptation maintains these patterns because each stock is adapted to the temperature range that it experiences in its native region. Surprisingly, sardines participating in the sardine run off the East Coast were not genetically distinct and showed a clear affiliation with the cool-temperate stock, indicating that the former were migrants that originate from the cool-temperate Atlantic. The genomic results have confirmed the existence of only two sardine stocks/components off South Africa, hereafter referred to as Cool Temperate Sardine (CTS) and Warm Temperate Sardine (WTS), each of which has apparently adapted to different water

[1] Between 2009 and 2015, first a two discrete stock model was explored, followed by a two mixing-component hypothesis which allowed movement of 1-year-olds only from the west to the south coast (e.g. de Moor and Butterworth 2015).

temperatures and would experience reduced fitness and lower survival when outside their preferred temperature ranges. The new conceptual framework underlying current development of the sardine two-component assessment model is shown in Figure 4.

Information from models and observations have suggested that there is both passive and active movement of sardine between the two components and coasts. Coupled 3D hydrodynamic-individual based models (Miller et al., 2006; McGrath et al., 2020) have indicated that most of the eggs spawned off the West Coast are transported to nursery grounds located north of Cape Columbine via a jet current associated with a strong thermal front between cold upwelled water and warmer oceanic water flowing northward along the shelf-edge of the West Coast. Similarly, most eggs spawned off the South Coast are retained in inshore nursery grounds there by eddies and currents (Lett et al., 2006). However, some (9% in Miller et al., 2006; 17% in McGrath et al., 2020) eggs spawned off the South Coast are transported to the West Coast nursery area where they contribute to recruitment off the Western Coast, but models suggest that there is no transport of eggs from the West to the South Coast.

Data on the prevalence and infection levels of a parasite biotag hypothesized to only infect sardine when they are off the West Coast has indicated that there is active west to south movement of juvenile and adult sardine. Whereas average prevalence-at-length is higher for sardine collected off the West Coast compared to those collected off the South Coast (Figure 5), the occurrence of infected fish and the positive correlation of prevalence with length of those off the South Coast indicates that fish of all ages move there from the West Coast.

Biology and ecology

Sardine generally exhibit schooling behaviour, and are relatively short-lived, fast-growing fish (seldom reaching more than 5 years of age). The accuracy of ageing from otoliths is extremely variable because sardines frequently deposit two to three rings in each growth zone, and the pattern of ring deposition varies among years. Sardine have a protracted spawning season during which they can spawn multiple times, and larger females have a higher reproductive potential (number of spawnings). The relative quantitative importance of winter spawning by sardine off the South Coast is unclear.

Sardine are planktivorous and derive the majority of their nutritional input from zooplankton although phytoplankton can be occasionally important. They are fed on by a wide variety of predators (some of which are strongly dependent) including other fishes, marine mammals and seabirds, and hence play an important role in regulating ecosystem functioning. Shifts in sardine distribution and fluctuations in sardine abundance have been hypothesised to have had substantial ramifications for top predators, in particular the distribution and relative abundance of seabird species for which sardine are an important dietary component such as Cape gannets *Morus capensis* and African penguins *Spheniscus demersus*, and recruitment of an important linefish, geelbek *Atractoscion aequidens*.

Purse-seine fishery

Sardine and anchovy *Engraulis encrasicolus* generally account for more than 80 %[2] of the total pelagic purse-seine catch, the remainder being made up largely by redeye round herring

[2] Since 2000, sardine and anchovy accounted for less than 80% of the total purse-seine catch in 2010-2011, 2019 and 2021.

Etrumeus whiteheadi and juvenile horse mackerel *Trachurus capensis*. Adult sardine are targeted for canning and bait. Approximately 85% of the sardine catch is canned, whilst the remainder is frozen and packed in boxes for local and international bait markets. Juvenile sardine are also caught as by-catch in the anchovy recruitment (reduction) fishery on the West Coast.

The first pelagic fishing operations began in South Africa in 1935, but commercial operations started in the St Helena Bay area only in 1943 in response to the increased demand for canned products during the Second World War, with purse-seiners operating between Lambert's Bay and Cape Hangklip. Initially targeting sardine and horse mackerel, the purse-seine industry prospered from the late 1950's with sardine dominating the escalating catches until 1964 (Figure 6).

Following rapid declines in the landings of sardine during the mid-1960s, the industry changed its fishing strategy and used smaller-meshed nets to target juvenile anchovy as the recruits moved from the West Coast nursery grounds to the spawning grounds on the Agulhas Bank. Anchovy dominated the catches for the next two and a half decades (peaking at around 600 000 t in the late 1980s) while catches of sardine gradually increased throughout the 1990s under a conservative management strategy. Sardine catches increased substantially in the early 2000s (reaching 374 000 t in 2004) as a consequence of exceptionally good sardine recruitment and subsequent rapid growth in the size of the population, particularly on the South Coast (Figure 7). These large catches of sardine coincided with increased catches of anchovy and resulted in annual total pelagic fish landings in excess of 500 000 tonnes between 2001 and 2005.

A prolonged period of low sardine recruitment since 2004, resulted in a rapid decline in the size of the sardine stock with sardine TACs and catches dropping to levels in the order of 90 000 t between 2008 and 2014 and to 45 560t in 2017 and 65 000t in 2018 (in the 1990s, 90 000 t had been proposed as the level below which the sardine industry would need to undergo substantial restructuring in order to remain viable, but a more recent socio-economic study indicated that the industry has developed strategies to cope with fluctuations and reductions in sardine TAC by e.g., increased diversification and importation of frozen cutlets for local canning; Hutchings et al. 2015). Following the declaration of Exceptional Circumstances for sardine in December 2018 after recording a sardine survey biomass estimate which was below the range simulated during the development of OMP-18, the 2019 directed sardine TAC was reduced to 12 250t, with only 2050t landed. The TACs have remained relatively low at 32 000t, 26 800t, and 33 350t in the three most recent years while Exceptional Circumstances declarations have remained in place, with catches falling well below these limits, and advice has been based on best assessments.

The recent low sardine TACs have been insufficient for profitable operation of the major canning facilities and the bulk of canned sardine products produced in South Africa in recent years have contained sardine that are sourced from Morocco and elsewhere. This has enabled the industry to retain market share and to keep their workers employed, though unfavourable exchange rates have affected profitability and threatened the long-term viability of the canning industry, particularly if directed sardine TACs remain at low levels.

During the early years of the fishery, most of the fishing effort was concentrated on the West Coast where sardine were abundant for most of the year, resulting in intensive development of infrastructure related to fish processing centred around the harbour at St. Helena Bay. During the 1960s and 1970s there was an expansion of the fishing ground for sardine southwards and eastwards as far as Cape Agulhas. Since the mid-1990s, following the eastward expansion of the sardine distribution, fishing effort increased further east, particularly in the Mossel Bay area, with the establishment of a new cannery in Mossel Bay in 2007. A small portion (typically <10%) of the sardine TAC was also regularly taken in the vicinity of Port Elizabeth on the South Coast.

