Assessment of interaction between giant crab trap and benthic trawl fisheries

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Contents

Acknowledgments

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Executive summary

Giant crab (GC) and bottom trawl (BT) fisheries have overlapping fisheries grounds in some areas around Tasmania (TAS). This has led to conflict around several distinct issues which were:

(i) direct gear interactions (e.g. loss of crab traps);
(ii) fishing mortality of giant crabs as byproduct of the trawl fishery;
(iii) mortality/damage to crabs that come in contact with trawl gear; and
(iv) indirect impact on crab productivity through changes to habitat.

A previous project (FRDC 2004/066) examined habitat types in the areas where the fisheries interacted and habitats / locations that were important for the crab fishery were identified from which a spatial management arrangement could be developed.

A resolution to the conflict between the fisheries was previously attempted with co-management rather than regulatory response. The fisheries defined voluntary exclusion zones that the trawl sector agreed to avoid. However, the interaction remained with crab fishers reporting that bottom trawl effort continued to occur in the areas where there had been agreement to cease trawling. Tasmanian crustacean fishers identified the analysis of interactions as a high priority research need for several years and this project resulted.

Gear Interaction

Gear interaction means direct contact between gear from the different sector and was raised as a concern by crab fishers because it can result in the loss of their traps. Of the separate issues described above, this was their lowest concern and the most easily resolved.

There appeared to be high potential for interaction between benthic trawl and crab trapping on the West Coast, where approximately 80% of the BT effort overlapped with grounds used for GC fishing between 2008 and 2012. This proportion dropped to 65% in 2014. On the East Coast, the proportion of BT effort that intersected areas used for GC trapping fluctuated between 30% and 40%. The potential gear interaction between both fisheries increased from 2008 to 2012 and then decreased to 2015. This issue has been a minor concern because the scale of the loss is small relative to concerns around productivity, plus there are simple solutions for resolving the problem. There have been attempts to prevent gear interactions by encouraging communications between fishers from sectors so that trawlers could avoid passing through sets of crab traps. Anecdotal information from fishers is that this approach has been generally successful although not always.

Fishing mortality of crab from bottom trawling

Fishing mortality of giant crab from trawl can potentially occur in two ways – the observed catch that is retained in trawl gear, some of which may be released unharmed, plus damage to crabs that come in contact with trawl gear but are not retained in the gear. Only a small amount of giant crab bycatch was recorded in trawls and this varied with latitude (highest GC catch in the Northwest). The scale of GC bycatch reported by BT indicates that this is a minor issue, as per gear interaction.

No data is available on the scale of any mortality of crabs that come in contact with trawl gear but are not retained. Collecting information on this would require dedicated field research.

Habitat interaction

Giant crabs are associated with a specific habitat type which is unconsolidated sediment supporting a low turf / thicket cover of bryozoans. Dragged gear removes bryozoan turf / thicket habitat and recovery rates are greater than one year. The distribution of this habitat has been determined through previous research (Williams *et al.* 2009; Pitcher *et al.* 2015) and was contrasted against recent spatial patterns in BT. The BT effort overlayed on the bryozoan zone showed the same general temporal pattern of the overall BT effort on both West and East Coast. On the West, there was increase in spatial overlap with bryozoan habitat up to 2012 while overlap on the East peaked in 2010. Swept area analyses indicated that around 15% of bryozoan habitat is exposed to BT effort per annum on the West Coast assuming a net width of 50 m (noting that AFMA generally applies a net with of 100 m in assessing BT swept area). Giant crab traps can also be dragged on occasion, including during hauling, although the footprint is minor relative to BT.

Attempts to regulate interactions with co-management and voluntary agreement failed. Effort continued to occur in agreed exclusion areas and peaked in 2012. BT effort tended to be greatest on the deeper areas of the bryozoan habitat with 34% of total effort in the 180-270 m depth of the voluntary exclusion areas while only 2-3% of total effort occurred in the 150-180 m depth region. Most of the BT effort in 150-180 m occurred within the agreed exclusion areas with very little overall effort (< 1%) at this depth in the areas to be open to trawling under the voluntary agreement.

BT effort on the GC ground, especially on bryozoan turf/thicket off the west coast remains an unresolved issue and would be expected to have implications for crab productivity. Overall BT effort in the region has reduced since 2012 and this reduction has been evenly distributed spatially.

Keywords

Giant crab, bottom trawl, effort, spatio-temporal overlap, bryozoan thicket, bryozoan turf, co-management, conflict resolution

1. Introduction

1.1 Background

Giant Crab (*Pseudocarcinus gigas*) have been harvested by trap fishers off Tasmania (TAS) and Victoria since at least the 1870s (Royal Commission Report 1882; McCoy 1889) but were increasingly targeted in the 1990's when live product supply chains into Chinese markets were established. Catch peaked in 1994/95 at 291 tonnes and was then constrained at 100 tonnes in 2000 with a total allowable catch. The TAC has been steadily reduced since then so that only 21 tonnes tons was taken in 2015 (Emery *et al.* 2015). Biomass and catch rate have continued to fall despite large cuts in catch and the fishery was subsequently classed as overfished in the 2016 Status of Australian Fish Stocks Report (www.fish.gov.au). Model projections of the stock under the low TACs that have been applied for the last decade led to expectations of stock rebuilding but no signs of recovery have been observed (Emery *et al.* 2015).

The Southern and Eastern Scale and Shark (SESS) fishery is a multispecies and multisector fishery that extends from Southern Queensland, around Tasmania to Cape Leeuwin (Southern Western Australia) (AFMA 2014); with effort from around Tasmania since the mid 1980's (Tilzey 1994). The Commonwealth South East Trawl Sector, henceforth benthic trawl (BT) fishery, and the giant crab (GC) fishery overlap around Tasmania, between approximately 150 to 350 m depth (Williams et al. 2009), since GC fishery expanded in 1991 (Gardner 1998). This common fishing ground covers most of the main crab fishing grounds, especially off Western Tasmania and Victoria (AFMA 2014), which leads to interaction between the fisheries. Since early 2000's GC fishers have expressed concern that BT fishery has been operating close to shelf break as this has been enabled by modern technology. Crab fishers have expressed concern around interaction issues of: (i) loss of crab traps; (ii) mortality of crabs retained in trawl gear, (iii) mortality of crabs contacted but not captured by trawl gear; and (iv) reduced productivity due to habitat changes.

The loss of crab traps is the most minor and easily resolved of these issues. In 2004 BT and GC fishers agreed to increase radio communication and discuss gear locations so that trawl operators would be better able to avoid any traps. Fishers have reported that this process generally operates effectively although there are also reports of occasional problems. Regardless, this issue remains one where the size of the problem is modest and the solution is straightforward.

The concern around potential loss of productivity through habitat interactions includes changes to settlement habitat that could affect recruitment, and change in abundance of prey species. Previous research has shown that bottom towed gears may damage habitat and communities although the effect is moderated by the habitat type, rates of recovery and the footprint (Burridge et al. 2003; Pitcher et al. 2015). The Tasmanian shelf-break habitat important to this study is known to be a bryozoan turf habitat that forms on unconsolidated sediment (Williams et al. 2009). GC are found between 18 m and 400 m depth, but most commonly on this bryozoan habitat, between 140 m and 270 m depth,(Poore 2004). Highest abundance of GC is associated with bryozoan thicket or turf habitat. Areas in the NW of Tasmania have been identified as being especially important for recruitment based on both distributions of undersized individuals and simulation of larval dispersion (Williams et al. 2009). Based on biophysical modelling and video tows, these areas have high-density bryozoan patches (Williams et al. 2009; Pitcher et al., 2015).

Crustacean larvae usually actively select complex microhabitats to settle, as they provide food and refuge increasing the survival of postlarvae and juvenile (Hedvall *et al.* 1998; Stevens and Swiney 2005; Webley *et al.* 2009; Pirtle and Stoner 2010; Alves *et al.* 2013). Giant crab juveniles collected by dredge (Rathbun, 1926; McNeill 1920) and observed by video (Williams et al., 2009) were associated with microhabitat such as sponge cavities. Bryozoan thickets provide habitat for a variety of species, given their structural complexity (Batson *et al.* 2000; Cocito 2004; Wood *et al.* 2012, 2013), and GC diet includes mobile fauna such as crustaceans, gastropods and asteroids part of the biological community that develops on bryozoan turf/thicket (Heeren and Mitchell 1997).

Dragged gear (including both crab trap and trawl) is known to remove bryozoan turf / thicket habitat and recovery rates are slow with little recovery observed on impacted sediment even after one year (Williams et al. 2009). Although both gear types remove habitat when dragged, a risk assessment conducted by Williams *et al*. (2009) concluded that there was a far higher risk from BT effort, in contrast with a negligible risk from crab trapping due to the size of the footprint. Differences in impact as a result of footprint has been documented in numerous field studies also. For example, cumulative BT effort on highly swept areas increases the risk of habitat removal (Burridge *et al.* 2003). In contrast, no detectable effect on benthic assemblages was found as consequence of occasional dragging of lobster/crabs pots in the northern Atlantic (Coleman *et al.* 2013). Lewis *et al.* (2009) examined the impact of traps on coral damage and found that average area impacted for deeper sets was 1.1 m^2 per trap (GC trap sets in Tasmania have averaged less than 50,000 p.a. for the last decade). Concerns around indirect impacts of BT on GC through habitat effects led to the development of voluntary exclusion zones by trawl fishers following a meeting between the sectors in 2004. Later work on habitat distribution by Williams et al. 2009 confirmed that the voluntary exclusion zones would be bryozoan turf / thicket habitat in their natural state.

Giant crab catch through the SESS fishery is regulated with bycatch limits on the number of retained crabs to five individuals per trip (AFMA 2014). Data on this catch is collected through logbooks and enable this source of mortality to be determined. There is potentially additional unobserved fishing mortality from crabs that are not retained. In the crab fishery the number of undersize and other discards is recorded for each shot and discard mortality assumed to be negligible, based on trials with crabs placed in cages on the seafloor and the survival of crabs retained for sale, which is entirely live trade. Mortality of non-retained crabs that come in contact with trawl gear is unknown and could not be measured through this study.

Determining whether the fishing mortality of crabs contacted by dragged gear is significant is potentially a topic that warrants further research because it has been a problem in crab fisheries elsewhere. For instance, concern over mortality of the red king crab (*Paralithodes camtschaticus*) in the Bering Sea led to area closures to the heavy bottom trawling gear used in that fishery (Armstrong *et al.* 1993). Methods are available to assess the scale of any impact in the SE Australian situation and include towing auxiliary nets (Rose 1999) with retention of specimens to assess any immediate or delayed mortality (Rose *et al.* 2013; Azmi *et al.* 2014).

1.2 Need

The Tasmanian giant crab fishers and the Tasmanian Government have rated trawl interactions as their highest priority research need for several years through the annual Tasmanian marine resource research advisory group process. Resolving this conflict requires information and analysis because the issues are complex.

1.3 Objectives

1. Measure spatial overlap between giant crab and benthic trawl fisheries that creates interaction between the fisheries, and temporal variation in this interaction.
2. Determine changes through time in benthic trawl effort on habitats that support the giant crab fishery, including in the voluntary exclusion zones.
3. Determine trends in crabs retained by trawl gear in the context of removals by trap fishing.

