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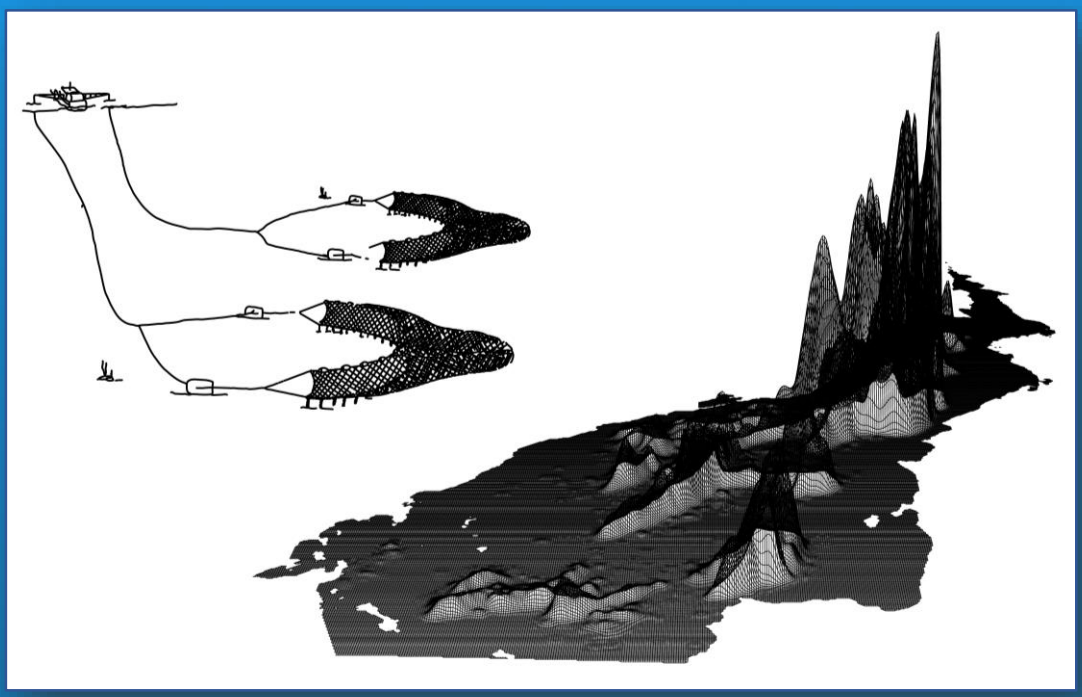
# Determining the trawl footprint of the Spencer Gulf Prawn Fishery




## Craig J. Noell



**SARDI Publication No. F2016/000565-1**
**SARDI Research Report Series No. 939**



**SARDI Aquatics Sciences**
**PO Box 120 Henley Beach SA 5022**



**February 2017**

**Report to PIRSA Fisheries and Aquaculture**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## EXECUTIVE SUMMARY

The aims of this study were to: (i) describe broad trends in trawl effort in the Spencer Gulf Prawn Fishery (SGPF) and establish a reference period for spatial analysis; (ii) develop two alternative methodologies for estimating the total area trawled over a given period (i.e. 'trawl footprint'); (iii) determine trawl footprint and projected footprint estimates using both methods; and (iv) discuss considerations for a spatial threshold to support ecological monitoring.

Total effort in the fishery declined by ~60% from 1976–2002 at a rate of 914 h $yr^{-1}$ and stabilised from 2003 onward at a mean (± SD) of 18,622 ± 1,235 h $yr^{-1}$. The decline in effort between these two periods was depicted spatially as a reduction in mean annual trawl intensity (in h $km^{-2}$ $yr^{-1}$) in most blocks in the middle of the gulf. Some of this effort was redistributed, with intensity becoming relatively concentrated in a few blocks within the Wallaroo region.

The distribution of trawl midpoints, available from 2003–2016 for ~40% of all trawl shots, revealed three main hotspots in most years—two in the Wallaroo region and one in the Middlebank region. Along with relatively stable effort and the availability of midpoints, this consistent trawl pattern provided the basis for establishing 2003–2016 as an appropriate reference period for determining the trawl footprint.

Given the availability of midpoint coordinates, distance and trawl width, and the simulation of trawl direction, trawl paths (line segments) and individual swept areas (polygons) were reconstructed to estimate trawl footprint. A total of 14 years of midpoints at a coverage of ~40% were aggregated to form the equivalent of ~5.5 years with 100% coverage to accurately describe and predict the change in trawl footprint.

Two alternative methods were used to estimate trawl footprint—a swept-area estimate based on amalgamated area of polygons and a density-derived estimate based on the pixel area in which mean trawl intensity (converted from line lengths per pixel) is above a predetermined level (cutoff).

The amalgamation of polygons culminated in a total swept-area trawl footprint for the fishery of 4,282 $km^2$, with less new ground trawled each year. Overlapping swept areas accounted for more than three-quarters (78.1%) of the total trawl footprint. The density-derived trawl footprint was estimated at 4,224 $km^2$ at a pixel size of 30 × 30 m and a cutoff intensity of 0.5 h $km^{-2}$ $yr^{-1}$ that separated the trawled area from the area of no/negligible trawling. Exponential models fitted to the annual swept-area and density-derived trawl footprint estimates yielded similar projected footprints (asymptotes) of 4,468 and 4,253 $km^2$, respectively.

The inclusion of erroneous data that are difficult to detect is likely to result in an overestimate of the swept area; however, if using the density-derived method to estimate trawl footprint, this can be partly offset by adjusting the minimum cutoff intensity. The pending introduction of electronic logbooks

should eliminate many of the errors that could not be detected, particularly those relating to coordinates. Programming code has now been developed to accommodate paper and electronic logbook data for updating and monitoring the trawl footprint estimate.

Four influential factors that need to be considered in developing a threshold for the SGPF from trawl footprint estimates are discussed: (i) a clearly defined purpose for developing a threshold; (ii) the method used to estimate the footprint upon which the threshold is based; and if using a density-derived estimate of threshold; (iii) the cutoff intensities; and (iv) intensity categories for defining footprint.

Estimates of trawl footprint of the SGPF may be considered a surrogate measure of the impact of trawl effort and, therefore, a potential cost-effective alternative to bycatch surveys. However, they do not preclude the monitoring of bycatch altogether. Rather, regular estimates of trawl footprint may be supplemented with monitoring of individual bycatch species of interest. Together, these two sources of information are considered to provide the most informative measure of fishing pressure possible, and are necessary for demonstrating and supporting an ecosystem approach to managing this fishery.

## ACKNOWLEDGMENTS

Funds for this research were provided by PIRSA Fisheries and Aquaculture, obtained through licence fees. SARDI Aquatic Sciences provided substantial in-kind support. The management committee of the Spencer Gulf and West Coast Prawn Fishermen's Association and Steve Shanks (PIRSA) provided feedback and support on the study. Dr Fred Bailleul and Dr Jonathan Carroll provided technical support and advice on using R and as a geographical information system. The catch and effort data from the SARDI Information Management System were provided by Melleessa Boyle of the Information Systems and Database Support Unit at SARDI Aquatic Sciences. This report was formally reviewed by Dr Jason Tanner and Dr Owen Burnell of SARDI Aquatic Sciences, and Steve Shanks of PIRSA Fisheries and Aquaculture, and approved for release by Dr Stephen Mayfield, Science Leader, Fisheries (SARDI Aquatic Sciences).

## 1. INTRODUCTION

It is widely perceived that bottom trawling impacts on the benthic habitat—directly and indirectly (Jennings and Kaiser 1998). Recognition of impacts such as those that modify the trawled area has led to consideration of the broader ecosystem as part of best-practice fisheries management (Pikitch et al. 2004), which is aligned with requirements established to achieve ecocertification. One trawl fishery that has fully embraced the principles of ecosystem-based fisheries management is the Spencer Gulf Prawn Fishery (SGPF) in South Australia. Accredited by the Marine Stewardship Council (MSC) in 2011 (MRAG Americas Inc. 2016), the SGPF comprises 39 double-rigged trawlers and targets a single species, western king prawn (*Melicertus latisulcatus*).