Currently the cannery in Mossel Bay and the various smaller sardine processing establishments on the South and East Coasts have access to about 28% of the annual TAC (based on RH affiliation and vessel home-port locations). The amount of sardine caught east of Cape Agulhas increased gradually from 2001 onwards, peaking in 2005, the first year in which more sardine were caught east of Cape Agulhas than west of Cape Agulhas (Figure 8). In recent years the proportion of directed sardine caught off Port Elizabeth has increased sharply with close to 40% on average being landed there over the last 5 years, mainly as a result of the unavailability of sardine in the traditional west coast fishing areas.

The harvest proportion levels on the previously modelled western component of the sardine resource have been higher than that on the southern component in most years, sometimes substantially so (Figure 9).

Catches of sardine on the South Coast have exceeded those taken on the West Coast during two periods (2005-2008 and 2019-2022). The majority of those sardine caught on the South Coast during the first period were landed at Mossel Bay and transported back to factories on the West Coast, either by large refrigerated-sea-water vessels or by truck. During the most recent period, about half of the sardine have been landed at Port Elizabeth and either processed there or trucked to Mossel Bay for canning. Presently, the majority of sardine processing infrastructure is still based on the West Coast and most of the lease agreements and systems established for the offloading of sardine in Mossel Bay for road transport, by West Coast-based Rights Holders, during years when the sardine TACs and availability of sardine on the South Coast were high, have been discontinued.

Biomass surveys

The biomass and distribution of sardine and anchovy, and also of other schooling pelagic and meso-pelagic fish species such as round herring, juvenile horse mackerel and lantern- and light fish (*Lampanyctodes hectoris* and *Maurolicus walvisensis*, respectively) are assessed biannually using hydro-acoustic surveys based on a random stratified sampling design. These surveys, which have been conducted without interruption (apart from the recruit survey of 2018 and an unsuccessful survey in December 2021, which covered only a small portion of the standard survey area with a faulty echo-sounder) since 1984, comprise a summer biomass survey and a winter recruit survey. Biomass estimates obtained from these surveys are key inputs into the anchovy and sardine assessments and form the basis for recommendations of annual TACs of anchovy and sardine.

The surveys cover the entire area of the South African continental shelf between Hondeklip Bay on the west coast and Port Alfred on the east coast during the summer biomass surveys (Figure 10a). Sampling effort during the recruit surveys is concentrated mainly on the inshore areas of the shelf, but the survey is extended westward and northward to the Namibian Border (Orange River Mouth; Figure 10b). Although recruit surveys initially covered only the main distribution of anchovy recruits, which was considered to extend as far as Cape Infanta on the South Coast, the most recent surveys have been extended further eastward, time permitting, to estimate the strength of sardine recruitment on the South Coast as well.

The survey estimate of sardine biomass increased gradually from under 50 000 tons in 1984 to around 2.5 million tons in 2000, and whilst consecutive years of very good recruitment pushed the total biomass up to record levels above 4 million tons in 2002, a period of prolonged poor (or below average) recruitment since 2004 has led to a decline in the adult biomass to below 500 thousand tons in most years since 2007, and to recent lows of about 250 000 t in 2016 and 2020, about 190 000t in 2019 and a thirty-year low of only 91 000t in 2018 (Figure 11).

The contribution of the biomass west of Cape Agulhas to the total sardine biomass was larger than that of the biomass east of Cape Agulhas up until 1998. In 1999, a large increase in the biomass east of Cape Agulhas relative to that west of Cape Agulhas caused a "shift" in the relative distribution of sardine to the Central and Eastern Agulhas Bank. Further increases in the biomass of sardine east of Cape Agulhas after 1999 were mainly as a result of the influx of a large number of 1-year old sardine in 2001 and 2002 emanating from very successful west coast recruitment. Since 2008, the biomass of sardine was more evenly distributed between the west and south coasts with close to or more than 50% of the biomass being located in the area to the west of Cape Agulhas, but close to 80% of the biomass was again found to be distributed east of Cape Agulhas in 2019 and 2020 (Figure 12).

Assessment and Management

Management of the small pelagic fishery in South Africa has changed over time. A combined small pelagic TAC was implemented from 1971 and is recorded as having been the most effective and important means of limiting exploitation. However, although total yield stabilised, this 'stability' masked a highly unstable species composition with catches changing from predominantly large sardine to anchovy of only two age classes. Species specific TACs were introduced from 1983 to encourage diversification, protect the depleted sardine resource and prevent over-exploitation of anchovy. Other small pelagic species were designated 'non-quota' in 1983 again to encourage diversification. Since 1991 the sardine and anchovy directed fisheries have been regulated using a Management Procedure (MP) approach, which is an adaptive management system that is able to respond, without increasing risk, to major changes in resource abundance. The first joint anchovy-sardine OMP was implemented in 1994, with subsequent revisions. The OMP formulae are selected with the objectives of maximising average directed sardine and anchovy catches in the medium term, subject to constraints on the extent to which TACs can vary from year to year in order to enhance industrial stability. These formulae were conditioned on relatively low probabilities that the abundances of these resources drop below agreed threshold levels below which successful future recruitment might be compromised. Given the exceptionally low sardine biomass observed in November 2018, and subsequent years, Exceptional Circumstances were declared for sardine, with the MP being set aside and TACs and TABs being set, partially based on the results of short term projections from updated assessments (de Moor *et al*. 2022). The primary and overriding objective for managing sardine has become to avoid sardine biomass falling to a lower level and assist the recovery of sardine to a higher biomass level, while still having consideration for the socio-economic implications associated with any recommendation.

A joint anchovy-sardine OMP is needed because sardine and anchovy school together as juveniles, resulting in an unavoidable by-catch of juvenile sardine with the mainly juvenile anchovy catch during the first half of the year. This results in a trade-off between catches of anchovy (and hence juvenile sardine) and future catches of adult sardine, and the OMP aims to ensure some "optimal" utilization of both resources. TACs for both species and a Total

Allowable Bycatch (TAB) for sardine bycatch are set at the beginning of the fishing season, based on results from the previous November biomass survey. However, because the anchovy fishery is largely a recruit fishery, the TAC of anchovy and the associated juvenile sardine bycatch allowance is revised in mid-year following completion of the recruitment survey in May/June.

OMP-14, which was finalised in December 2014, was used to recommend TACs and TABs for the small pelagic fishery from 2015 to 2018. Although development of OMP-14 also included substantial analyses related to the implications of the sardine resource consisting of two components with different spatial distributions rather than a single stock, OMP-14 was still tuned using an operating model which reflected a single homogeneously distributed sardine stock.

OMP-18, which was adopted in December 2018, was, however developed using an operating model of the sardine resource consisting of two mixing components with differential exploitation levels. The model of two sardine components, assumed to be distributed west and east of Cape Agulhas, estimated the extent of west to south movement of fish of ages 1 and above each year. This assessment indicated that in terms of recruits-per-spawner, the western component was much more productive than the southern component by about an order of magnitude (de Moor *et al*. 2017). Simulations using this two-component Operating Model of population dynamics for the sardine resource assumed that the proportion of future catches west of Cape Agulhas would mimic that which has been observed in the past with the proportion of directed sardine catch taken west of Cape Agulhas decreasing when the ratio (TAC : west coast biomass) increased (Figure 13). A schematic representation of OMP-18 is given in Figure 14.