2. Methods

2.1. Data

This study used bottom trawling (BT) data from the Southern and Eastern scale and shark (SESS) fishery provided by the Australian Fisheries Management Authority (AFMA). The dataset included records of coordinates, time and date of fishing operation around TAS from the vessel monitoring system (VMS); and included tracks south of 39°S. Also, AFMA provided logbook data that contained bycatch in the SESS. Additionally, the Department of Primary Industries, Parks, Water and Environment (DPIPWE) made data from the Giant Crab Fishery available, which included catch details, number of traps, haul time, date and coordinates.

The VMS data did not specify the beginning/end of every shot so it was necessary to exclude components of the tracks not clearly related to fishing operations using distance/speed signals. Faster speeds were excluded based in part on the Fisheries Management Regulations 1992, amendment to the part 9A, where vessels must maintain speed over five knots when navigating in a closure. Therefore, a boat travelling at a speed higher than 5.0 knots could not be fishing. The median of the speed calculated from VMS data was 5.2 km/hr (2.8 knots), and the mode was 5.9 (3.0 knots). Reductions in speed to produce tracks lower than 7.4 km/hr (4.0 knots) were assumed to be trawled distances. A lower speed criteria was also applied with tracks involving speeds of less than 1 km/h removed from the data set. Additionally, the VMS data has no information on when the actual trawling begins/ends; this is, when the net touches/leaves the bottom. Therefore, all tracks were cut 2.0 km at the beginning/end to account for the time/distance that the gear was in the water column.

To facilitate the spatial analysis the geographical coordinates were projected to the Universal Transverse Mercator (UTM) coordinate system. Values were expressed in meters and increase towards north and east. The data manipulation/analysis was carried out using the programing language and statistical environment R (R Core Team 2016). The spatial analysis and mapping was performed using the spatial R packages *sp* (Gentleman *et al.* 2009) and *rgdal* (Bivand *et al.* 2016). The package *doParallel* (Revolution Analytics and Weston, 2015) was used to simultaneously run spatial analyses on a cluster of 49 drives.

Effort was analysed using logbook data from the crab fishery and VMS data from BT. The use of both of these data sources involves assumptions, which can influence estimates of the spatial scale of effort. (i) GC effort normally involves the use of longlines of crab traps with fishers sometimes only recording the central point of the long line. Thus the gear extends beyond this point. (ii) We excluded periods at the start and end of each BT tow to account for periods when the BT net was being deployed or hauled. Actual deployment/haul period may differ from that which we applied. (iii) We estimated the seafloor contact distance assuming a flat surface - actual distance on a sloping sea floor would thus be longer. (iv) BT gear does not necessarily contact with the sea floor across the entire width of the net so estimation of swept area included sensitivity of BT width in contact with the seafloor (50 m and 100 m width scenarios). (v) The ecological implication of swept area estimates for BT will be affected by the extent of overlap between trawls as overall BT footprint will be reduced if trawl paths overlap.

2.4. Spatio-temporal overlap between benthic trawl and giant crab fisheries

The historical GC fishing ground was used as a base area to assess the common use of the space by both fisheries and calculate an overlap index (OI). To define the historical GC fishing ground all shots were mapped and a polygon was drawn around the cloud of points (GC fishers record the latitude and longitude of gear location). Isolated shots were not considered. The OI does not measure direct gear encounters, but higher values do imply higher probability of gear interaction for any constant level of cooperation between the sectors. The common fishing ground was gridded with 1.0 × 1.0 km cells where the total effort of both fisheries was calculated. The total GC effort in every cell was:

$$GC\ Effort = \sum_{i=1}^{s} (Number\ of\ traps\ \times Soak\ time)$$

The total effort of BT in every cell was:

$$BT\ Effort = \sum_{i=1}^{s} Trawled\ distance$$

In both cases *i* is the *i*th shot and *s* is the total number of shots/traps per cell.

The OI was the product between both efforts, and scaled by the maximum value; thus the index took values between zero and one.

Maps were made showing the distribution of OI values for the whole data and aggregated by years for both West and East Coast.

Generalized Additive Models (GAM) with integrated smoothness estimation were fitted to assess the spatial and temporal changes of the OI, separated models for both East and West coast of TAS. The predictors of the OI were time, treated as a factor (years), and smooth functions (penalized cubic regression spline) for the latitudinal and longitudinal gradient, which were fitted by each level of the factor coast (East and West coast of TAS):

$$\begin{aligned} PII_i = \alpha + factor(year_i) + f(latitude_i)factor(coast_i) \\ + f(longitude_i)factor(coast_i) + \varepsilon_i \end{aligned}$$

Where year is a categorical explanatory variable with eight levels (2008, … , 2015), latitude and longitude are continuous variables representing the central point of the 1.0x1.0 km cells where the OI was measured. The index *i* represents every cell, *α* in the intercept and *ε* in the error term. A Gamma distribution was used to account for the error distribution, given the right-skew and positive values of OI. The R package *mgcv* was used to fit these GAM models (Wood 2004).

2.5. Spatio-temporal overlap between the benthic trawl fishery and giant crab habitat

BT effort over this habitat area was measured as an index of potential impact on this habitat. The bryozoan habitat was defined based on seabed video observations in transects carried out in 14 points along the East and West coasts of TAS (Williams *et al.* 2009). Thicket/turf occurred across the bathimetric gradient between 150-200 m and 350-400 m depth, and given that towards shallow and deep waters the percentage of occurrence decreased, the bryozoan zone was defined as the strip along both East and West coast and between 200 and 350 m depth. Note that the resulting ribbon matches with the bryozoan zone reported by Pitcher et al. (2015). The BT effort was corrected by the resulting area of cells that were clipped by the 200 to 350 m depth levels:

$$BT\ Effort\ on\ bryozoan = \frac{\sum_{i=1}^{s} Trawled\ distance}{Area_j}$$

Where *i* is the *i*th shot and *s* is the total number of shot in the *j*th *cell*.

A GAM with similar characteristics to the previous one was fitted to describe spatial and temporal variations of the BT effort on the bryozoan area for both East and West coast of TAS.

The BT swept area was estimated for relevant habitats off both the East and West coast. This swept area was the product of the total trawled distance separately for each coast and the BT net width, and it was expressed as absolute values and as a proportion of the total bryozoan thicket area. Note that this is not an actual area, but a relative surface that take into account repeated effort in some areas; therefore, it informs about the scale of operation and is a surface equivalent to the fraction of the bryozoan area. We also assumed that the BT net could potentially impact a width of 100 m, based on advice from AFMA that this is an estimate that has been used to cover all AFMA trawl fisheries. However, we note that there is variation in net width between types of BT depending on the size of the gear and the action of the head of the trawl (trawl doors and bridles). For this reason, we also estimated swept area using an assumed net width half of that normally applied by AFMA (ie 50 m rather than 100 m). Results from swept area using this value of 50 m net width were emphasised as this is less likely to inflate the impact of BT.

2.6. Bottom trawl effort on the agreed gear restriction area

The voluntary agreement between BT and GC fishers occurred during 2004 and aimed to create spatial separation between both fleets in parts of the West Coast, and prevent risk of damage to some areas of bryozoan turf / thicket habitat (Fig. 1, Williams et al. 2009). The effectiveness of this agreement was examined here by determining the total annual BT effort in the exclusion zones. The agreement between both sectors is depicted in Fig. 2 and it was:

i) BT effort to have the same level of access along the entire coast deeper than 270 m (150 fm) or shallower than 150m (80 fm); south of 42º 45', north of 40º, and in the Ling Hole, Pieman and Strahan canyons.

ii) apart from the areas listed above, BT agreed to keep their effort out of the 180270 m (100-150 fm) depth band 40º to 42º 45' (termed “No BT access 180-270 m”), and 150-180 m (80- 100 fm) depth band 41º45’ to 42º 45' (termed “No BT access 150-180 m”).

iii) Additionally, BT and GC fishers to increase radio communication to avoid gear interaction.

Habitat in the 150 and 180 m depth for latitudes between 41° and 41°45’ was not addressed by the agreement and effort in this regional was also examined (termed “Open to BT 150-180 m”).

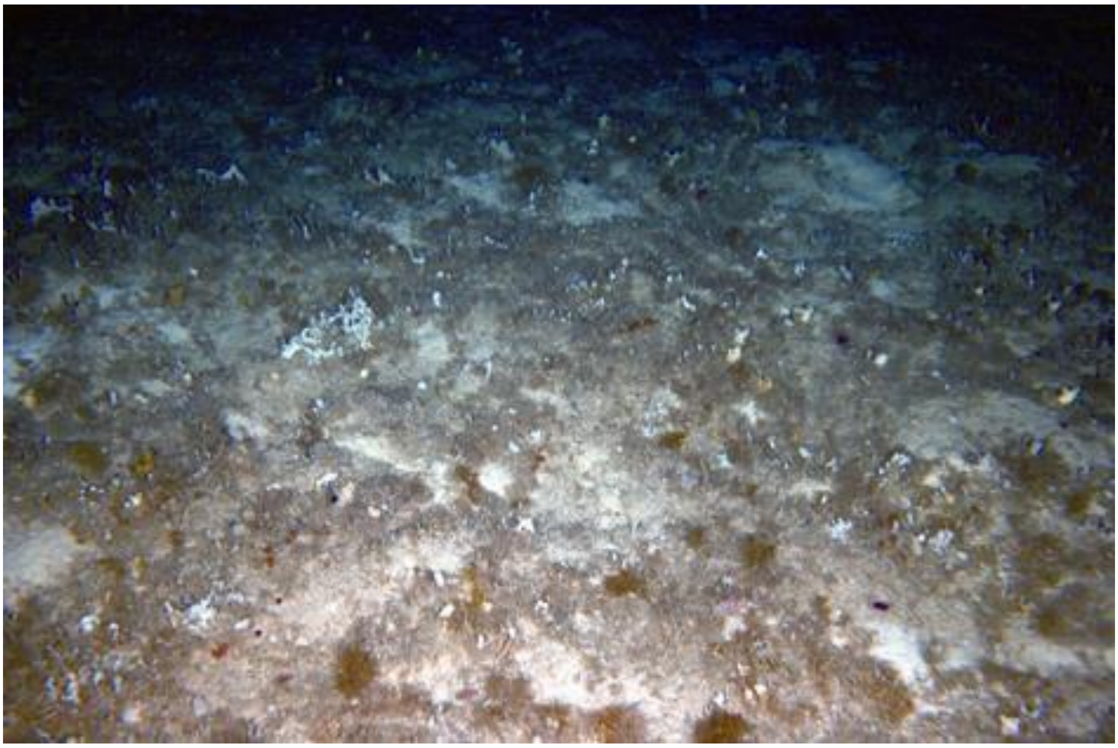

Figure 1. Bryozoan turf habitat (after Williams et al., 2009). This habitat is formed by low encrusting fauna, predominantly bryozoan, on unconsolidated sediment.