The SGPF employs a variety of strategies designed to mitigate its impact on the ecosystem—many of which are self-imposed by industry. Bycatch and contact with benthic habitat is largely avoided by extensive spatial and temporal closures[1], and survival of discarded bycatch is enhanced with efficient on-board handling practices (PIRSA 2014b). These strategies, combined with good governance (Zacharin et al. 2008; Zhu 2016), a conservative harvest strategy (PIRSA 2014b), a responsible fishing industry (Gillett 2008), independent gulf-wide bycatch surveys (Currie et al. 2009; Burnell et al. 2015), and ecological risk assessments (e.g. PIRSA 2014a), have been instrumental in this fishery gaining MSC accreditation . The gulf-wide bycatch surveys conducted in 2007 and 2013 (Currie et al. 2009; Burnell et al. 2015) in particular have proven to be an important source of information for addressing many of the MSC conditions. However, these types of surveys are expensive and limited in that they lack inter- and intra-annual representativeness of the fishery (both 2007 and 2013 surveys were conducted in February). Other bycatch research undertaken for this fishery, while accounting somewhat for temporal variability, were not as extensive with respect to spatial coverage or the number of species examined (Carrick 1997; Dixon et al. 2005; Svane et al. 2007). Notwithstanding these limitations concerning representativeness, previous bycatch research collectively indicates that the SGPF has a relatively low impact on the ecosystem. As a cost-effective alternative for ongoing monitoring that is also considered to be spatially and temporally representative of fishing, it has been proposed that the detailed mapping of trawl effort or 'footprint' can serve as a surrogate measure of the impact of trawling (Piet et al. 2007), a method that may be applicable for the SGPF. Trawl footprint is defined in this study as the total area trawled over a given period.

Prior to this study, the only available estimate of trawl footprint for the SGPF (Mayfield et al. 2014) was obtained from the interpolation of trawl midpoints. Here, trawl shot direction was simulated from another information source to reconstruct trawl paths and swept areas at midpoint locations, the rationale for which was to mimic the actual trawl footprint and obtain more reliable estimates. Trawl midpoints for the SGPF from the last 14 years were available for reconstructing trawl footprint. With these data, specific aims were to: (i) describe broad trends in trawl effort in the SGPF and establish a reference period for spatial analysis; (ii) develop two alternative methodologies for estimating trawl

[1] Self-imposed permanent closure policy (Spencer Gulf and West Coast Prawn Fishermen's Association, 2016).

footprint; (iii) determine footprint and projected estimates using both methods; and (iv) discuss considerations for proposing a spatial threshold to support ecological monitoring.

## 2. METHODS

### 2.1. Spatial extent of the fishery

The SGPF operates entirely within Spencer Gulf, South Australia, defined here as the waters north of the lines joining Cape Catastrophe on Eyre Peninsula (136.003°E, 34.985°S), Low Rocks (136.077°E, 35.165°S), and north of Shell Beach on Yorke Peninsula (136.884°E, 35.187°S), encompassing a total area of 22,698 km$^2$ (Figure 1). Trawling is prohibited at depths less than 10 m and restricted to commercial fishing blocks (described below) (Figure 1). Consequently, the estimated area available to the SGPF is 16,252 km$^2$, although it is acknowledged that not all of this area is suitable for prawn trawling due to complex topography (Carrick 2003) on the bottom and the preference of *M. latisulcatus* for sandy habitat (Tanner and Deakin 2001). Whilst the voluntary industry closures (adjacent Point Lowly and Port Broughton, and surrounding Wardang Island; Figure 1) are permanent, they are not legislated, and so are considered part of the available area.

### 2.2. Distribution of trawl effort

Historical catches of western king prawns by the SGPF date back to fishing year 1969, where a 'fishing year' is defined as the 12-month period from October to September according to the calendar year in which the period ended (e.g. October 2015–September 2016 = '2016'). Total catch and effort for 1969–2016 were verified as described by Noell et al. (2015). Spatially resolved catch and effort data, available from October 1982 onwards, are recorded by fishers in compulsory daily commercial logbooks, and include licence number, date, average speed and, for each trawl shot, catch, effort and fishing block (Appendix 1). From 1984–1987, the fishing block reference system underwent a transition from a regular 6' × 6' (~102 km$^2$) grid that covered the whole of Spencer Gulf ('original' blocks) to ten regions across most of the gulf to reflect the fishing grounds (Carrick 2003); the latter were subdivided into 125 irregularly shaped polygons ('current' blocks; mean: 166 km$^2$, range: 29–1,029 km$^2$).

Linear regression was used to describe inter-annual variation in total effort (and catch), while maps of trawl intensity by block (in h km$^{-2}$) were generated to examine spatial distribution of effort, but only after two necessary adjustments to the data. Firstly, to ensure spatial consistency from 1984–1987 (during the transition between block reference systems), only effort data logged in the predominant system were selected (i.e. original blocks from 1984–1986 and current blocks in 1987). Secondly, as logbook records from 1983–1990 were incomplete, the available effort in these years (25–99%, including those selected in the previous step)—considered to be representative of the fishery—was scaled up per block to annual totals. The distribution of effort was also examined at an annual scale and higher spatial resolution through kernel densities (or 'heat maps') of a representative proportion of trawl midpoints, which have been recorded in logbooks since 2003 (see Section 2.3.1).

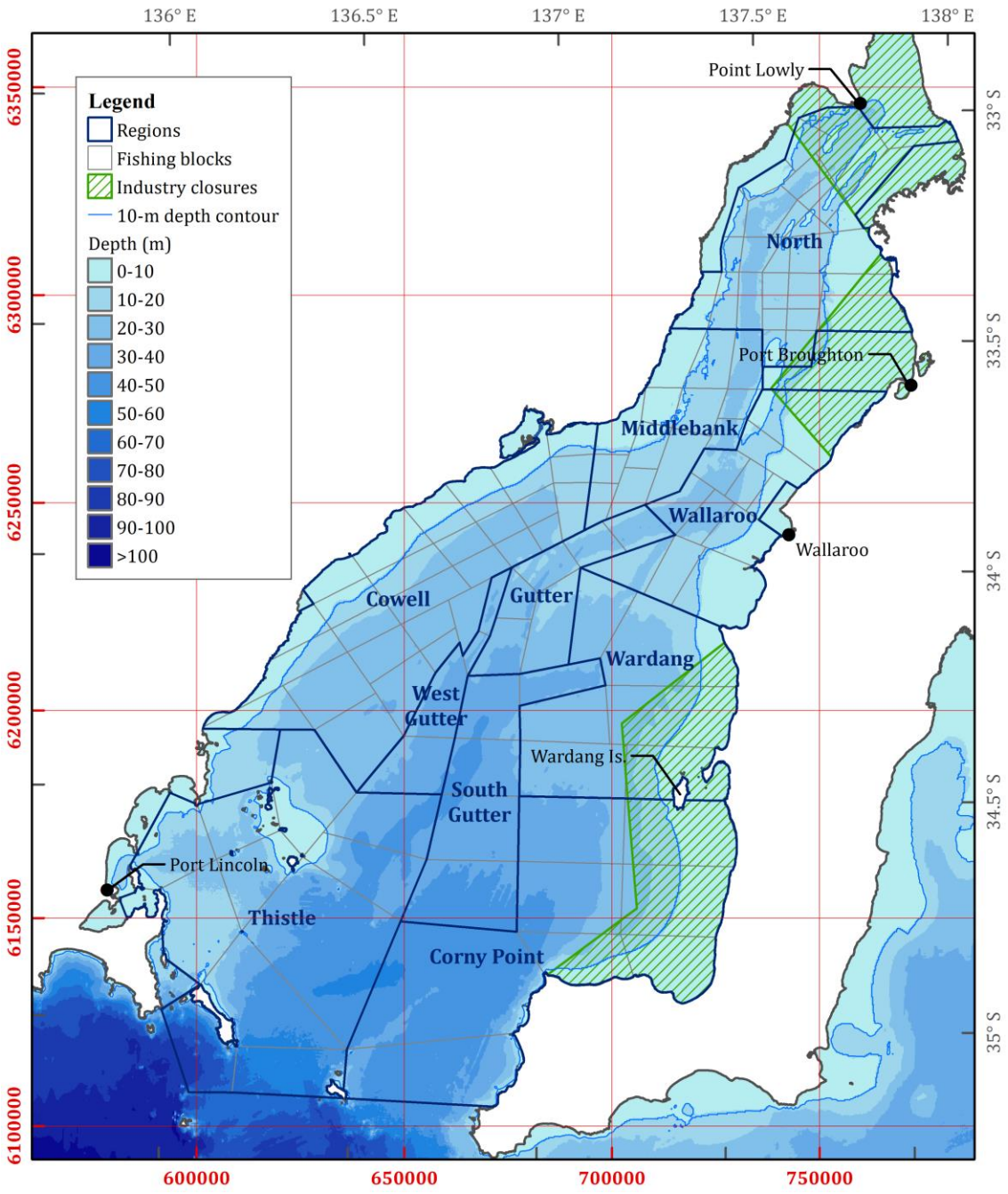


Figure 1. Map of Spencer Gulf, South Australia, showing regions and commercial fishing blocks of the SGPF, industry closures, key landmarks and depth contours. Eastings and northings of the Universal Transverse Mercator grid system are shown in red.