Formal spatial management was implemented for the first time in 2019, with each sardine Right Holder's West Coast allocation being capped at 43% of the TAC. Restrictions on the amount of the TAC to be taken west, and more recently also east, of Cape Agulhas have continued from 2019-2022 under Exceptional Circumstances.

In addition to the directed sardine and anchovy TACs, several bycatch limits and Precautionary Upper Catch Limits (PUCLs) are also stipulated. Juvenile sardine and juvenile horse mackerel are both taken as by-catch during anchovy-directed fishing operations and associated TABs are set. Small-sized sardine landed with the directed sardine catch is also catered for in a small bycatch pool as is the bycatch of juvenile and adult sardine with round herring and anchovy with sardine (for sardine only Right Holders). In addition, a PUCL of 100 000 tons applies for round herring when the survey estimate of biomass is above 750 000t, and 50 000 tons for mesopelagic fish species.

Ecosystem considerations in this fishery currently include the experimental closure of areas to fishing around some important seabird (e.g. African penguin and Cape gannet) breeding colonies (islands) in an attempt to assess the impact of localized fishing effort on the breeding success of these birds and to inform managers on the likely scale of any benefit for penguins that could be expected from long-term closures to fishing around these colonies. A model of penguin dynamics was also previously developed for use in conjunction with the small pelagic fish OMP so that the impact on penguins of predicted future pelagic fish trajectories under alternative harvest strategies could be evaluated. These studies have so far indicated that even with large reductions in the sardine TAC there would be little benefit for penguins.

Data

The full set of data available as inputs into the sardine (and anchovy) assessments are described in detail elsewhere (e.g. de Moor *et al*. 2019) and hence summarised only briefly here:

1. Commercial Catch Data

   Monthly catch length frequencies are constructed for the sardine landings. From 1987 onwards, these are available by area (east and west of Cape Agulhas).

   Between 1987 and 2011, sardine landings were categorized as either directed (>50% sardine mass in landing) or bycatch by the scale monitor. The bycatch was recorded as being either caught with anchovy or round herring, with the allocation determined by the species which had the highest mass in the landing. From 2012 onwards, the sardine landings have again been categorized as either directed >14cm (>50% sardine mass in landing) or bycatch by the scale monitor. The bycatch is now recorded as either 'small' (≤14cm) sardine with directed >14cm, or 'small' (≤14cm) bycatch with anchovy or round herring. Anchovy is seldom landed with adult sardine and/or round herring. The >14cm sardine bycatch is assumed to be primarily bycatch with round herring and the time series is assumed comparable with the 1987-2011 time series of bycatch with round herring.

   The sardine bycatch with anchovy (or 'small, <14cm sardine bycatch) is used separately in the assessment to the directed sardine catch and sardine bycatch with round herring. Quarterly data used in the assessments are taken over the months November y-1 to January y, February to April y, May to July y, and August to October y.

2. Survey biomass estimates and weighted length frequencies

   Time series of total biomass estimates and associated CVs from the acoustic surveys in November are available from 1984 to 2020[3], corresponding to the standard survey area between Hondeklip Bay and Port Alfred. Length frequencies (scaled to the total biomass) are also available.

   Time series of recruit biomass and associated CVs from the May/June recruit surveys (1985-2017, 2019-2022) are also available. The average recruit weight is calculated by applying a length-weight regression to the survey weighted length frequency. In the assessments, the recruit numbers are used together with the CVs on recruit biomass.

3. Ageing

   Inconsistencies between age-length keys derived for sardine by various otolith age-readers preclude the use of age data in the assessments.

4. Parasite infection rates

   Time series of infection prevalence of the "tetracotyle" type digenean endoparasite by length as sampled from November surveys from 2010 to 2020, are available. This is the proportion of sardine-by-length that are infected with the parasite. The prevalence for

[3] The (extremely short) survey in December 2021 did not provide an adequate estimate of biomass and is thus excluded from the time series.

west component sardine is estimated using data from fish collected to the west of Cape Agulhas (20°E), whereas that for south component fish is based on samples collected between 22°E (roughly Mossel Bay) and 30°E (roughly Port St Johns). This is to exclude age-1 individuals in the hypothesized mixing zone (20°-22°E) that may be west component fish. An alternative time series of south coast prevalence based on samples collected between Cape Agulhas and 30°E is used for a model sensitivity test. Alternative information on the intensity of parasite infection, i.e. numbers of parasite per infected fish, is also available but is not currently used in the assessment.

Stock assessments

The assessment of the South African sardine resource which informed the Operating Model used during the development of OMP-18 was conditioned on data available up to November 2015. Following the declaration of Exceptional Circumstances for sardine since December 2018, an updated assessment has been annually conditioned on data from 1984 to the most recent year before projecting forward one year under alternative catch options to provide management advice. The assessments are reported elsewhere (e.g., de Moor *et al*. 2017, de Moor 2022) and hence described only briefly here.

The two-mixing component model is age-structured with a plus group of age 5. A distribution of length-at-age is used to model the length-structure of the population at fixed times during the year, and the growth curve differs by year to allow for variations in the time of peak recruitment (thus being able to accommodate early/late recruitment). Recruitment to each component is estimated independently during conditioning. Any stock-recruitment curves are estimated after conditioning, with recruitment to each component assumed to be dependent on the "effective" spawner biomass of that component only (where the "effective" spawner biomass allows for alternative assumptions of the proportion of south component spawning biomass to west component spawning biomass as a proxy for south coast spawning contributing to west coast recruitment (Miller *et al*. 2006)).

Spawner biomass is calculated assuming a maturity-at-length ogive which changes over time, and using weight-at-length. The trawl survey selectivity-at-length is assumed to be logistic (hence allowing for some escapement of small fish). The estimated component-specific commercial selectivity-at-length curve is described by a logistic distribution at greater lengths. Time-varying commercial selectivity is assumed, with selectivity varying by quarter and year (de Moor *et al*. 2017, de Moor 2022).