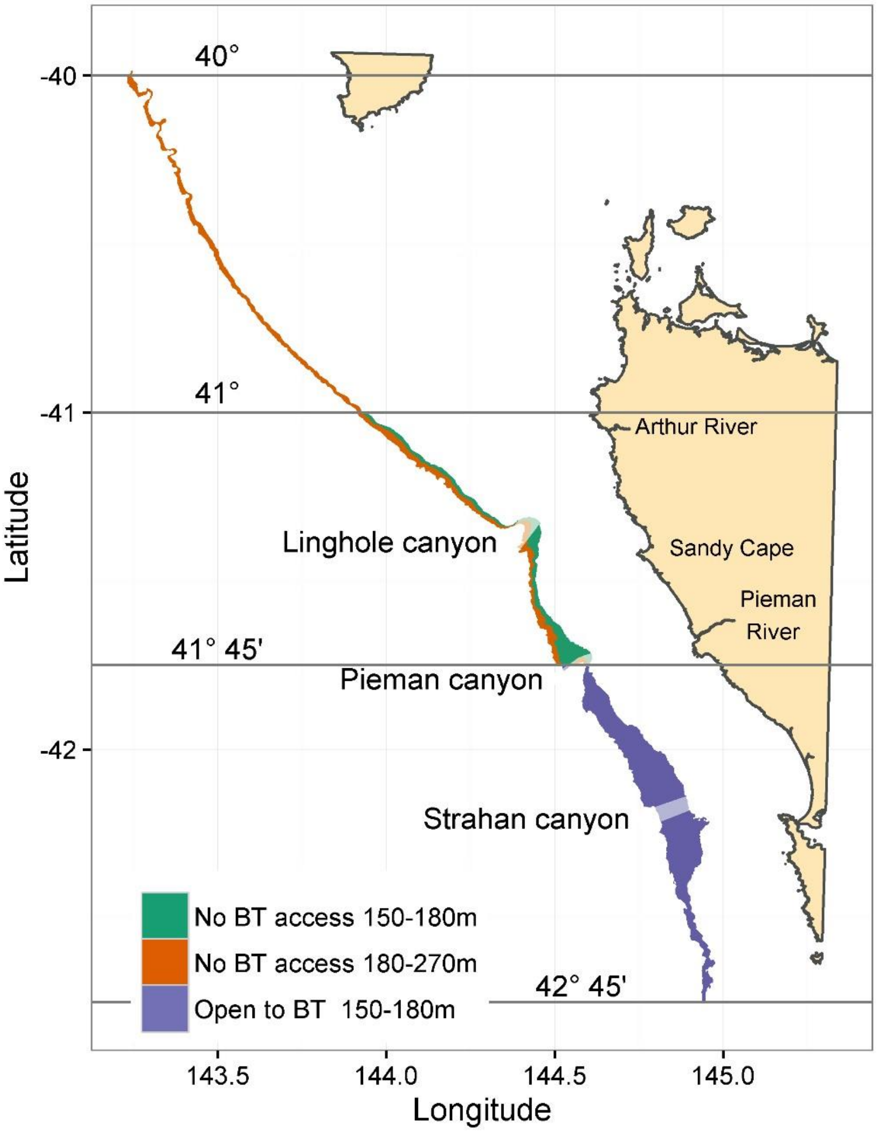

Figure 2. Area-based agreement around distribution of BT effort in the West Coast in TAS. The No BT access 180-270m area covers most bryozoan thicket off the West Coast of TAS. Not illustrated is a small region of the fishery intersected by the Zeehan Commonwealth Marine Park in the far north.

2.7. Trends in crabs retained by trawl gear

Temporal and spatial variation of GC as bycatch in BT operations was evaluated using a generalized additive model (GAM). In this case, the longitudinal explanatory variable was replaced by depth because this is more informative of the spatial variation of GC as bycatch. A smoothing function was used to model both depth and latitude, also fitted for each level of the factor coast (East/West). The bycatch data was limited; therefore, separate models were non-viable. A zero-inflated approach was used given the large number of null records of GC; thus the model was:

$$GC_i = \alpha + factor(year)_i + f(latitude)_i + f(depth_i)factor(coast_i) + \varepsilon_i$$

Where *i* is the *i*th shot, α in the intercept and ε in the error term.

3. Results

3.1. Spatio-temporal overlap between benthic trawl and giant crab fisheries

The spatial overlap of effort of the two fisheries (Overlap Index, OI) showed significant trends in both East and West coast of TAS over the latitudinal gradient (non-parametric terms, Table 1). On the West Coast, the OI revealed a decreasing pattern northwards (Fig. 3), reflecting a larger proportion of low OI values (less than 0.0079, blue dots) from Sandy Cape northwards (Fig. 4. This trend with latitude was largely driven by a significant trend of declining BT effort northward (Fig. 3, Table 1). In contrast, there was no significant trend in GC effort with latitude (Table 1). The OI on the East Coast varied less with latitude (Table 1, Fig. 3 and 5) with spatial patterns driven by significant trends in both GC and BT effort.

Table. 1. Generalised additive linear model (GAM) outputs describing changes in the overlap index (OI) of BT and GC fisheries over the time and space; and outputs of GAMs explaining variations in both GC and BT effort over the space. P-values for the smoothing terms are approximated so values near 0.05 are not necessarily significant (Wood 2006).

Model	Term	Factor	Estimate	Std.Error	t-value	p-value
Overlap Index (OI)	Parametric	Intercept	-6.829	4.119	-1.658	0.10
		Year 2009	0.099	0.151	0.658	0.51
		Year 2010	0.566	0.151	3.752	<0.001
		Year 2011	0.630	0.158	3.987	<0.001
		Year 2012	0.814	0.168	4.857	<0.001
		Year 2013	0.529	0.170	3.112	0.002
		Year 2014	0.126	0.169	0.747	0.46
		Year 2015	0.416	0.205	2.031	0.04
		Factor	edf	Ref.df	F	p-value
	Non-parametric (smooth)	Latitude E coast	7.706	8.431	15.741	<0.001
		Latitude W coast	8.655	8.943	9.196	<0.001
		Longitude E coast	4.742	5.71	17.238	<0.001
		Longitude W coast	2.205	2.539	6.588	<0.001
GC effort	Non-parametric (smooth)	Latitude W coast	8.76	8.974	1.231	0.27
		Latitude E coast	8.774	8.973	3.647	<0.001
		Longitude W coast	7.081	7.405	1.543	0.14
		Longitude E coast	2.048	2.401	2.505	0.07
BT effort	Non-parametric (smooth)	Latitude W coast	8.775	8.977	55.851	<0.001
		Latitude E coast	7.195	8.088	14.432	<0.001
		Longitude W coast	7.256	7.537	57.257	<0.001
		Longitude E coast	1.761	2.056	3.293	0.04

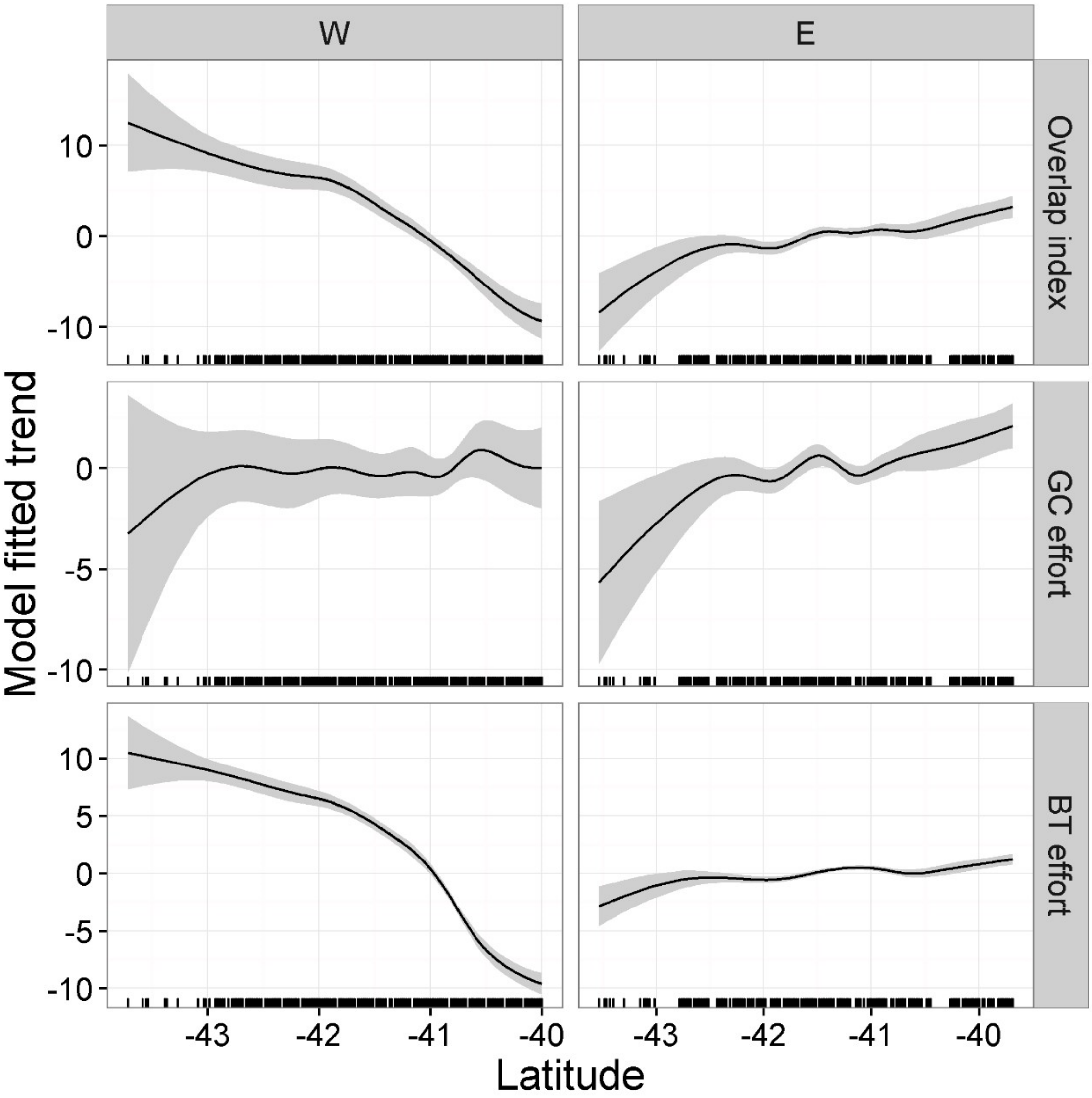

Figure 3. The pattern of changes over the latitudinal gradient of the overlap index (top), and effort in the giant crab (middle) and bottom trawl (bottom) fisheries off the West and East coasts.