## 2.3. Spatial analysis

The once-off preparation of spatial layers was done using ArcGIS (Appendix 2). All other analyses of spatial data were programmed using the R statistical language (R Core Team 2016), with most tasks completed using the 'rgdal' (Bivand et al. 2016), 'raster' (Hijmans et al. 2015), 'CircStats' (Agostinelli 2009), 'rgeos' (Bivand and Rundel 2016) and 'spatstat' (Baddeley et al. 2016) packages. The workflow was separated into four modules: (i) logbook data processing; (ii) reconstruction of trawl

paths (line segments) and swept area (polygons); and calculation of trawl footprint through (iii) amalgamation of polygons; and (iv) classification of line densities.

*2.3.1. Logbook data processing*

Since 2002, fishers have been required to provide, in addition to fishing blocks, the midpoint location (in degrees decimal minutes according to the WGS84 datum) of at least three trawl shots each night—at the start, middle and end (Appendix 1). Disregarding the first year as one in which fishers were familiarising themselves with this requirement, logbook data from 2003–2016 were selected for analysis. During this period, 109,784 midpoints were recorded out of a total of 253,722 trawl shots. The distance of each shot, used later to calculate swept area, was determined from the product of effort (h) and the vessel-specific mean trawl speed (5–8 km $h^{-1}$)—the latter obtained at the best possible temporal resolution (i.e. daily, monthly, yearly).

These positional records were subjected to a series of non-spatial and spatial filters to obtain the final midpoints. Firstly, a small number (~1%) were identified as having excessively long trawl duration (>3.5 h), dubious coordinates (i.e. minutes were blank or ≥60) or located outside a bounding rectangle (longitude <135 or >139°E, latitude <32 or >36°S). Secondly, the midpoints were converted to spatial data and joined to shapefiles to identify those that were located inside fishing blocks/regions, but excluding depths <10 m and the three industry closures. As a result of these non-spatial and spatial filters, 100,013 midpoints, representing 39.4% of all trawl shots, were retained for trawl footprint calculations, while the remaining midpoints (*n* = 9,771) were considered erroneous and omitted.

*2.3.2. Reconstructing trawl paths and swept area*

Trawl midpoints were transformed to the Universal Transverse Mercator (UTM) grid system (GDA94/MGA zone 53) so that they could be treated as Cartesian coordinates (in false eastings and northings) and start/end points of line segments representing trawl paths and vertices of polygons representing swept areas could be calculated by trigonometry. The UTM system was also considered appropriate for trawl footprint calculations as it is conformal with minimal area distortion within a zone (Zhu 2016). Given the midpoint coordinates, calculated distance, a constant trawl width[2] (29.92 m) and the assumption that trawl shots are often conducted in a straight line (G. Palmer, pers. comm.), the only remaining variable required to create the line segments and polygons was direction. Although not recorded in fishing logbooks, trawl direction was sourced from regularly conducted surveys, each of which comprises ~200 trawl shots throughout the gulf and is considered, in terms of direction, to be representative of normal fishing. Survey shots are designed to be between fixed start and end positions; however, the spatial variability in actual paths trawled between surveys was considered sufficient justification for examining trawl shot direction across several surveys. Based on the directions of survey shots completed during fishing years 2014 and 2015 (*n* = 1,069) (Figure 2), von

[2] In this study, trawl width is the total distance between both pairs of otter boards (of a double-rig configuration) at the leading edges. It is variable, and depends on sweep length, board dimensions, vessel speed and angle of attack (G. Palmer, pers. comm.).

Mises distribution parameters, mean direction $\mu$ (mu) and concentration $\kappa$ (kappa) (Mardia and Jupp 2009), were determined for each region (Table 1). For each midpoint, a region-specific direction was randomly generated from a distribution based on these parameters (and standardised between 90 and 270°) (Figure 2). Prior to these simulations, the random generator seed was set to enable results to be reproduced and demonstrated to fishery managers and industry representatives. Retaining attributes of fishing year and region for each midpoint, the calculated start/end coordinates and vertices were converted to line segments and polygons.

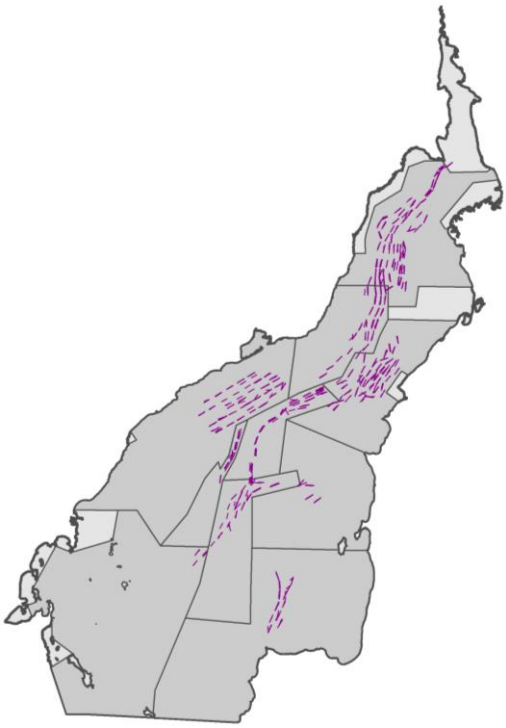

Figure 2. Trawl paths by region, obtained from surveys in fishing years 2014 and 2015 ($n$ = 1069).

Table 1. von Mises distribution parameters for trawl shot direction by region, obtained from surveys in fishing years 2014 and 2015.

| Region | Shots ($n$) | Mean direction $\mu$ (mu) | | Concentration $\kappa$ (kappa) |
|---|---|---|---|---|
| | | Radians | Degrees | |
| North | 274 | -2.831 | 197.8 | 7.83 |
| Middlebank | 117 | -2.888 | 194.5 | 10.39 |
| Wallaroo | 213 | -2.535 | 214.8 | 6.34 |
| Cowell | 158 | -2.136 | 237.6 | 71.35 |
| Gutter | 136 | -2.361 | 224.7 | 4.06 |
| Wardang | 20 | -2.385 | 223.3 | 1.61 |
| West Gutter | 40 | -2.828 | 198.0 | 29.72 |
| South Gutter | 59 | -2.587 | 211.8 | 4.39 |
| Thistle | 7 | -2.472 | 218.4 | 175.18 |
| Corny Point | 43 | -2.866 | 195.8 | 12.36 |

*2.3.3. Calculating the swept-area trawl footprint*

The final midpoints, representing 39.4% ($n$ = 100,013) of all shots over 14 fishing years, equated to 100% coverage over ~5.5 years (termed 'equivalent years'). This also translated to 40.5% of actual effort (in hours) and 37.1% of the total catch. Based on a mean of 18,123 shots per year, the polygons reconstructed from these midpoints were randomly sampled without replacement to obtain nested subsets of 5, 4, 3, 2 and 1-year equivalents (again, setting the seed for reproducibility), and then amalgamated (or dissolved) using the 'aggregate' function in the raster package. Computationally, the dissolution of this number of polygons ([1+2+3+4+5+5.5] × 18,123) was particularly demanding and required a computer with fast processing capabilities (e.g. with 32 GB of RAM, the runtime for this task was ~48 h). The cumulative trawl footprint of the amalgamated polygons was calculated for the entire fishery and by region. Using non-linear least squares, an exponential decay model (increasing form), $y = C\ e^{-kt}$, was fitted to these estimates (including regions with large swept areas relative to available area) to determine $C$, its asymptote, and $k$, the growth constant. Note that, because mean trawl duration was slightly longer for shots with midpoints recorded than those without, the actual total effort for the 1–5 and 5.5-year equivalent samples was 1.03, 2.06, 3.08, 4.11, 5.13 and 5.66 'average effort' years. Therefore, while terminology refers to the former, the latter values (in years or hours) were used for relevant calculations.

*2.3.4. Calculating a density-derived trawl footprint*

An alternative measure of trawl footprint was calculated based on trawl line densities. Unlike the swept-area trawl footprint, which is an absolute measure of the area trawled, the density-derived trawl footprint relates to the area in which the mean annual trawl intensity is above a predetermined level. Using the 'pixellate' function in the spatstat package, image matrices at different resolutions (output pixel sizes of 500 × 500, 100 × 100, 50 × 50 and 30 × 30 m) were created from the line segments representing individual trawl paths. Here, each pixel was assigned a density value $D$, which equaled the sum of trawl line lengths within the pixel (m px$^{-1}$), and related to trawl intensity $I$ (in h km$^{-2}$) according to the formula:

$$D = IYS\left(\frac{px_{\text{dim}}}{1000}\right)^2 ,$$

where $Y$ is number of equivalent years (with 100% coverage), $S$ is mean speed (m h$^{-1}$) and $px_{\text{dim}}$ is pixel dimension (m). The 'tessellate' function was then used to group pixels by intensity category, where cutoffs were similar to those used by Currie et al. (2011) and interpreted by Mayfield et al. (2014) (i.e. 0-0.1 = 'no/neglible fishing', 0.1-1 = 'low', 1-10 = 'moderate, >10 = 'high'). Using this method, trawl footprint was calculated as the sum of pixels falling within the low, moderate and high intensity categories, and fitted to the same exponential model used for the cumulative swept-area footprint.