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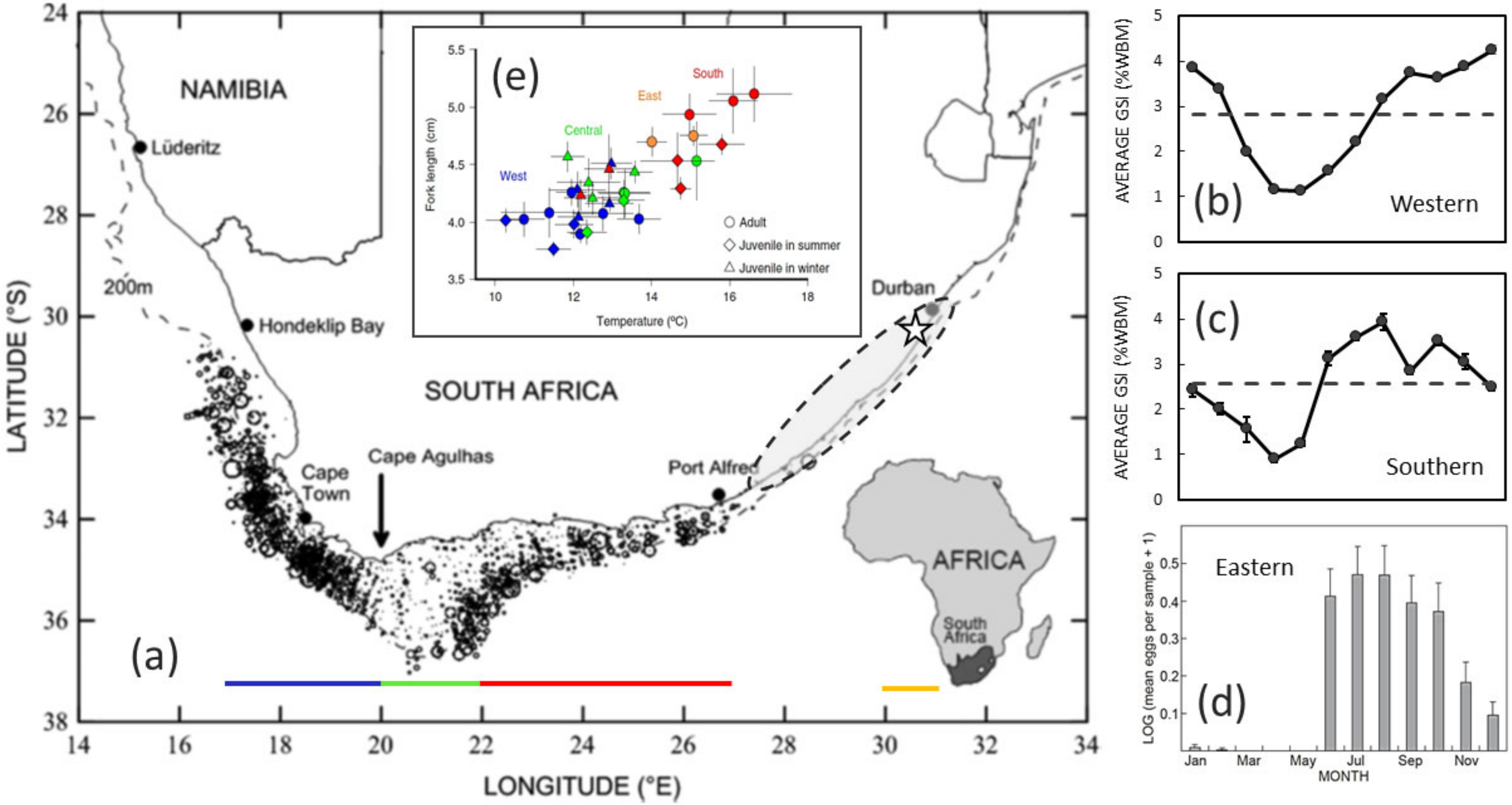

Figure 1: Map of the southern African coastline (a) showing places mentioned in the text, the 200 m depth contour (dashed line) and the composite egg density (eggs per square metre; circles with diameter proportional to abundance, maximum size = 9193 eggs·m^{-2}) derived from CalVET net samples collected during annual pelagic biomass surveys conducted between Hondeklip Bay and Port Alfred from 1986 to 2010 (from de Moor et al., 2017); (b) and (c) average monthly gonadosomatic index (GSI) of western and southern sardine sampled from commercial catches sampled over the period 1995-2015 (dashed line shows the overall average GSI for each); (d) average monthly abundance of eastern sardine eggs collected off Park Rynie (indicated by a white star in (a)) over the period 1987-2007 (from Connell, 2010); and (e) relationship between mean (and std. err.) natal temperature (estimated from otolith core oxygen stable isotope data; note that these values are relative and likely underestimate actual values by ca. 3°C) and mean (and std. err.) fork length at 60 days post hatch (estimated from otolith microstructure [daily ring increment width] analysis) of juvenile and adult sardine sampled from four regions around South Africa; west (17-20°E; samples collected within the range indicated by a blue line in (a) and blue symbols in (d)), central (20-22°E; green), south (22-27°E; red) and east (30-32°E; orange) regions (from Sakamoto et al., 2020).

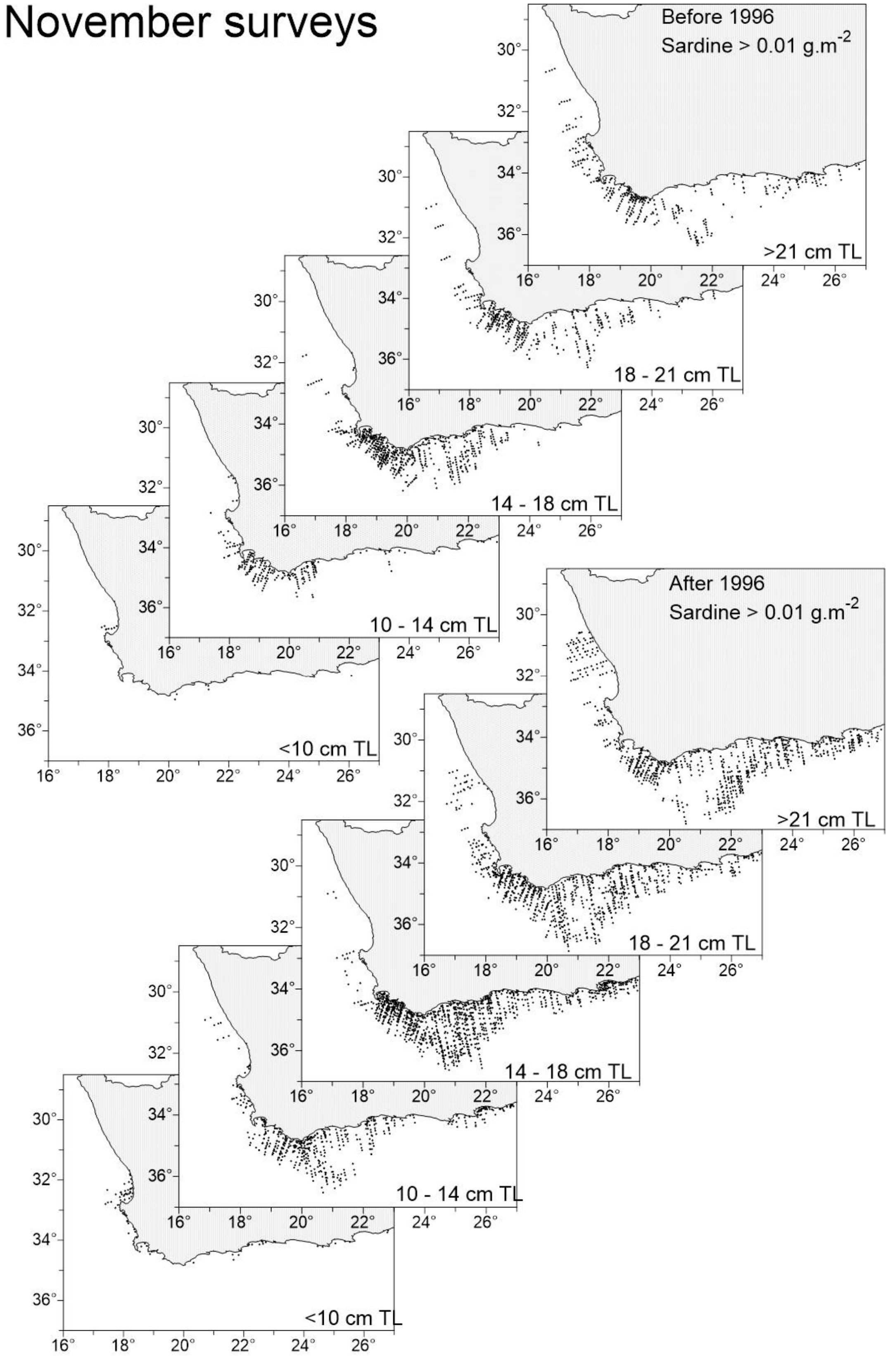

Figure 2: Map of the southern African coastline showing the distribution of sardine by size class (irrespective of abundance) during summer biomass surveys for two periods where biomass levels differed: 1984-1996 (average biomass 363 781 t) and 1997-2012 (average biomass 1 515 337 t).