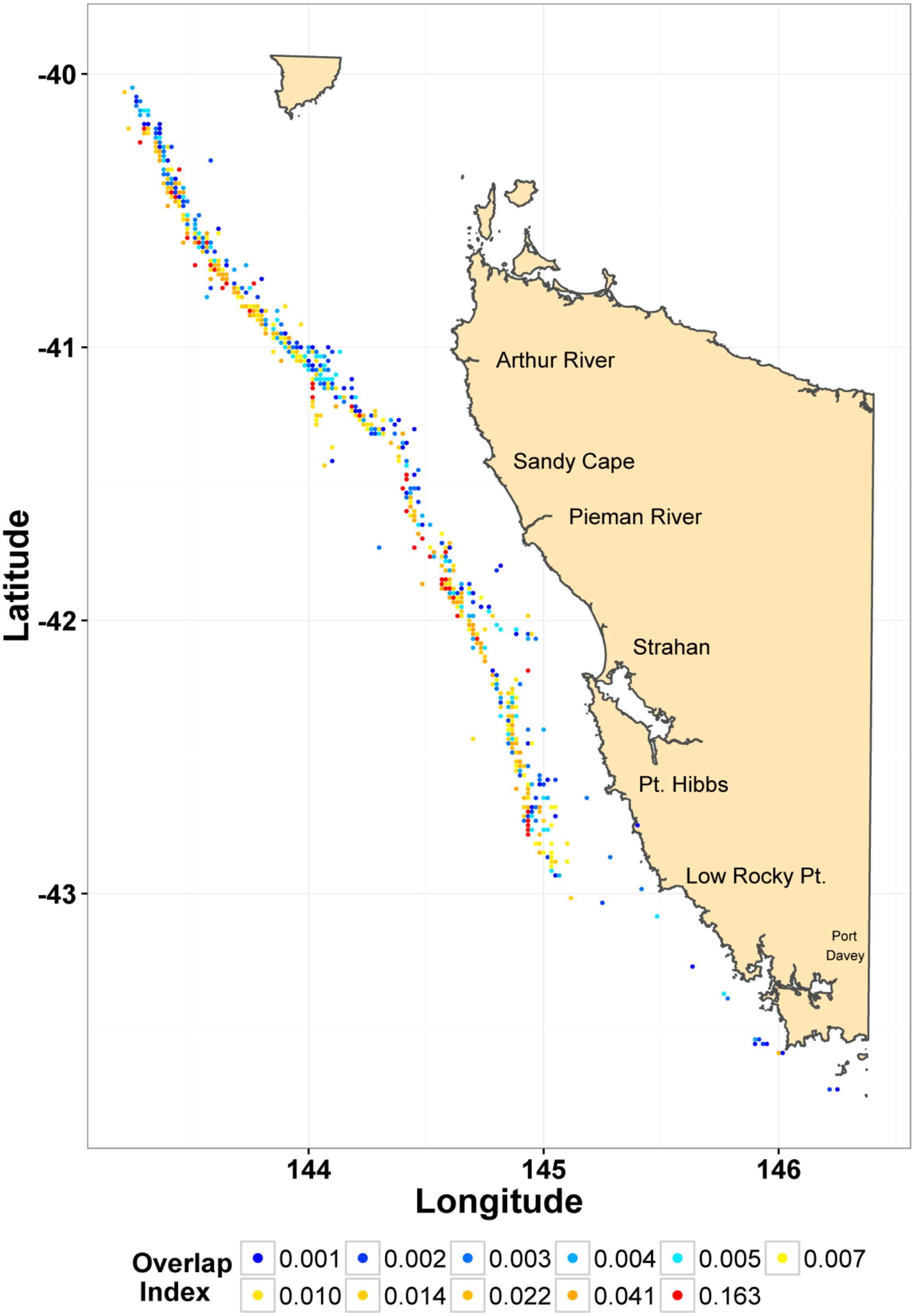

Figure 4. Spatial distribution of overlap index on the West Coast of TAS, measured over a grid of 1x1 km. Higher overall indices imply greater risk of gear interaction.

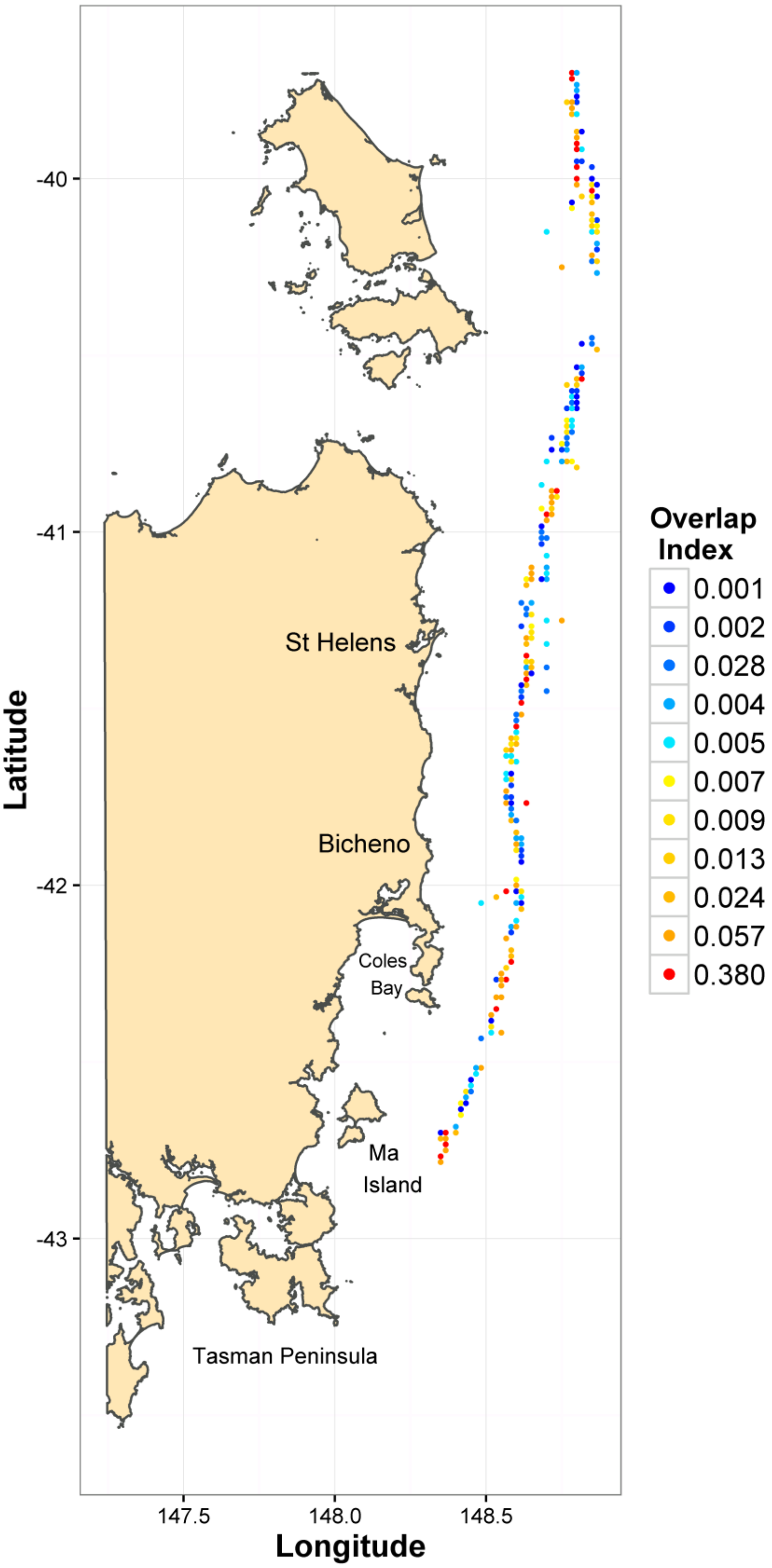

Figure 5. Spatial distribution of overlap index values on the East Coast of TAS, measured over a grid of 1x1 km. Higher overall indices imply greater risk of gear interaction.

Although both the east and west coasts run mainly north-south, there was a longitudinal gradient in both coasts with decreasing OI towards the East. This appeared to be driven more by spatial distribution of BT effort rather than GC effort (Fig. 6, Table 1).

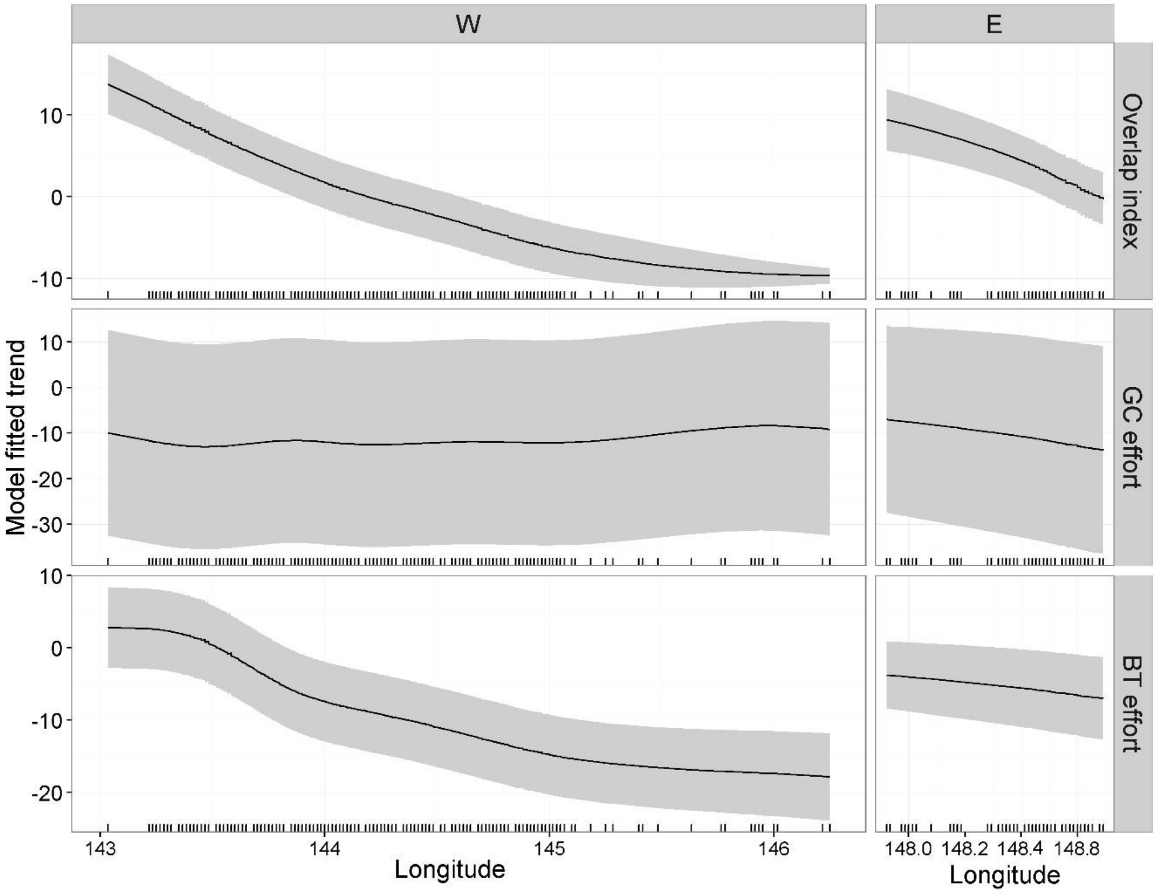

Figure 6. The pattern of changes in the longitudinal gradient of the Overlap index (top), effort in the giant crab (middle) and bottom trawl (bottom) fisheries in the West and East coast.