## 3. RESULTS AND DISCUSSION

This study demonstrates the successful application of two methods to estimate the trawl footprint of the SGPF. Estimates were based on the reconstruction of trawl paths and individual swept areas using detailed effort data from fishing logbooks and, until electronic logbooks are implemented across the fleet, included simulations of trawl direction from known survey trawl paths. All analyses were programmed and completed using open-source software, with the view that updated estimates will need to be produced at least annually.

### 3.1. Reference period for determining trawl footprint

Annual total effort in the SGPF reached a peak of 42,882 h in fishing year 1976 (Figure 3a), only eight years after the fishery began. This coincided with the introduction of current legislation that restricted the number of licences and vessels to 39. While the size and composition of the fleet has largely remained the same since, trends in effort were divided, visually, into two distinct periods: (i) from 1976–2002, where it declined steadily and significantly at a rate of 914 h $yr^{-1}$ (regression: $t_{(25)} = 18.32$, $p < 0.001$); and (ii) from 2003 onward, where it stabilised (regression: $t_{(12)} = 1.04$, $p > 0.05$) around a mean (± SD) of 18,622 ± 1,235 h (~43% of the historic peak). Despite the overall reduction in effort since 1976, catch has not been compromised (regression: $t_{(39)} = 0.20$, $p > 0.05$), with annual landings of 1891 ± 298 t.

When this decline in effort between periods 1987–2002 (current blocks; effort declining) and 2003–2016 (current blocks; effort stable) was depicted spatially, a reduction in mean annual trawl intensity was evident in most blocks in the middle of the gulf, especially those in the North and Middlebank regions (Figures 3c, 3d and 4). Some of this effort was redistributed, with effort becoming concentrated in a few blocks within the Wallaroo region (Figure 4). On closer examination of the latter period, the distribution and density of trawl midpoints revealed three main hotspots in most years—two in the Wallaroo region (one extending into the northern end of the Gutter) and one in the Middlebank region (Figure 5). Along with relatively stable effort and the availability of midpoints, this consistent trawl pattern provided the basis for establishing 2003–2016 as an appropriate reference period for determining a more detailed trawl footprint of the fishery.

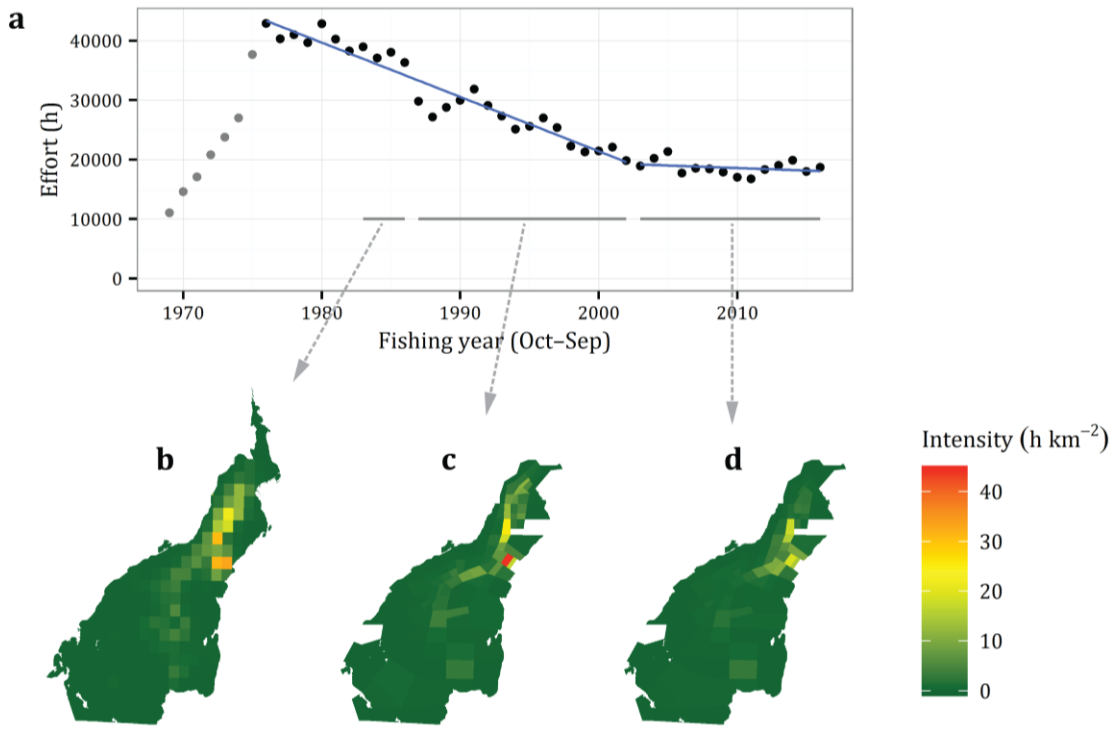


Figure 3. Temporal and spatial distribution of trawl effort in the SGPF, shown as (a) annual fleet totals for fishing years 1969–2016, and mean annual intensity by block from (b) 1983–1986 (original blocks; effort declining), (c) 1987–2002 (current blocks; effort declining) and (d) 2003–2016 (current blocks; effort stable).

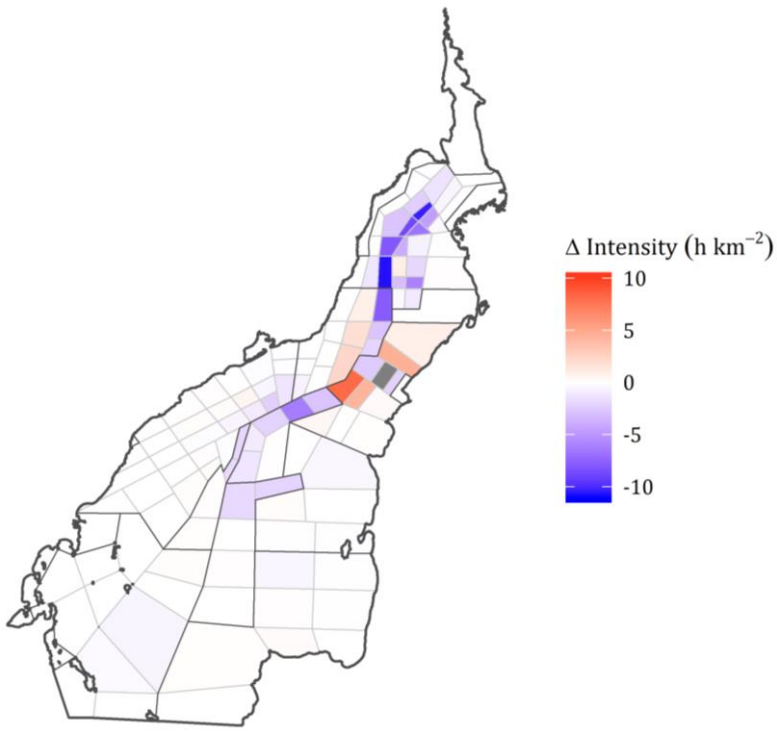


Figure 4. Change in mean annual trawl intensity by block between the periods 1987–2002 (effort declining) and 2003–2016 (effort stable). Note: a large difference of -25 h km$^{-2}$ for block 43 (shaded grey) was omitted to prevent distortion of the colour-scale gradient.