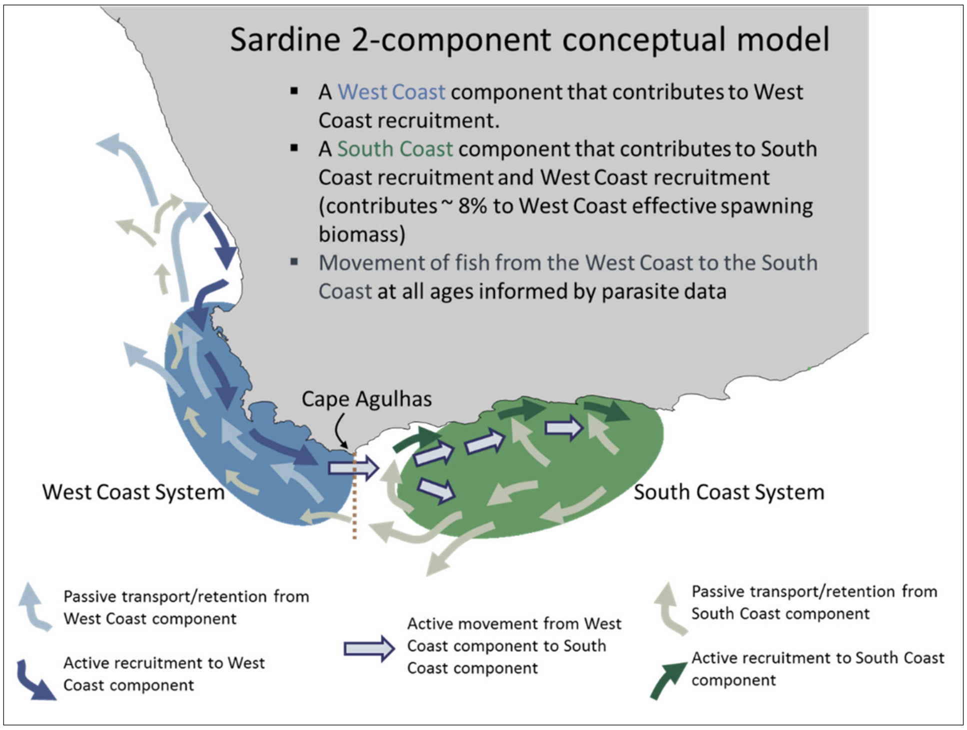

Figure 3: The conceptual model showing spawning grounds (ellipses) and passive (for early life history stages) and active (for recruit and older fish) movement of sardine from and between the hypothesized western and southern components used to inform the sardine two-stock assessment model developed in 2016.

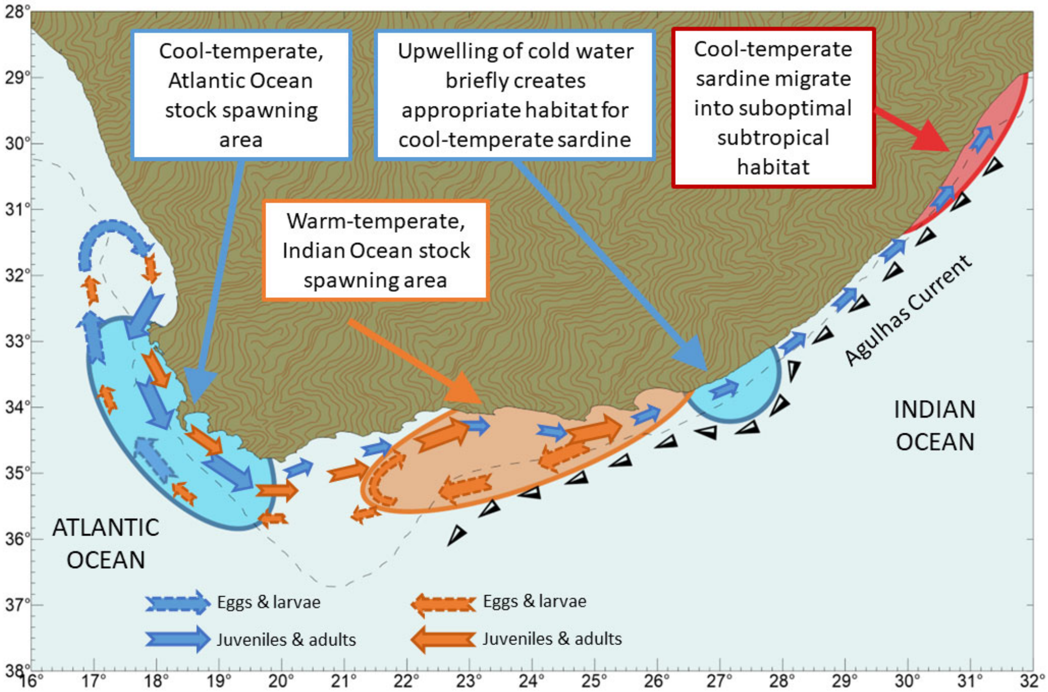

Figure 4: The conceptual model showing spawning grounds (ellipses) and passive (for eggs and larvae) and active (for juvenile and adult fish) movement of sardine from and between the hypothesized western and southern components used to inform the sardine two-stock assessment model presently in development. Modified from Teske et al., (2021).