Overlap through time was scaled by setting the OI in 2008 to a value of 1 (Table 1). This base year was selected because it was the date from which VMS was provided. Overlap trended upwards through time to a peak in 2012 then declined so that by 2014-15 it was at the same level as in 2008 (Fig. 7). The OI pattern off the West Coast tracked BT effort while on the east coast OI was more influenced by the GC effort profile (Fig. 8). On the west, a high proportion of BT effort overlapped with GC fishing grounds, almost 80% between 2008 and 2012 and 70% between 2013 and 2015 (Fig. 9). The proportion was less on the east where the BT effort proportion fluctuated between 30 and 40% throughout the period.

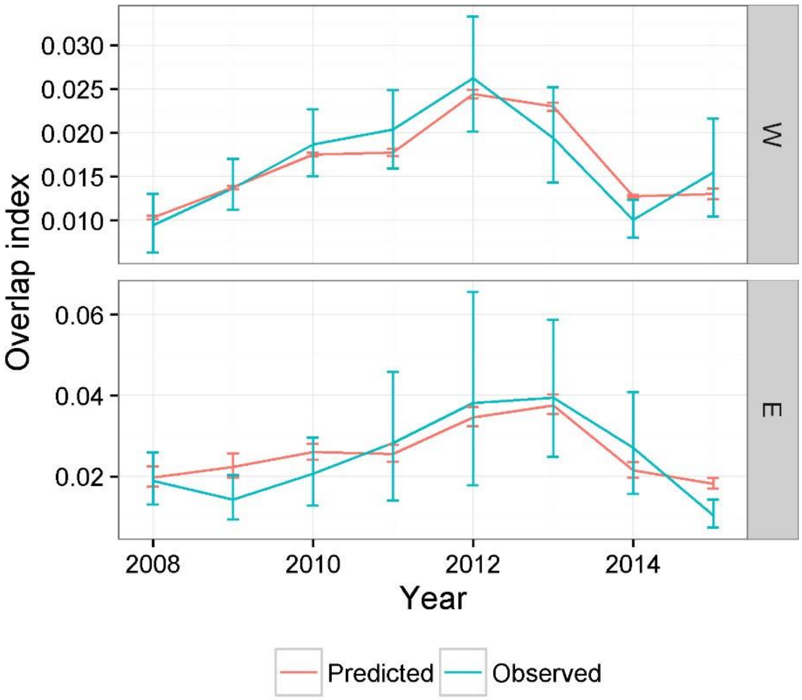

Figure 7. Mean change of overlap index between BT and GC fisheries over time. Bars are confidence intervals.

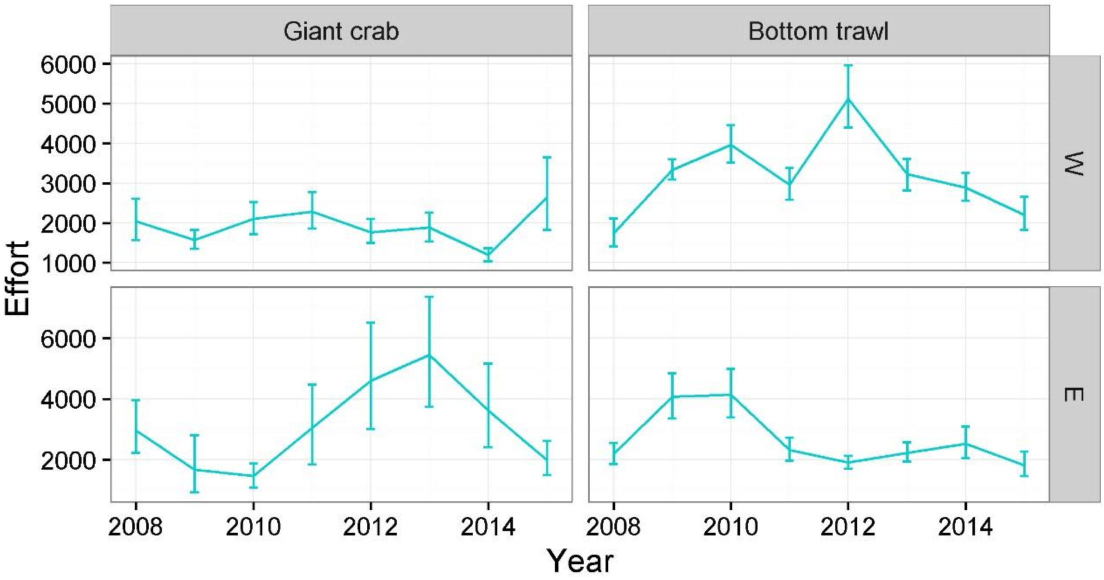

Figure 8. Observed mean change of BT and GC fishing effort over time. Mean values calculated in 1000 x 1000 m cells. Bars are confidence intervals. Giant crab effort = trap days and Bottom trawl = trawled distance (m).

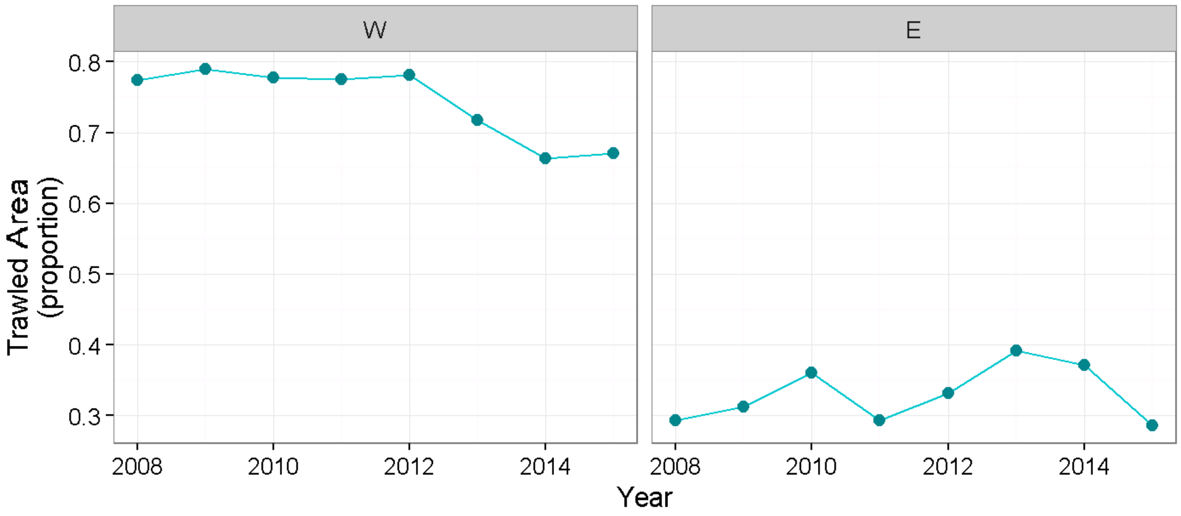

Figure 9. Proportion of the annual BT effort on GC fishing grounds, relative to the total BT effort on the West and East Coast of TAS.

There was spatial and temporal variability in the number of cells with overlap between both fisheries. In the West, greatest number of cells with overlap occurred between 2009 and 2010, while on the east coast this measure of overlap peaked in 2013 (Figs. 10 and 12).

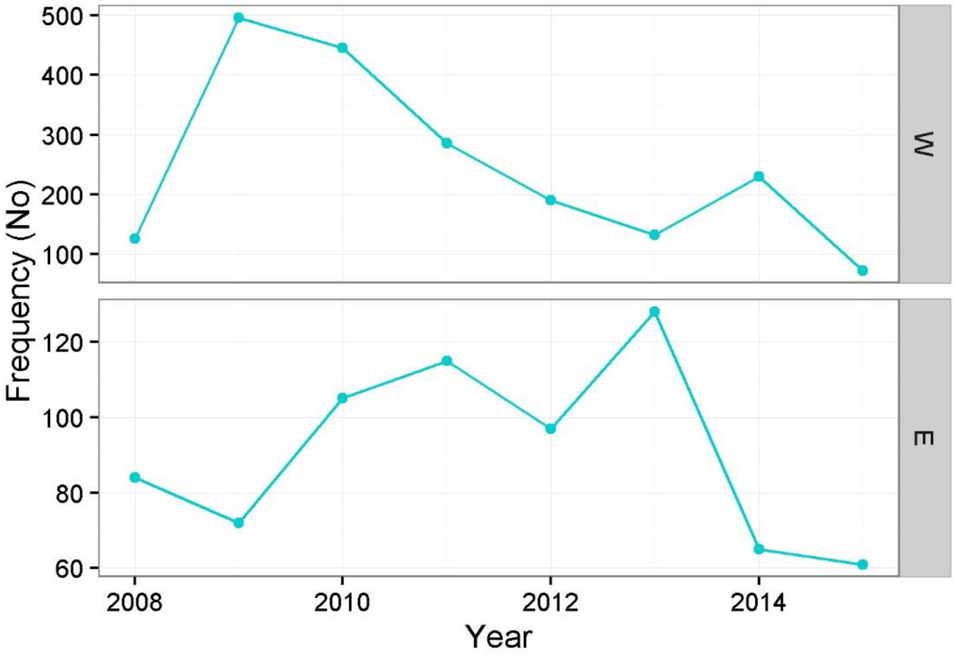

Figure 10. Number (frequency) of cells where there was both GC and BT effort.