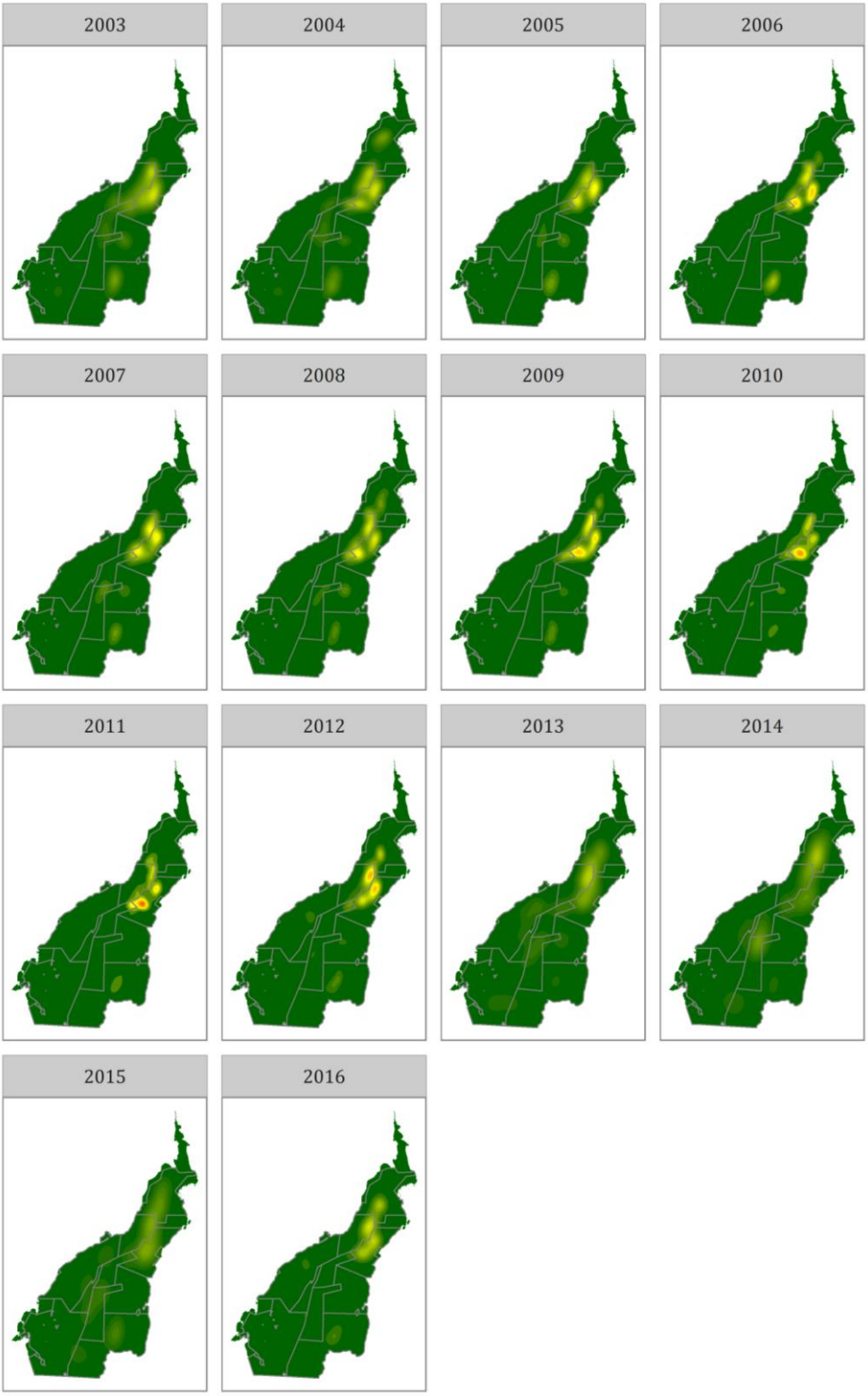


Figure 5. Annual heat maps of trawl effort in the SGPF, illustrated by kernel densities of midpoints recorded in logbooks from 2003–2016.

## 3.2. Trawl footprint estimates

### *3.2.1. Swept-area trawl footprint*

The amalgamation of polygons over the equivalent of ~5.5 years (Figure 6) culminated in a total swept-area trawl footprint for the SGPF of 4,282 km$^2$ (Table 2). Due to a small portion of the reconstructed polygons extending outside the available area, a discrepancy was identified in the total trawl footprint of 13 km$^2$; however, this was considered trivial relative to the majority of the data. Among the regions with the most area trawled relative to the available area, the trawl footprint occupied 480 km$^2$ in the North (39.0% of the available area), 513 km$^2$ in Middlebank (61.4%), 726 km$^2$ in Wallaroo (82.2%) and 340 km$^2$ in the Gutter (45.9%) (Figure 7). Because the annual increments approaching these totals were increasing but at a diminishing rate (with virtually the same level of effort), this meant that less new ground was being trawled each year. At ~5.5 years, overlapping swept areas accounted for more than three-quarters (78.1%) of the total trawl footprint (Table 2; Figure 6).

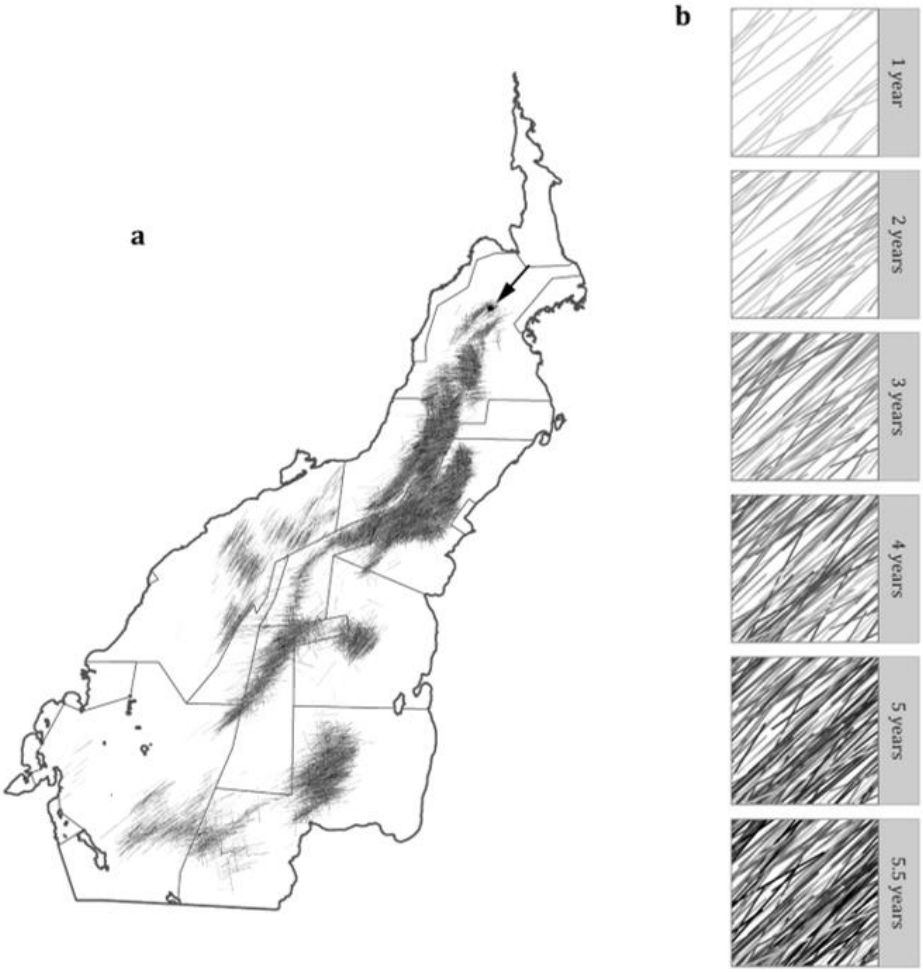


Figure 6. Accumulation of reconstructed trawl-swept areas (polygons) over ~5.5 years for (a) the whole fishery and (b) a 2 x 2 km area in the North region (location shown on map).

Table 2. Cumulative effort, swept area (unamalgamated and amalgamated polygons) and overlap over ~5.5 years.

| Effort | | | | Swept area ($km^2$) | | Overlap (%) |
|---|---|---|---|---|---|---|
| Trawl midpoints | Years (equiv.) | Hours | Years (actual) | Unamalg. | Amalgamated | |
| 18123 | 1 | 19114 | 1.03 | 3547 | 1933 | 45.5 |
| 36246 | 2 | 38319 | 2.06 | 7106 | 2799 | 60.6 |
| 54369 | 3 | 57398 | 3.08 | 10643 | 3380 | 68.2 |
| 72492 | 4 | 76516 | 4.11 | 14189 | 3806 | 73.2 |
| 90615 | 5 | 95619 | 5.13 | 17729 | 4132 | 76.7 |
| 100013 (total) | 5.5 | 105469 | 5.66 | 19552 | 4282 | 78.1 |