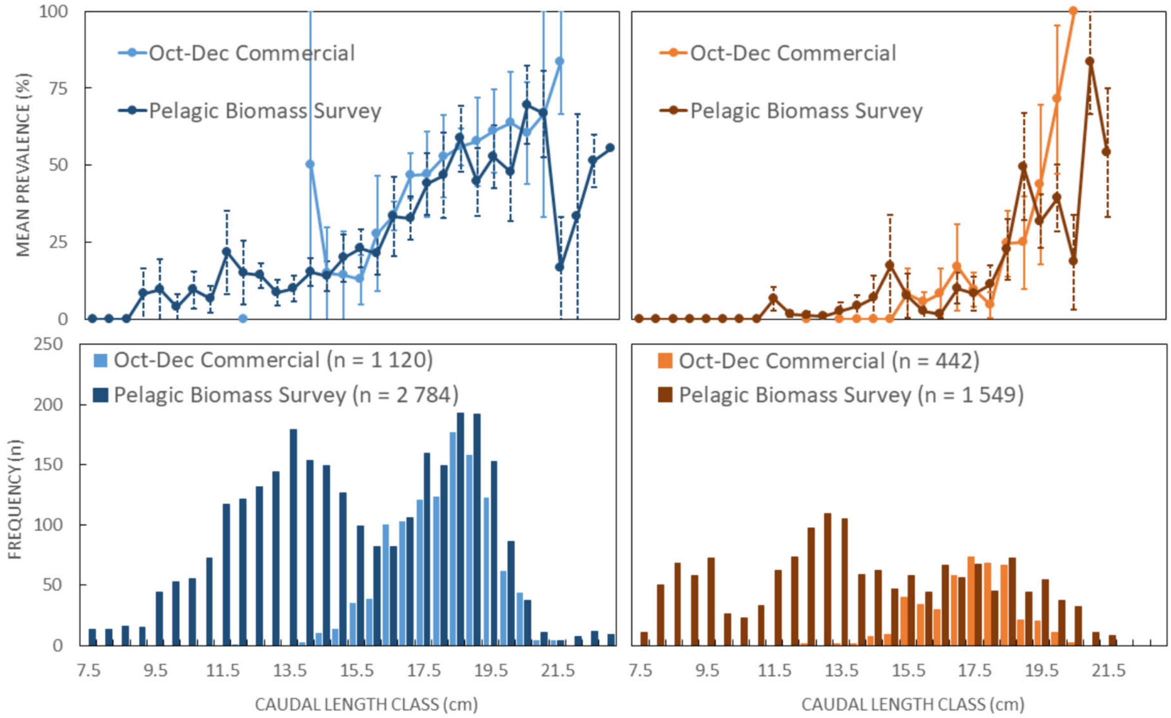

Figure 5: Mean (2010–2018) prevalence-at-length plots (upper) and composite length frequency histograms (lower) for western (left/blue) and southern (right/orange) sardine sampled from biomass surveys (darker colour) and Oct-Dec commercial catches (lighter colour) datasets. Standard error bars for the mean prevalence-at-length plots shown were calculated from the number of years in which fish of each size class were sampled and not from the number of fish of a given length class sampled. From van der Lingen (2021).

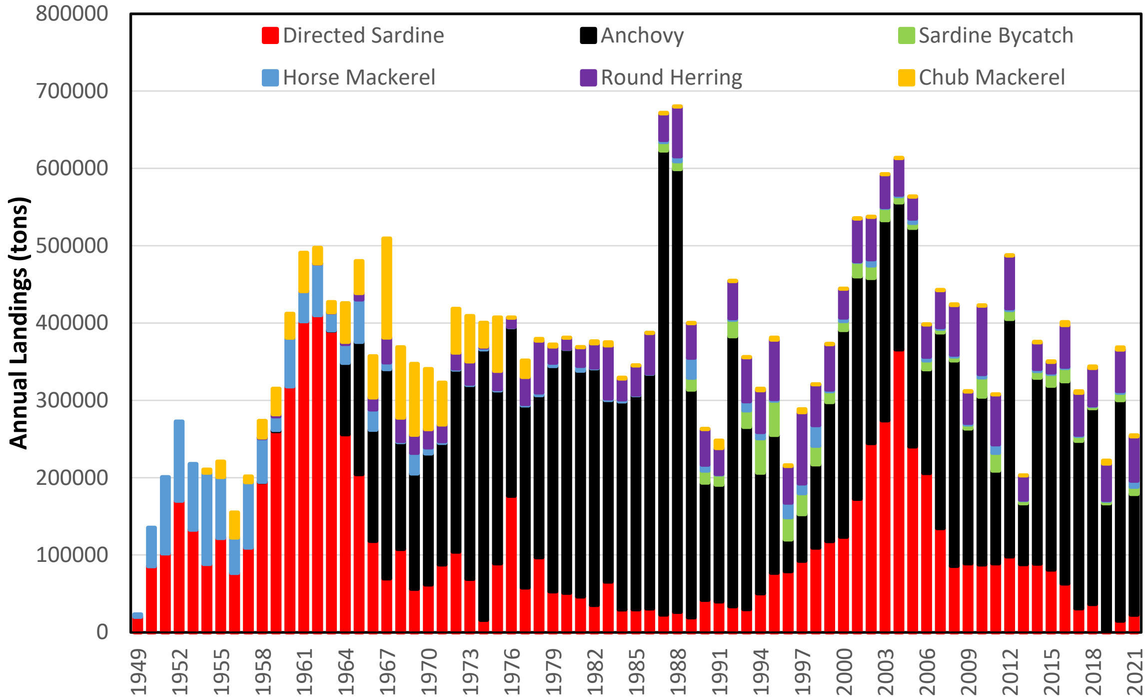

Figure 6: Annual landings of sardine and other small pelagic fish by the South African purse-seine fishery since 1949.

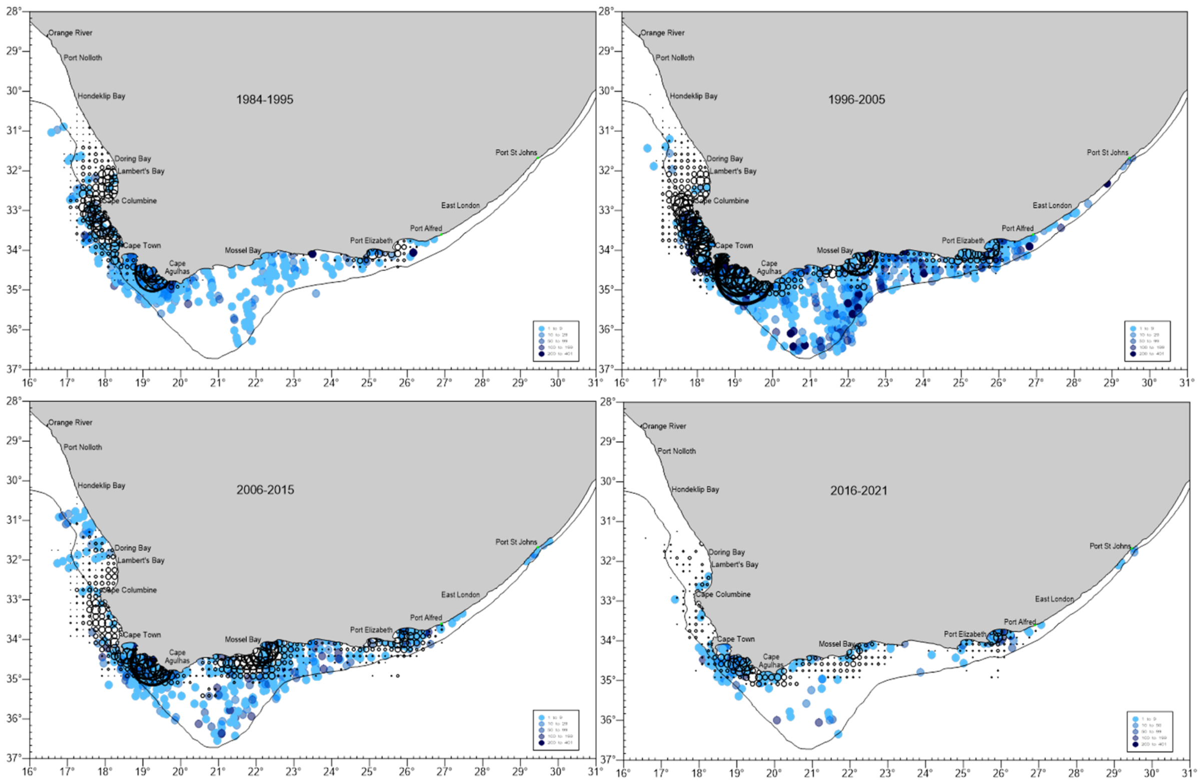

Figure 7. Composite maps of sardine catches (open circles, proportional size) and sardine density from hydro-acoustic surveys (dots) for three 10 year periods and the most recent 6 years.