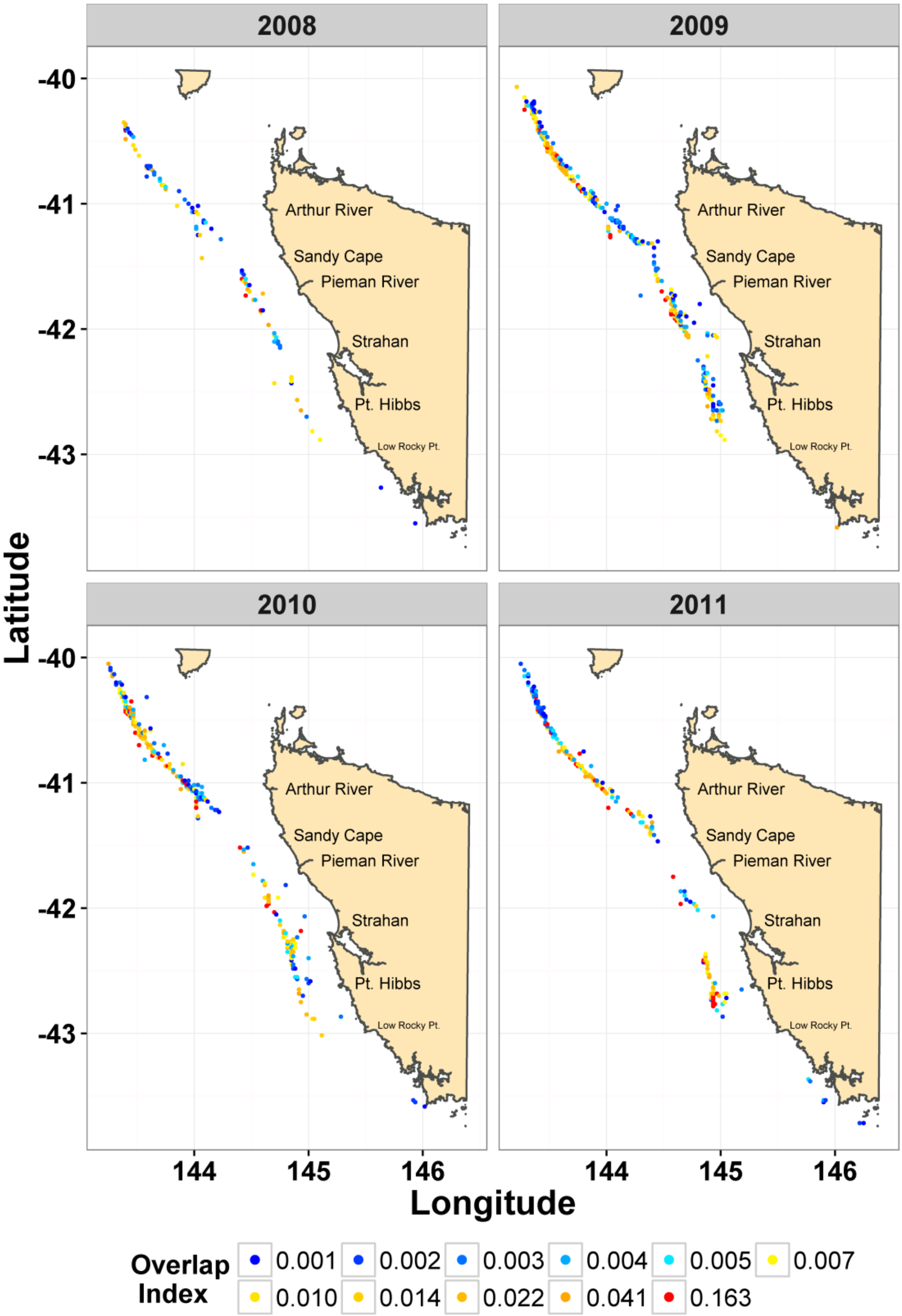

Figure 11. Latitudinal and temporal changes (years 2008 to 2011) of Overlap Index (OI) between BT and GC fisheries on the West coast of TAS. Overlap index is for 1×1 km cells (*Continued*).

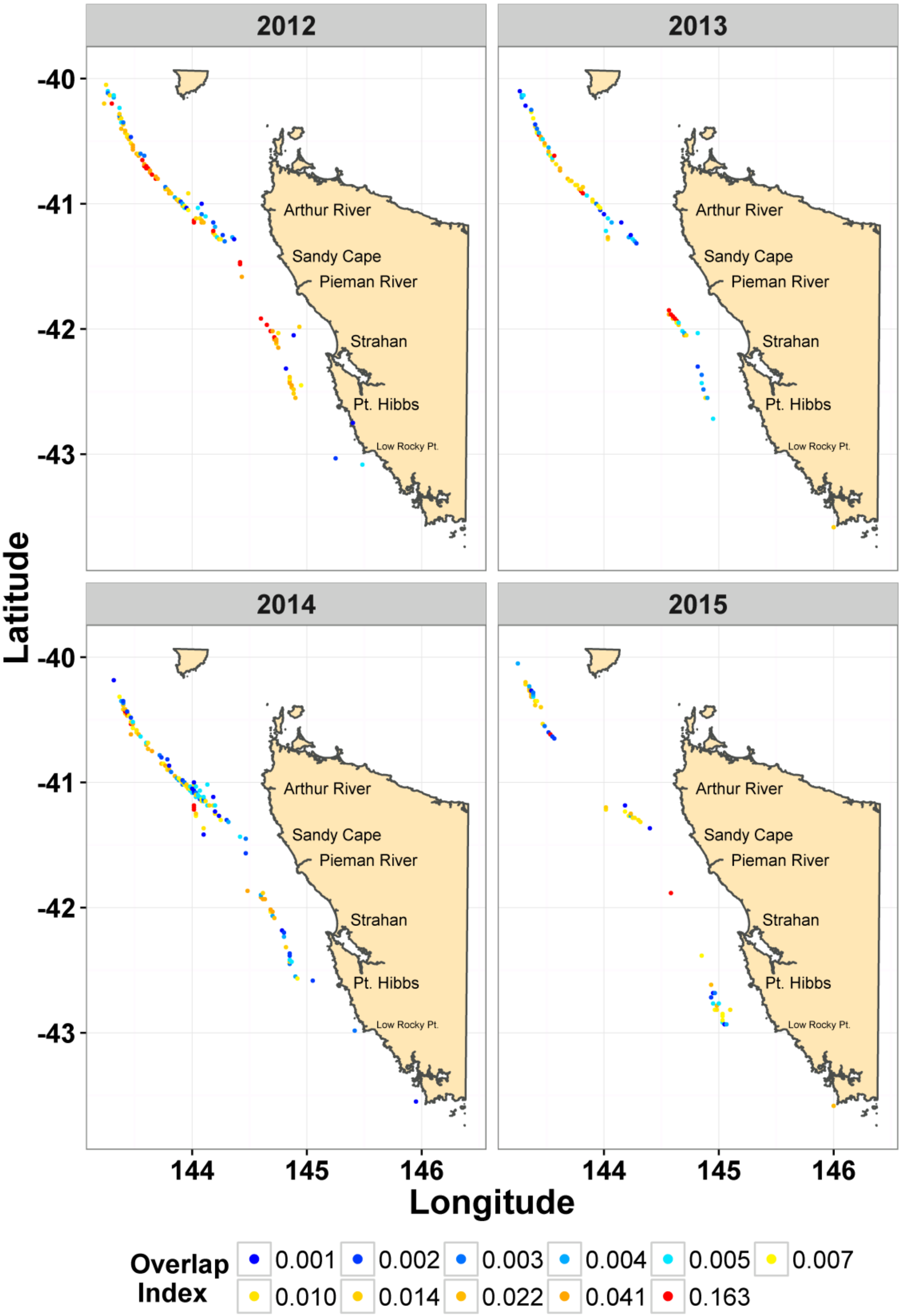

Figure 11. (*Continued*) Latitudinal and temporal changes (years 2012 to 2015) of Overlap Index (OI) between BT and GC fisheries on the West coast of TAS. Overlap index is for 1×1 km cells.

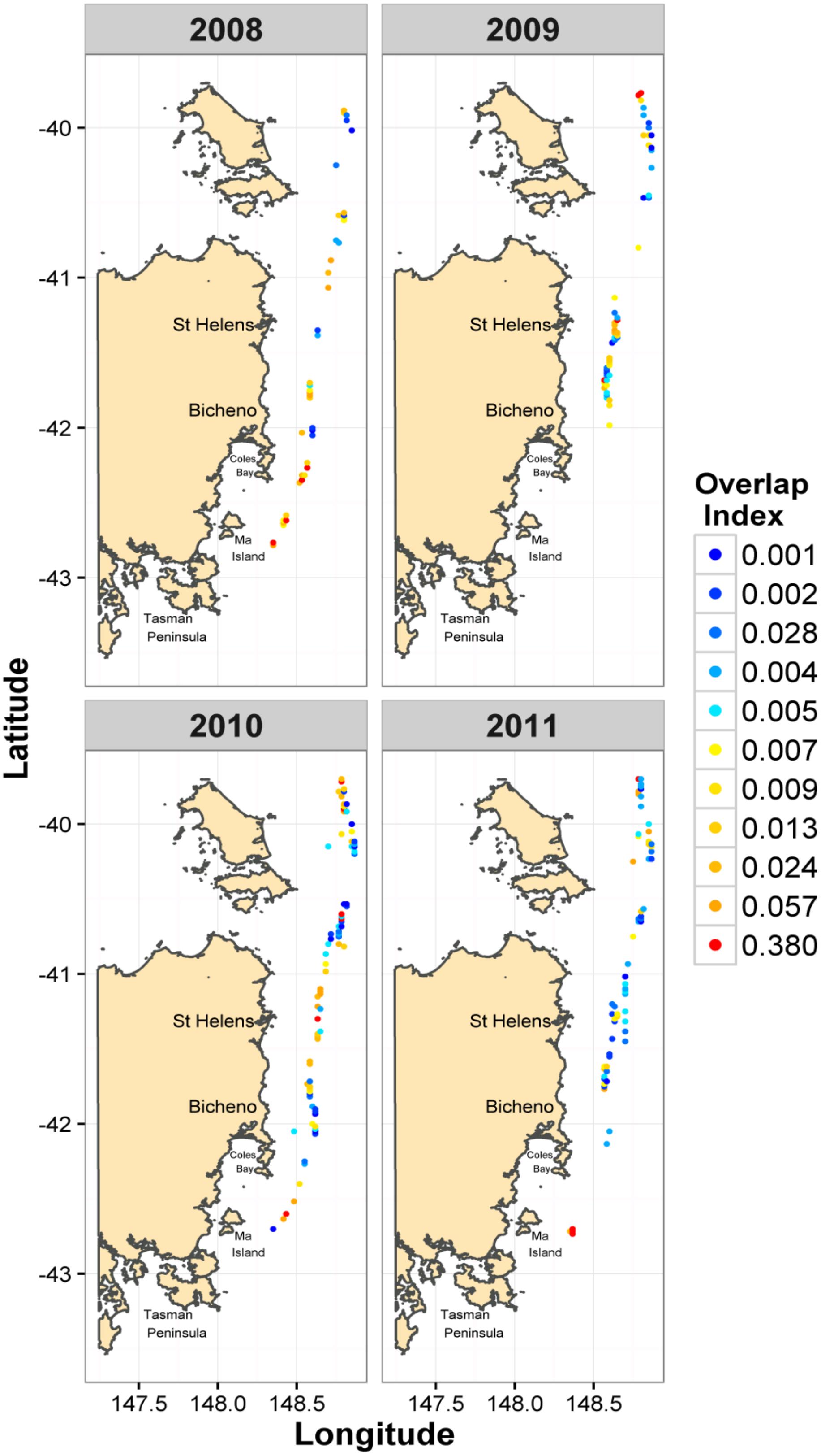

Figure 12. Latitudinal and temporal changes (2008 to 2011) of overlap index (OI) between BT and GC fisheries on the East coast of TAS. OI measured for 1×1 km cells (*continued*).