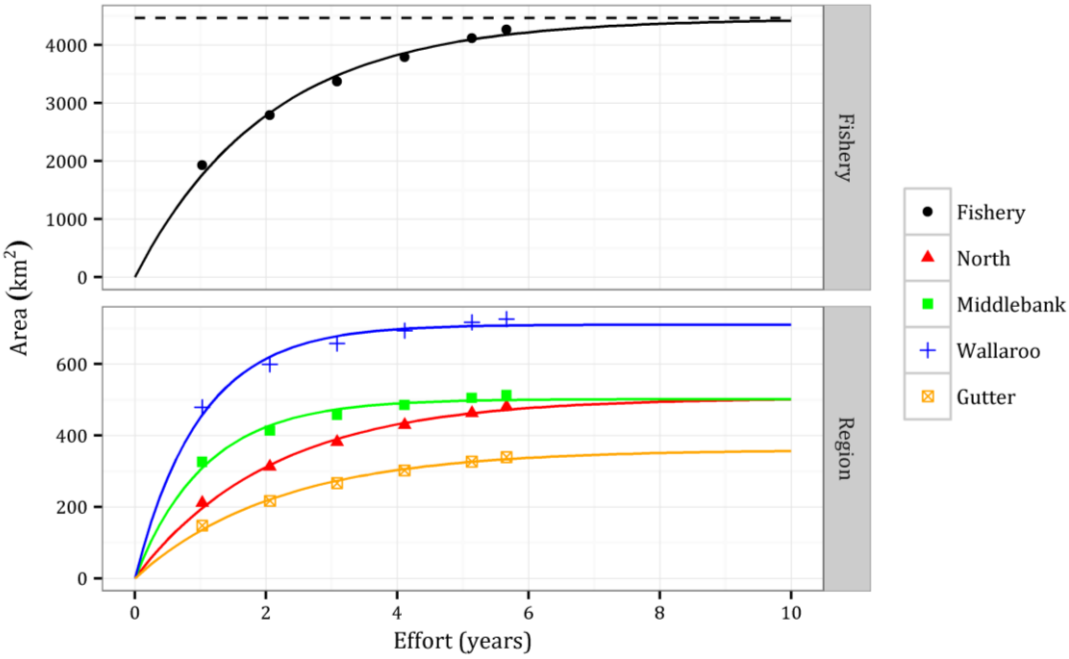


Figure 7. The predicted relationships between effort and total swept-area trawl footprint (top) and within selected regions (bottom) over ~5.5 years (and projected to 10 years). The dashed line in the top graph represents the estimated trawl footprint asymptote for the fishery (4,100 $km^2$).

Exponential models fitted to the cumulative total and regional trawl footprints yielded asymptotes of 4,468 $km^2$ for the entire fishery—equating to 27.5% of the area available to trawling and 19.7% of the whole gulf—and 505, 502, 710, and 360 $km^2$ for the North, Middlebank, Wallaroo, and Gutter regions, respectively. That the total and regional trawl footprints were close to (at least 95%) or, in some cases, had reached their projected estimates (Middlebank and Wallaroo) (Table 3; Figure 7) further demonstrates the consistency in the trawl pattern between years. It also suggests that there is likely to be little further increase to the trawl footprint, providing the fleet continues to behave in the same way that it has for the last 14 years.

Table 3. Estimated parameters of the exponential decay model (increasing form) fitted over ~5.5 years to the cumulative swept-area trawl footprint (including selected regions) and density-derived estimates of trawl footprint (with a pixel size of 30 × 30 m and cutoffs of 0.1 and 0.5 h km$^{-2}$ yr$^{-1}$).

| Region | Asymptote *C* (km$^2$) | | | Growth constant *k* (yr$^{-1}$) | | |
|---|---|---|---|---|---|---|
| | Estimate | SE | *t*-value | Estimate | SE | *t*-value |
| *Swept-area trawl footprint* | | | | | | |
| Total | 4468 | 139 | 32.1*** | 0.492 | 0.042 | 11.7*** |
| North | 505 | 13 | 40.3*** | 0.480 | 0.032 | 14.9*** |
| Middlebank | 502 | 10 | 50.0*** | 0.932 | 0.083 | 11.3*** |
| Wallaroo | 710 | 13 | 55.8*** | 1.006 | 0.085 | 11.9*** |
| Gutter | 360 | 10 | 34.7*** | 0.462 | 0.035 | 13.2*** |
| *Density-derived trawl footprint* | | | | | | |
| Total (cutoff 0.1) | 4684 | 140 | 33.6*** | 0.557 | 0.050 | 11.1*** |
| Total (cutoff 0.5) | 4253 | 104 | 40.8*** | 0.628 | 0.051 | 12.3*** |

These data could also be used to monitor inter-annual spatial shifts in effort. While a consistent trawl pattern over 14 years provided justification for random sampling of typical-year aggregates of midpoints at 100% coverage, it has the effect of smoothing out any actual variations over this period, thus limiting the ability to detect when a spatial shift in effort may have occurred. If the total swept-area trawl footprint estimated in this study is treated as a baseline, then it should be possible to identify any future deviations from this and further interrogate the data to locate where these deviations occurred. If the trawl footprint was to continue to expand beyond the current footprint, the model-fitted asymptote would also increase, and a review of any threshold derived from this (see Section 3.5) may be warranted. Further testing would also be required to discern whether the change is attributed to fishing or an artefact of the sampling method used to create the baseline.

### *3.2.2. Density-derived trawl footprint*

Trawl footprint estimates derived from trawl line densities were influenced by the output resolution (pixel size) at which trawl intensity was determined (Figure 8) and the minimum intensity (cutoff) for separating trawled and non-trawled areas. Based on a cutoff of 0.1 h km$^{-2}$ yr$^{-1}$, the total density-derived trawl footprint (at ~5.5 years) was estimated at 6,877 km$^2$ at a pixel size of 500 × 500 m, but this estimate reduced with pixel size to 4,592 km$^2$ at 30 × 30 m (Figure 9). While the latter resolution might be excessive for some applications (e.g. zoning), the accuracy and precision of the trawl footprint estimate is considered to improve as the pixel dimensions approximate the width of the trawl opening (29.92 m), as less ‘smearing’ of trawl effort occurs over extraneous surrounding area (Penney 2011). The effect of the cutoff on the trawl footprint was also examined, specifically the intensity that separates the area of low intensity trawling from the area of no/negligible trawling. To be consistent with other studies involving the SGPF (Currie et al. 2011; Mayfield et al. 2014), this delineation was set at 0.1 h km$^{-2}$ yr$^{-1}$ for all pixel sizes, although for 30 × 30 m pixels, the trawl footprint was also calculated with a cutoff of 0.5 h km$^{-2}$ yr$^{-1}$. The higher cutoff resulted in the re-classification of 368 km$^2$ from low intensity to no/negligible trawling, and therefore a reduced trawl footprint estimate of 4,224 km$^2$ (not shown).

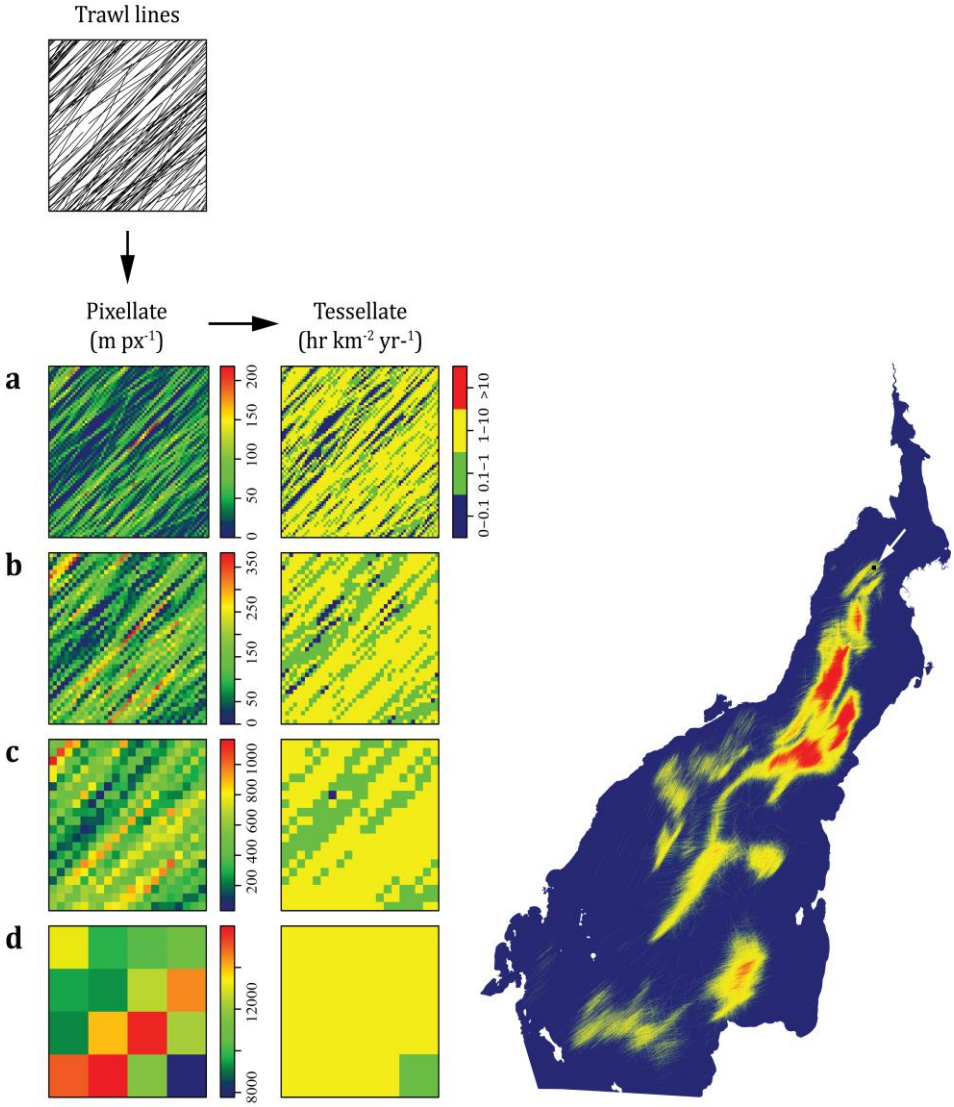


Figure 8. The conversion of trawl line lengths per pixel to density (pixellation) and intensity category (tessellation) at (a) 30 × 30, (b) 50 × 50, (c) 100 × 100 and (d) 500 × 500 m pixel sizes, demonstrated for a 2 x 2 km area in the North region of the fishery as an example (location shown on map of trawl intensity).