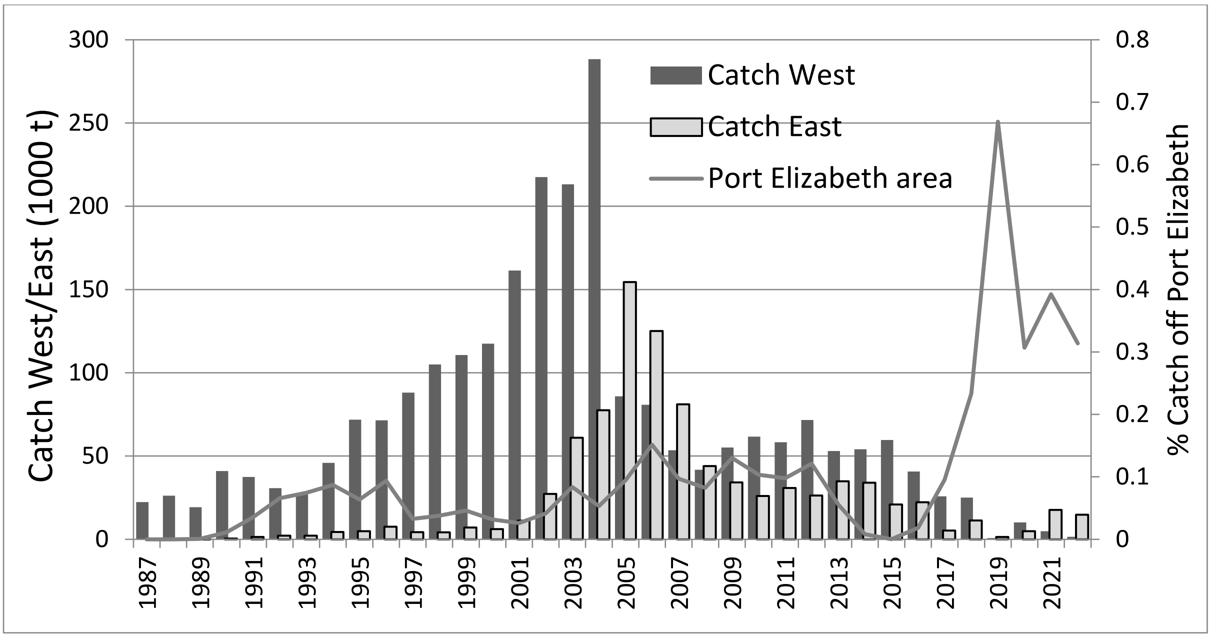

Figure 8. Annual spatially-disaggregated landings of directed sardine by the South African purse-seine fishery for the area to the west and east of Cape Agulhas. Also shown is the percentage of the total catch landed at Port Elizabeth (note this is a subset of the catch in the area to the East of Cape Agulhas).

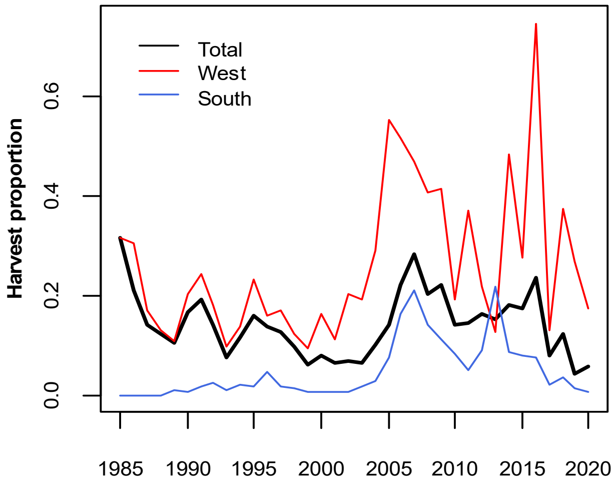

Figure 9. Harvest proportion (catch in current year/model predicted biomass in previous year) for the area to the west of Cape Agulhas, East of Cape Agulhas and for the entire coast, from de Moor (2022), using the previous stock structure hypothesis.

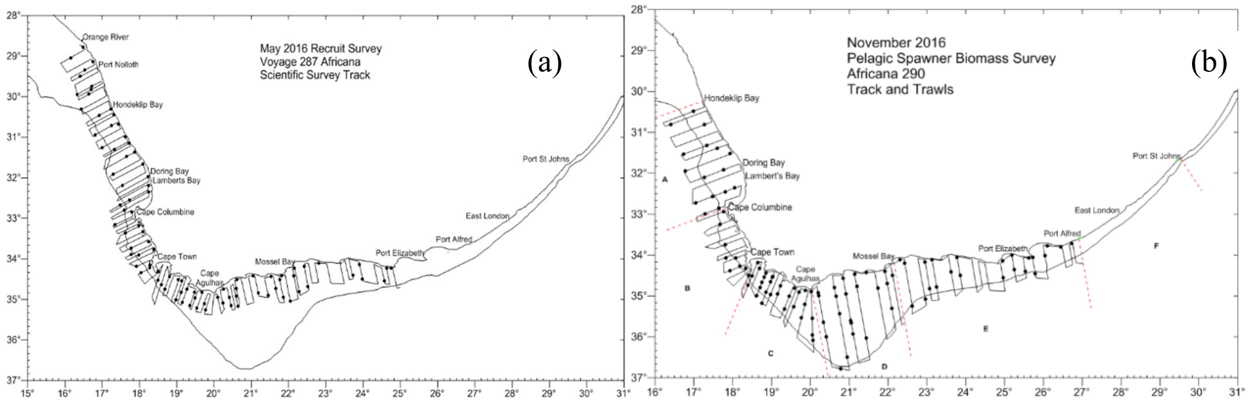

Figure 10: Typical random-stratified hydro-acoustic survey design for summer biomass surveys (a) and winter recruitment surveys (b).