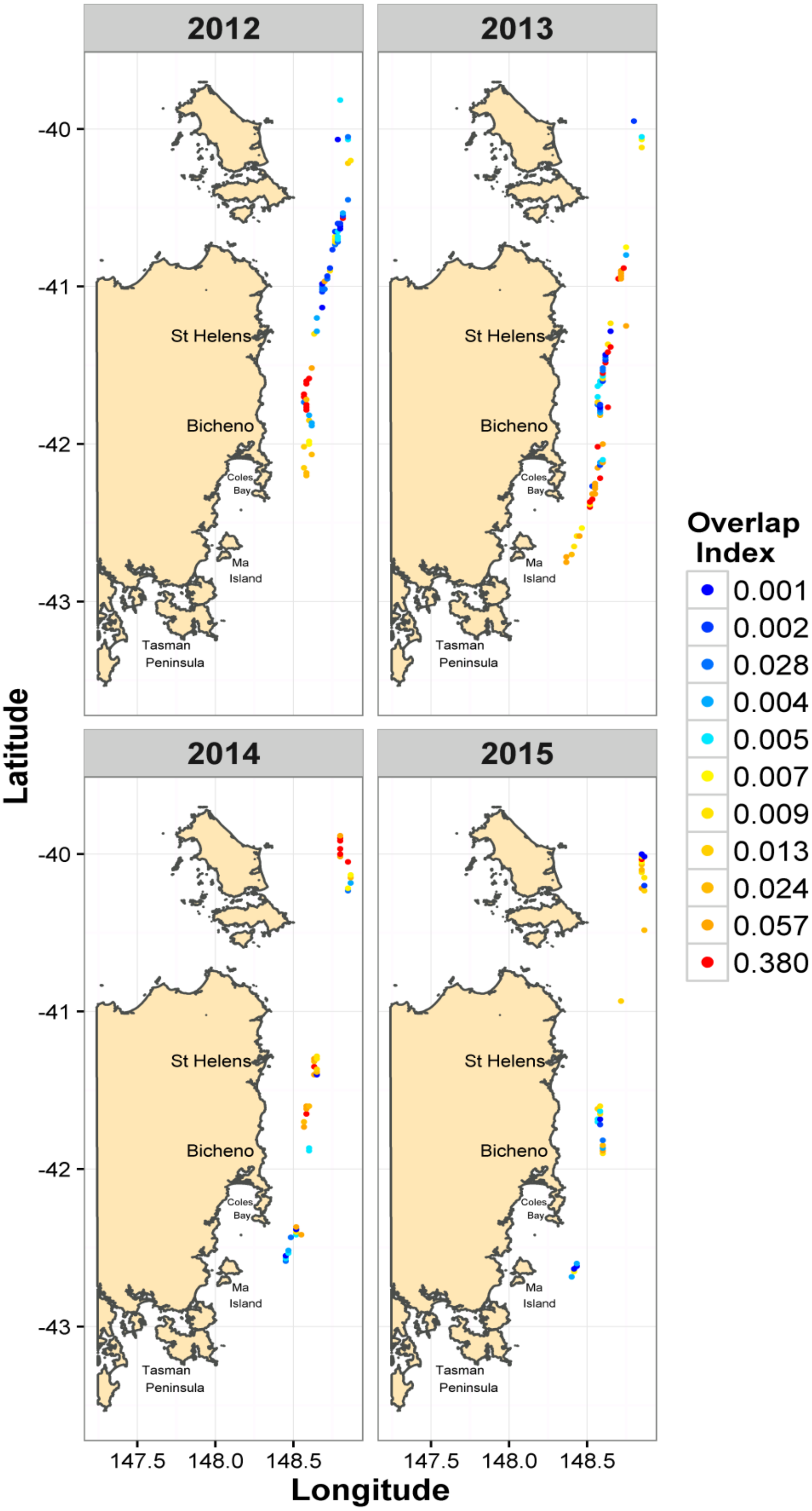

Figure 12. (*Continued*) Latitudinal and temporal changes (2012 to 2015) of overlap index (OI) between BT and GC fisheries on the East coast of TAS. OI measured for 1×1 km cells.

3.2. Bottom trawl effort in the voluntary exclusion zone

The BT effort in the voluntary exclusion zones had the same general pattern described in the previous section for the wider West Coast. Effort in these exclusion zones peaked in 2012 (Fig. 13). The BT effort was highest in the voluntary exclusion zone of 180-270 m depth, and lowest in the agreed open area of 150-180 m depth.

Most of the total West Coast BT effort occurred outside the voluntary exclusion zones with only 1 and 2% and 2 and 4% in the No BT access 150-180m and 180-270 m areas respectively. Very little trawl effort occurred in the agreed open area in the 150-180m depth range with BT effort remaining lower than 1% in this area throughout the period.

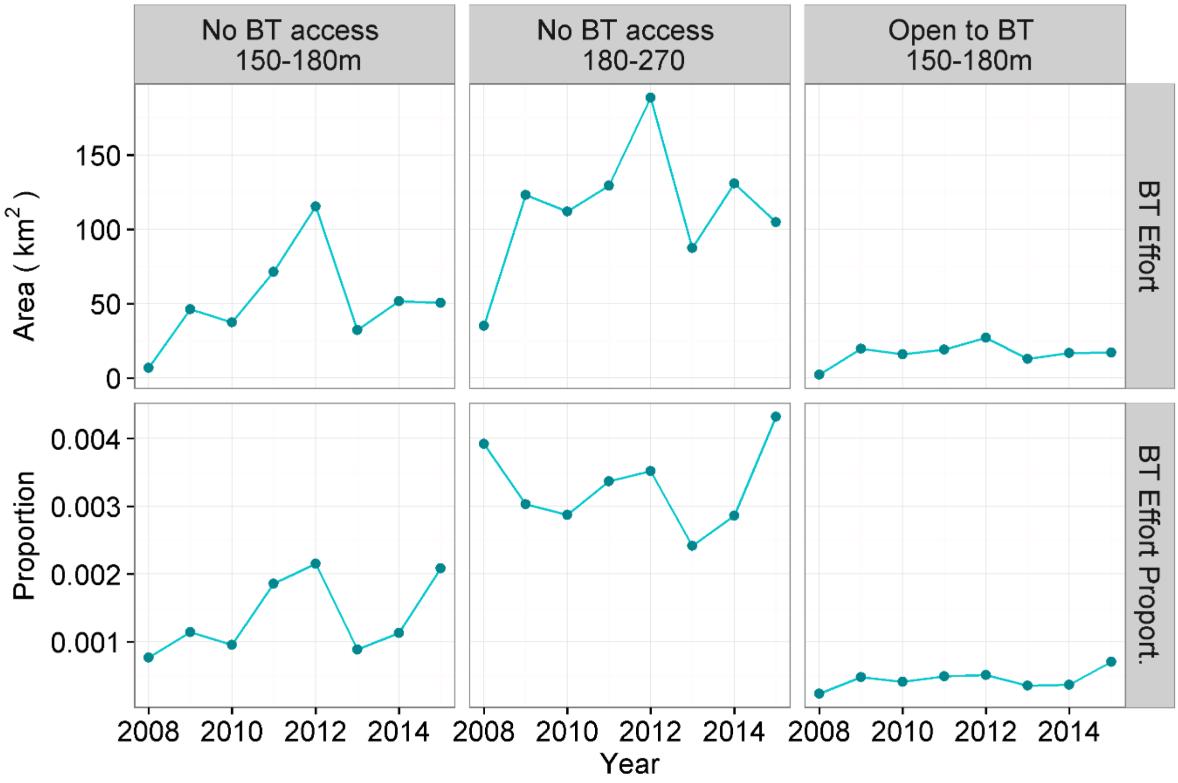

Figure 13. Total BT effort (trawled area, km^2) on the defined areas as No BT access in the agreement between both sectors, and its proportion relative to the total effort (trawled area, km^2) on the West Coast of TAS.

The BT effort measured as number of vessels trawling was highest in the voluntary exclusion 180-270m area, varying between 8 and 11 vessels per annum (Fig. 14). The other two areas had a stable number of vessel operating over the period, fluctuating between four and nine vessels.

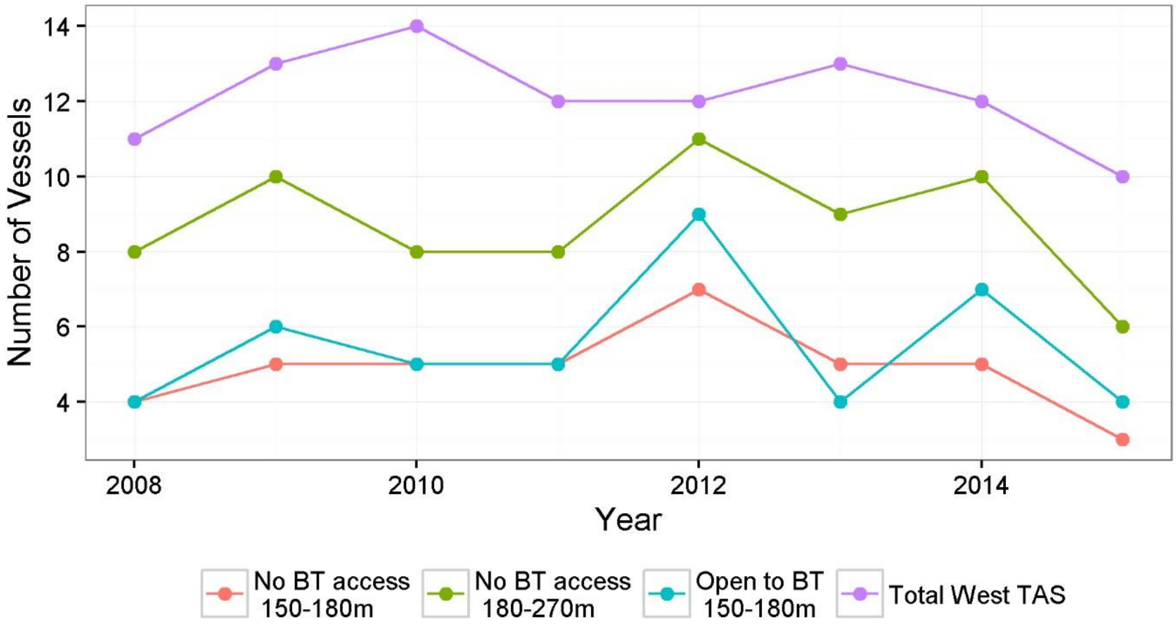

Figure 14. Number of vessels trawling in defined areas off the West Coast of TAS.

3.3. Spatio-temporal overlap between benthic trawl effort and bryozoan habitat

The BT effort on the agreed BT gear restriction area showed variable levels, ranging between 1% and 67% p.a. depending on assumptions around net width (Table 2). The swept surface followed the same general pattern of the BT effort with a peaked in 2012. Swept area percentage was higher in both of the areas where BT was to be excluded (150-180 me and 180-270 m depth) than in the agreed open area (150-180m depth), typically <5% throughout the study period. As it was stated in the method section, the areas and percentages presented here are a measure of operation, and they are not actual values because of potential occurrence of multiple shots in some areas.

Table 2. Total annual swept area within the voluntary agreement zones off the West Coast. Percentage were calculated based on the total surface of each access agreed area. Note that the swept area and percentage are provided to give a scale of the operation. Since the same region may be swept multiple times (with increasing damage) the actual proportion of the habitat area swept will be lower.