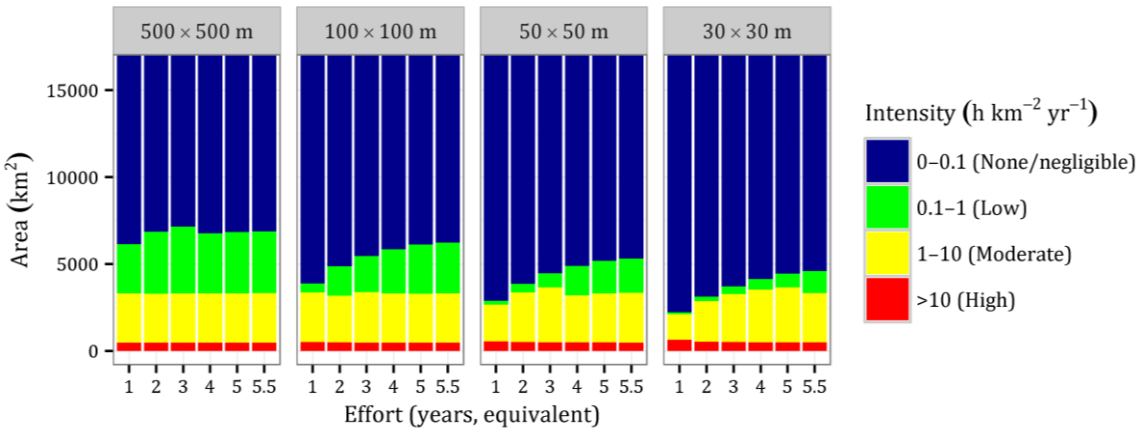


Figure 9. Stacked barplot showing estimates of the density-derived trawl footprint—comprising areas of low, moderate and high intensity—by pixel size over ~5.5 years.

As mean trawl intensity per pixel can increase or decrease as the timeframe over which the mean is calculated increases, the density-derived trawl footprint can also fluctuate (unlike the swept-area estimate, which can only stay the same or increase). While areas of low, moderate and/or high intensity varied over ~5.5 years for all pixel sizes, the sum of these components appeared to plateau—similar to the swept-area estimate—for pixels 100 × 100 m and smaller (Figure 9). Therefore, based on the 30 x 30 m pixel size as an example, the same exponential model was fitted to density-derived estimates of trawl footprint. Applying cutoffs of 0.1 and 0.5 h $km^{-2}$ $yr^{-1}$ (for comparison, as above), these models yielded asymptote estimates of 4,684 and 4,253 $km^2$, respectively (Table 3).

3.3. Data considerations

An important first step in quantifying the trawl footprint is to minimise any issues that may result from errors recorded in logbooks or entered into the database. While it was relatively easy to identify obvious errors (e.g. midpoint coordinates located on land), outliers (e.g. unusually slow or fast trawl speeds) and suspect data (e.g. inconsistent coordinate units), which were subsequently omitted or corrected where possible, there are probably other subtle errors that would be more difficult to detect. Almost 10% of the orginal data were omitted from the analysis, mostly because the midpoint coordinates were located outside the bounds of the fishery, at depths <10 m, inside closures or on land; therefore, it is reasonable to assume that another unquantified proportion of midpoints also contained errors but were retained by virtue of their coordinates falling within the available area. Given that trawling in the gulf is highly clustered within a relatively small area, the inclusion of erroneous data—assumed to be distributed randomly—is likely to result in an overestimate of swept area, as it is more likely to lie in the larger untrawled area than in the smaller trawled area. As shown above, this overestimate can be partly offset by increasing the minimum cutoff intensity.

The decision to form equivalent-year groups of randomly selected trawl midpoints was to more accurately describe and predict the change in trawl footprint over time. Midpoints were recorded, on average, for ~40% of all shots over 14 years. Exploratory analysis of the swept-area trawl footprint—the product of these midpoints—demonstrated an increase each year but, while the rate of increase slowed in some years due to overlapping areas, it did not level-off as much as expected. This suggested that, at a midpoint coverage of ~40%, either several more years of data were required to get a better estimate of the true trawl footprint or there was insufficient overlap each year to generate the required plateau effect. By comparison, the equivalent-year groups resulted in a much better model-fit, where the estimated total trawl footprint plateaued to within 5% of the projected footprint. So, while the estimate of total trawl footprint based on all midpoints was ultimately the same, a more sensible trajectory was obtained when the data were aggregated into an equivalent number of years with 100% coverage. An alternative to aggregating random samples is to sample the available midpoints in sequence, which means that, at 40% coverage, the entire sample would have been divided up into ~2.5-year blocks. However, while the annual spatial trawl pattern is consistent

between years, within-season temporal differences in the distribution of effort (e.g. Noell and Hooper 2015) precluded the formation of equivalent-year groups using consecutive samples.

In the absence of information on trawl paths, the estimation of trawl footprint in this study was predicated on the ability to reconstruct trawl paths and swept areas from midpoints and trawl direction, speed and duration. Data were available for all of these variables, except trawl direction, which was simulated by region from surveys. Errors associated with these variables were assumed to be random, with simulated trawl direction probably being the main source of uncertainty. To estimate the effect of direction on the estimated trawl footprint, the initial plan was to run many (e.g. thousands) simulations—randomly varying the sampled midpoints and their direction with each run—and obtain confidence intervals around the mean; however, this was thwarted by the long runtime per simulation (~40 h). Nevertheless, five simulated estimates were obtained; these yielded an imprecision (as indicated by coefficient of variation) of <0.1%, suggesting that propagation of errors associated with trawl direction has little effect on the total trawl footprint.

### 3.4. Potential improvements with electronic fishing logbooks

Electronic logbooks are currently being developed and trialled for the SGPF, and are planned for implementation within the next two years. Theoretically, their introduction should eliminate many of the errors identified above, particularly those relating to coordinates and trawl direction. Coordinates for the start and end positions will be required for 100% of shots, and there will be the potential for administrators of the system to extract locations at regular intervals (similar to polling rates in vessel monitoring schemes). All of these technological improvements should enable the most accurate estimates of trawl footprint. A logical step would therefore be to verify the accuracy of trawl footprint estimates in this study with those derived from electronic logbooks at an appropriate time. Based on the number of midpoints required in this study to obtain a stable trawl footprint, this may be at least a few years after electronic logbooks are implemented. Ideally, until then, electronic logbook data will be incorporated into the existing database and used to build on and further consolidate the trawl footprint determined in this study. Either way, programming code has now been developed to accommodate both forms of data for updating and monitoring the trawl footprint estimate.

### 3.5. Considerations for setting a threshold

In proposing a threshold for the SGPF, there are four main considerations: (i) purpose of the threshold; (ii) the method used to estimate the trawl footprint; (iii) the cutoff intensities (if required); and (iv) intensity categories for defining footprint (if required). The original motivation for mapping trawl effort was to objectively define the trawl footprint, which would then be used as a surrogate for determining the extent of trawling pressure. While some fisheries might adopt the ‘freeze the footprint’ approach for spatial management (Shester and Warrenchuk 2007), others conditionally provide for fishing in new areas, or expanding fishing effort (or catch) beyond existing levels (e.g. Penney 2011).

Although the projected trawl footprints using the swept-area method and density-derived method (30 × 30 m pixels; minimum cutoff intensity of 0.5 h $km^{-2}$ $yr^{-1}$) were virtually the same, they are interpreted differently. Since the swept-area estimate is cumulative (Table 4), a larger buffer might be required because once the threshold is breached it will remain breached (unless it is revised again), whereas the density-derived estimate has the potential to vary about the mean. Regardless of which method is selected for ongoing monitoring, the most important requirement is to ensure that the same one is used (including specifications for the density-derived method) to compare between timeframes.