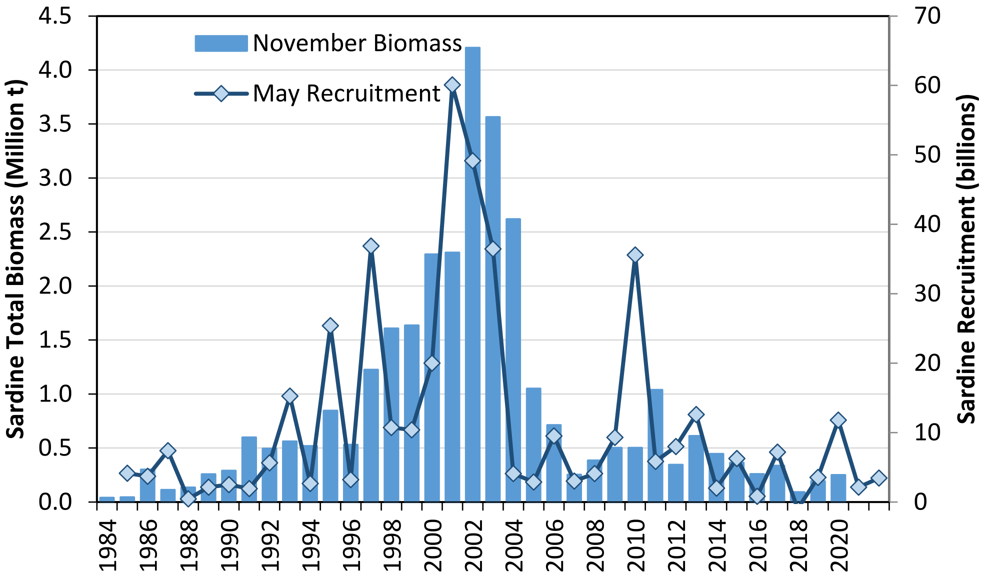

Figure 11: Time-series of acoustic survey estimates of total sardine biomass in October/November (bars) and recruitment in May/June (lines) since the start of the acoustic survey program.

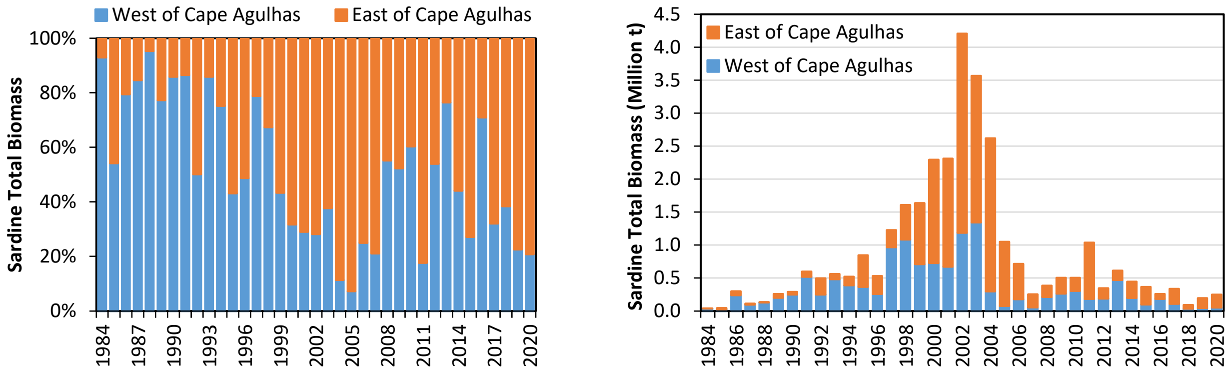

Figure 12: The proportion (left) and biomass (right) of sardine found to the west and east of Cape Agulhas during November acoustic surveys.

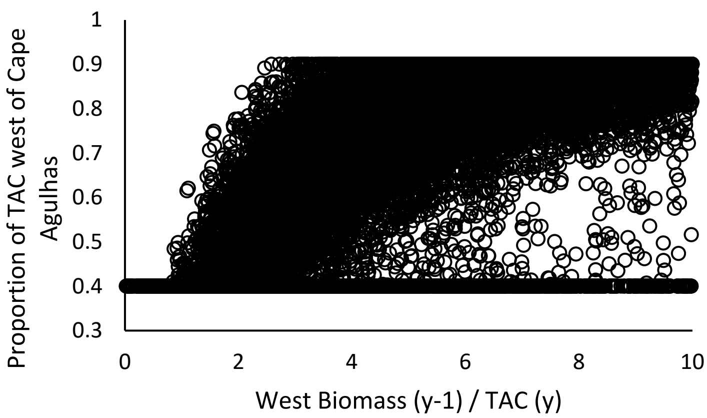

Figure 13: The future generated proportion of directed sardine TAC taken west of Cape Agulhas in year y plotted against the ratio of the west coast biomass in November (y-1) : TAC(y) for the 1000 simulations of OMP-18 on the baseline Operating Model.

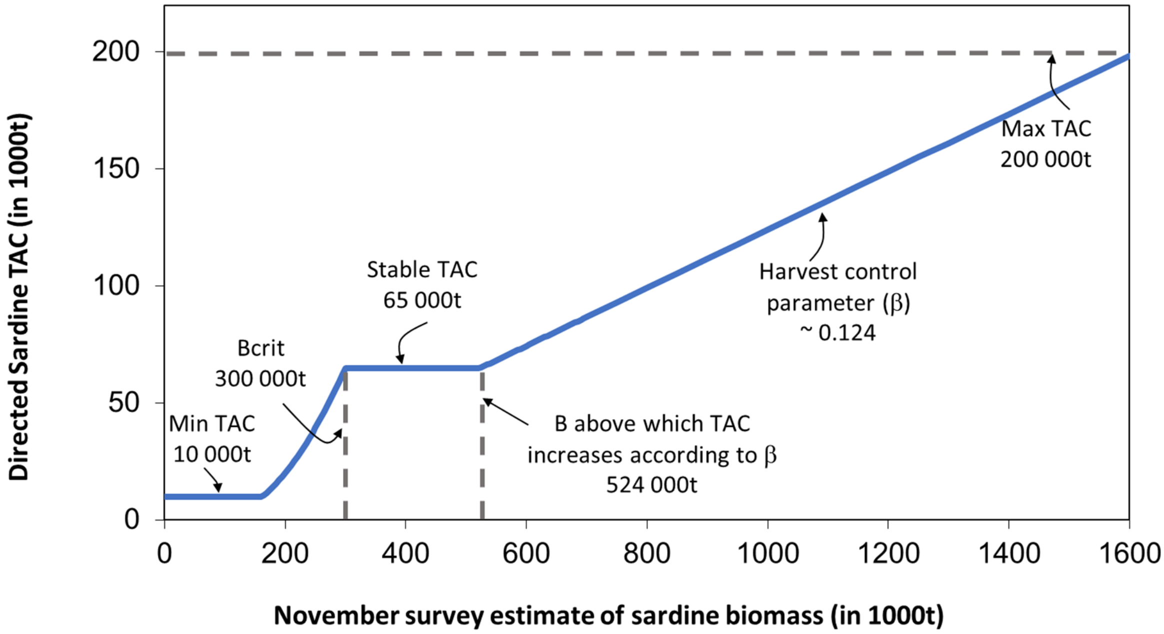

Figure 14: A schematic of OMP-18 sardine HCR. Changes from OMP-14 include a higher catch control parameter (up from 0.087 to 0.124) lower maximum TAC (down from 500 000t to 200 000t), a decreased stable TAC (65 000t down from 90 000t) and the introduction of an absolute minimum TAC at 10 000t.