Table 4. Qualitative comparison of swept-area and density-derived trawl footprint estimates obtained in this study.

| Characteristic | Swept-area trawl footprint | Density-derived trawl footprint |
|---|---|---|
| Estimate of total trawl footprint | 4,282 $km^2$ (based on trawl width 29.92 m) | 4,224 $km^2$ (based on pixel size 30 × 30 m, minimum cutoff intensity 0.5 h $km^{-2}$ $yr^{-1}$) |
| Predicted asymptote | 4,468 $km^2$ | 4,253 $km^2$ |
| Type of estimate | Cumulative | Mean |
| Spatial object | Polygons (swept area) | Trawl paths (line segments) |
| Method | Amalgamation of polygons (overlaps dissolved) | Density of lines (lengths per pixel) |
| Output | Complex polygon | Pixels classified into intensity categories |
| Influences on estimate | None (absolute measure) | Resolution of output (i.e. pixel dimensions) and cutoff intensities |
| Long-term behaviour of estimate | Increases at a decreasing rate towards asymptote – cannot decrease | Variable mean (depends on influences) |
| Timeframe for reliable estimate | Several years with 100% coverage | Several years with 100% coverage |
| Computation runtime | 1–2 days | 2–3 hours |
| Likely result of undetectable errors in coordinates | Overestimate of trawl footprint | Overestimate of trawl footprint but can be offset through adjustment to minimum cutoff intensity |

Should the density-derived method be chosen, the trawl footprint estimate will vary depending on the minimum cutoff intensity that separates the trawled area from the area of no/negligible trawling (Table 4). If there are suspected errors in the midpoint coordinates, then a feasible strategy to offset the resulting overestimate is to increase the cutoff (as explained in Section 3.3). While density-derived trawl footprint estimates in this study comprised low, moderate and high intensity categories, the omission of the low intensity category (for example) will reduce the footprint estimate by the same amount.

Irrespective of the approach chosen, it is unlikely that trawl footprint will be a panacea for addressing ecological responsibilities of the fishery. As estimates of the trawl footprint are a surrogate measure of the impact of trawl effort (not a substitute for monitoring bycatch species), consideration should be given to monitoring species of interest to supplement regular estimates of footprint within the ongoing ecosystem monitoring program for the fishery. Together, these two sources of information are

considered to provide the most informative measure of fishing pressure possible, and are necessary for demonstrating and supporting an ecosystem approach to managing this fishery.

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## 5. APPENDIX

Appendix 1. Logbook example.

SARDI
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**SOUTH AUSTRALIAN WESTERN KING PRAWN DAILY FISHING LOGBOOK FORM**

**SAP**

LICENCE NO: P40 | DATE: 22 / 4 / 2005 | FISHING PERIOD: from 20 / 4 / 05 to 28 / 4 / 05

SKIPPER NAME: FRED RICH | SIGNATURE: Fred Rich | VESSEL NAME: STRIKER

| SHOT NO. | BLOCK NO. | START TIME | FINISH TIME | TRAWL MINS | CATCH (KG) | DEPTH (metre) | Wildlife Interaction | MIDPOINT OF TRAWL SHOT LATITUDE | MIDPOINT OF TRAWL SHOT LONGITUDE | COMMENTS |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 43 | 20:30 | 21:00 | 30 | 60 | 22.6 | | 33 · 53 · 62 | 137 · 28 · 91 | BC/H, SNAP/10 160/6.8 |
| 2 | ↓ | 21:10 | 21:40 | 30 | 150 | 23-24 | | · · | · · | |
| 3 | | 21:45 | 22:30 | 45 | 275 | 23.0 | | · · | · · | |
| 4 | | 22:35 | 23:25 | 50 | 250 | 24.5 | | · · | · · | |
| 5 | | 23:30 | 0:00 | 30 | 129 | 20.6 | | · · | · · | |
| 6 | ↓ | 0:10 | 1:00 | 50 | 0 | — | | STEAMING TO TOPEND | | |
| 7 | 52 | 1:00 | 2:00 | 60 | 720 | 21.6 | | 33 · 56 · 80 | 137 · 15 · 21 | |
| 8 | ↓ | 2:10 | 3:00 | 50 | 500 | 21.6 | | · · | · · | BC/H |
| 9 | | 3:10 | 4:00 | 50 | 450 | 21.8 | | · · | · · | |
| 10 | | 4:05 | 4:50 | 45 | 315 | 21.8 | | · · | · · | |
| 11 | ↓ | 4:55 | 5:30 | 35 | 175 | 20.0 | | · · | · · | |
| 12 | 50 | 5:35 | 6:10 | 35 | 105 | 19.8 | | 33 · 58 · 10 | 137 · 13 · 26 | |
| 13 | ↓ | 6:15 | 6:20 | 5 | 0 | 18.8 | | · · | · · | |
| 14 | ↓ | 6:20 | 7:00 | 40 | 84 | 17.5 | | · · | · · | |
| 15 | | : | : | | | | | · · | · · | |
| 16 | | : | : | | | | | · · | · · | |

AVERAGE TRAWL SPEED 3.2 knots | TOTAL 555 | 3,213

(WILDLIFE INTERACTION: If YES then tick and complete a form in the Wildlife Interaction Logbook)

BRINE CATCH: 0 . KG

COMMENTS (non-mandatory) - PRAWN SIZE BASED ON BUCKET COUNTS.

BLOCK: 43 SHOT NO: 1 NO. PRAWNS/BKT: 160 BKT WEIGHT: 6.8 KG

BLOCK: 52 SHOT NO: 7 NO. PRAWNS/BKT: 140 BKT WEIGHT: 6.6 KG

BLOCK: 50 SHOT NO: 12 NO. PRAWNS/BKT: 170 BKT WEIGHT: 6.8 KG

All information is mandatory except the comments sections and water temperature. The mid-point GPS locations of 3 trawl shots are required through the night, preferably at start, middle and last shot. If change or move to a different fishing block the mid-point location of the shot is required. Please use arrow or " for shots within same block and depth. Ensure that for zero by-product catch use "0" or "–".

FROZEN CATCH - SPECIFY GRADES IN KG

| GRADE | U6 | U8 | U10 | 10/15 | 16/20 | 21/25 | 26/30 | 30+ | S/B | | | TOTAL KG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| KG | 340 | 680 | 1,360 | 750 | 170 | 0 | 0 | 0 | 100 | | | 3,400 |

RETAINED BYPRODUCT: CALAMARY: 15.0 KG | BUGS: 1.0 KG | WATER TEMPERATURE: 20.9 °C

*WEST COAST ONLY:* ARROW SQUID: . KG | OCTOPUS: . KG | SCALLOPS: . KG

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Appendix 2. Pre-processing of spatial layers in ArcGIS.

| Step | Input file(s) | Input file type | Source | Tool | Method | Output file | Output file type | Description |
|---|---|---|---|---|---|---|---|---|
| 1. | *sgpf_reg.shp* | Polygon | Spatial Information Services (SA Govt) | | | | | Regions (amalgamation of fishing blocks) of the SGPF |
| 2. | *ausbath_09_v4* | Raster | Geosciences Australia (Australian Govt) | | | | | Australian bathymetry and topography grid |
| 3. | *sgpf_closures.shp* | Polygon | Created by author | | | | | Port Broughton and Wardang closures |
| 4. | *ausbath_09_v4*, *sgpf_reg.shp* | Raster | | Clip (Data Management) | Clip *ausbath_09_v4* to *sgpf_reg.shp* extent | *rastclip_sgpf* | Raster | Bathymetry grid for the SGPF |
| 5. | *rastclip_sgpf* | Raster | | Raster Calculator (Spatial Analyst) | 'Con("*rastclip_sgpf*" <= -10,1,0)' | *rastcalc_ex10* | Raster | Bathymetry grid coded by depth ('1' = depths ≥10 m, '0' = depths <10 m) |
| 6. | *rastcalc_ex10* | Raster | | Raster to Polygon (Conversion) | Convert raster dataset to polygon features; | | | |
| | | | | Editor | Delete polygons with 'gridcode' = 0 | *rast2poly_ex10.shp* | Polygon | Area of fishery (excl. depths <10 m) |
| 7. | *rast2poly_ex10.shp*, *sgpf_reg.shp* | Polygon | | Union (Analysis) | Compute a geometric union of input features | | | |
| | | | | Editor | Delete overlapping polygons and outlying vertices | *sgpf_reg_ex10.shp* | Polygon | Area of fishery by region (excl. depths <10 m) |
| 8. | *sgpf_reg_ex10.shp*, *sgpf_closures.shp* | Polygon | | Union (Analysis) | Compute a geometric union of input features | | | |
| | | | | Editor | Delete overlapping polygons and outlying vertices | *sgpf_reg_ex10clos.shp* | Polygon | Area of fishery by region (excl. depths <10 m and industry closures) |