Agreement	Total area (km^2)	Year	Trawl net opened			
			50 m		100 m	
			Swept area		Swept area	
			km^2	%	km^2	%
No BT Access 150-180m	171.6	2008	3.42	2.00	6.85	3.99
		2009	23.15	13.49	46.29	26.98
		2010	18.61	10.85	37.22	21.70
		2011	35.69	20.80	71.38	41.61
		2012	57.63	33.59	115.25	67.18
		2013	16.03	9.34	32.06	18.68
		2014	25.72	14.99	51.45	29.99
		2015	25.26	14.72	50.51	29.44
No BT Access 180-270m	314.1	2008	17.46	5.56	34.93	11.12
		2009	61.50	19.58	123.00	39.16
		2010	55.91	17.80	111.82	35.60
		2011	64.68	20.59	129.36	41.18
		2012	94.22	30.00	188.44	59.99
		2013	43.67	13.90	87.34	27.81
		2014	65.29	20.79	130.59	41.57
		2015	52.35	16.67	104.69	33.33
Open to BT 150-180m	644.0	2008	1.04	0.16	2.08	0.32
		2009	9.73	1.51	19.47	3.02
		2010	7.97	1.24	15.93	2.47
		2011	9.46	1.47	18.93	2.94
		2012	13.58	2.11	27.15	4.22
		2013	6.34	0.98	12.68	1.97
		2014	8.34	1.30	16.69	2.59
		2015	8.54	1.33	17.07	2.65

The analysis of swept area was repeated separately for the bryozoan turf/thicket habitat important to the crab fishery that habitat type. This showed that BT effort was concentrated over bryozoan turf/thicket habitat area (i.e. the percentage of the habitat with interaction was much higher). The area of bryozoan habitat exposed to BT effort as estimated by swept area varied between years (~3% to 50%) and peaked in 2012 (Table 3). Throughout the study period, the swept surface in bryozoan habitat was higher off the West than the East Coast. Swept area averaged around 15% of the total area of the bryozoan habitat p.a., assuming a net width of 50 m.

Table 3. Total annual swept area on the bryozoan thicket off the West and East Coasts of TAS. Note that the percentage is provided to give a scale of the operation. Since the same region may be swept multiple times (with increasing damage) the actual proportion of the habitat area swept will be lower.

Coast	Bryozoan area (km^2)	Year	Trawl net opened 50 m Swept area km^2	Trawl net opened 50 m Swept area %	Trawl net opened 100 m Swept area km^2	Trawl net opened 100 m Swept area %
W	924.5	2008	38.0	4.10	75.9	8.20
		2009	125.6	13.59	251.2	27.17
		2010	148.2	16.03	296.3	32.05
		2011	159.4	17.24	318.7	34.48
		2012	234.4	25.36	468.8	50.71
		2013	125.3	13.56	250.6	27.11
		2014	160.4	17.35	320.8	34.70
		2015	115.1	12.45	230.1	24.89
E	843.7	2008	34.9	4.14	69.8	8.28
		2009	100.5	11.91	200.9	23.81
		2010	90.6	10.74	181.2	21.48
		2011	63.6	7.54	127.2	15.07
		2012	81.5	9.66	162.9	19.31
		2013	50.9	6.03	101.7	12.06
		2014	39.2	4.64	78.3	9.28
		2015	27.8	3.30	55.6	6.59

The BT effort over the bryozoan turf / thicket habitat zone significantly decreased with latitude on the West Coast while the opposite pattern occurred on the East Coast (Table 4, Fig. 15). Longitude had less of an effect on both coasts (Fig. 16 and 17).

Table 4. Generalised additive linear model (GAM) outputs describing changes in BT effort over bryozoan turf / thicket habitat. P-values for the smoothing terms are approximated so values near 0.05 are not necessarily significant (Wood 2006).

Term	Factor	Estimate	Std.Error	t-value	p-value
Parametric	Intercept	3.710	2.657	1.397	0.163
	year 2009	0.612	0.038	16.157	< 0.0001
	year 2010	0.627	0.038	16.682	< 0.0001
	year 2011	0.615	0.038	16.101	< 0.0001
	year 2012	0.817	0.037	21.856	< 0.0001
	year 2013	0.526	0.039	13.480	< 0.0001
	year 2014	0.581	0.039	14.962	< 0.0001
	year 2015	0.377	0.039	9.555	< 0.0001
	Factor	edf	Ref.df	F	p-value
Non-parametric (smooth)	Latitude W coast	8.647	8.952	95.011	< 0.0001
	Latitude E coast	8.726	8.965	35.433	< 0.0001
	Longitude W coast	8.779	8.950	58.245	< 0.0001
	Longitude E coast	0.999	1.270	0.792	0.386

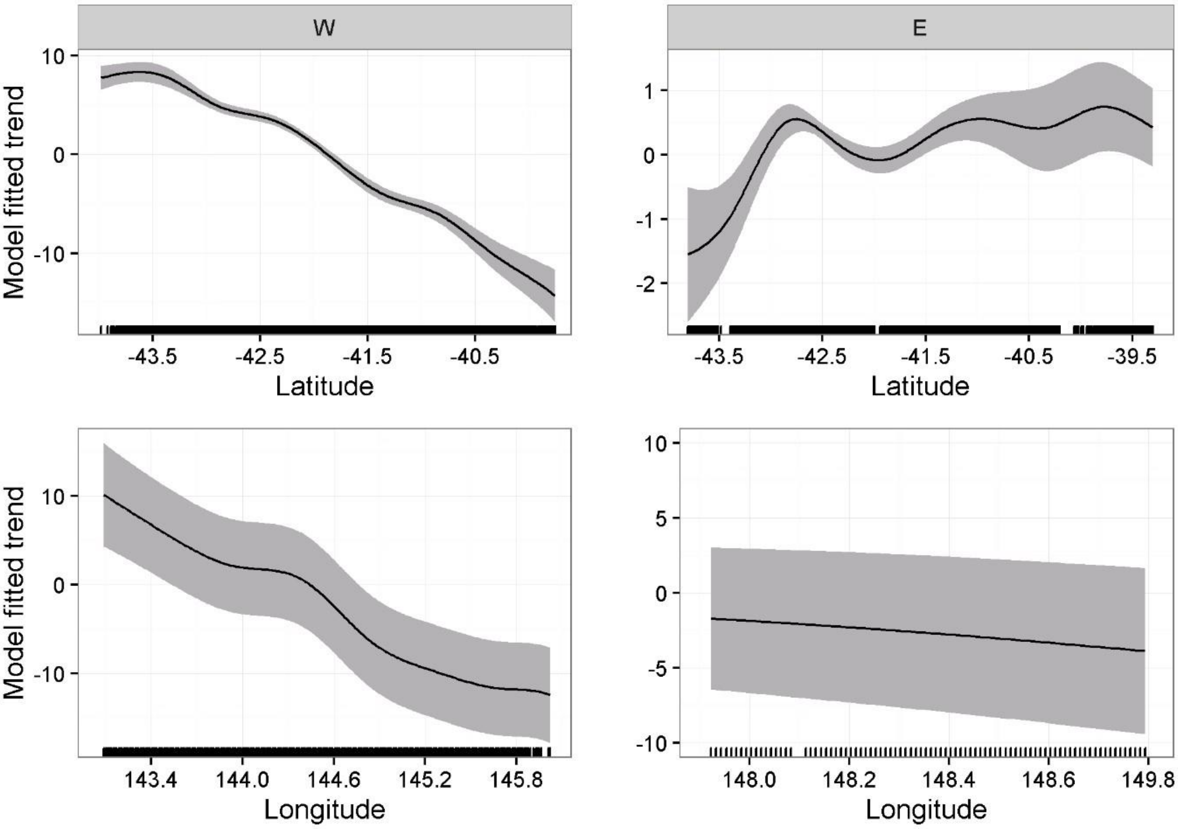

Figure 15. Changes in the latitudinal and longitudinal gradient of BT effort, trawled distance per unit of surface (km^2/km^2), on the bryozoan thicket in the West and East coast.

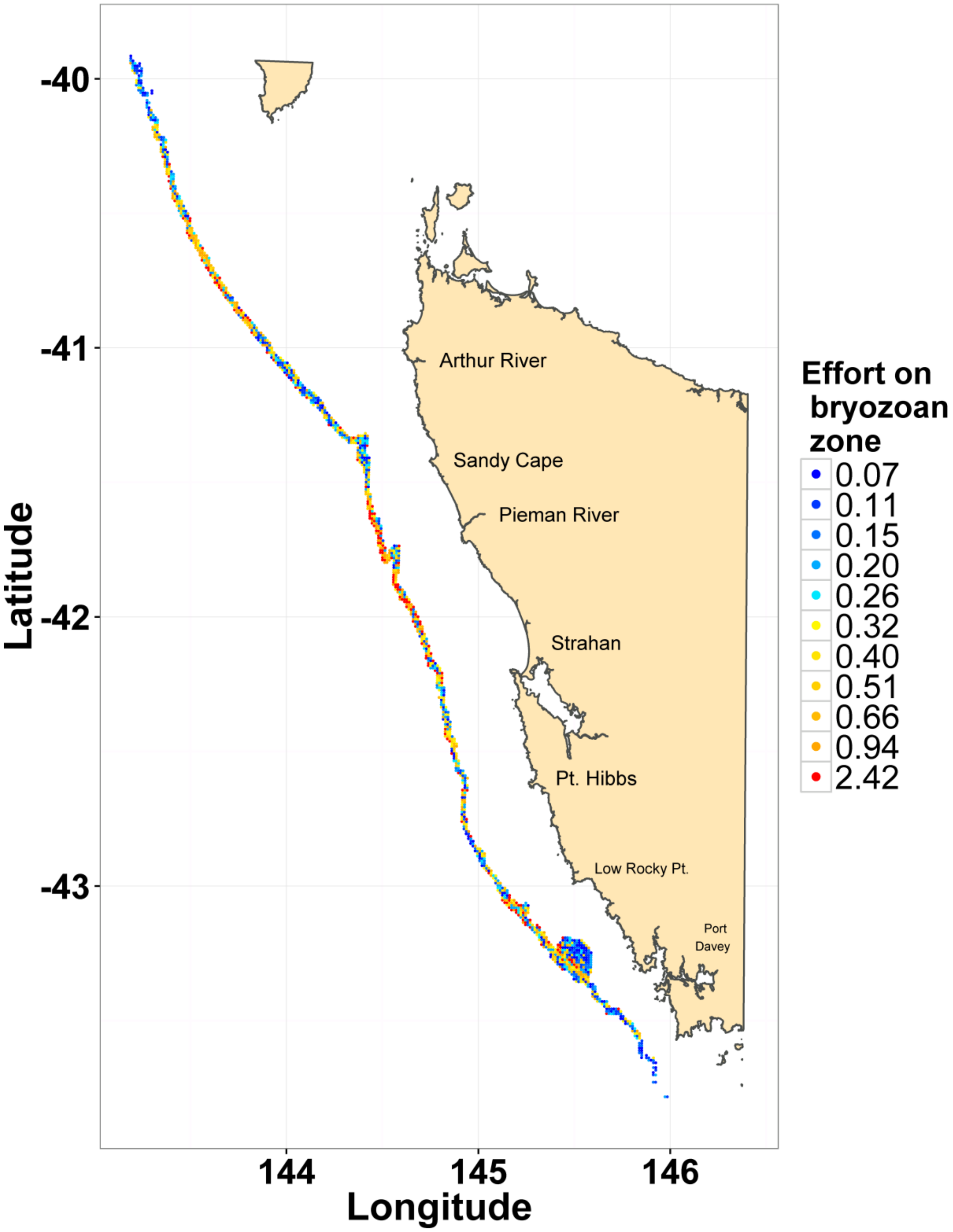

Figure 16. Spatial distribution of BT effort, trawled area per unit of surface (km^2/km^2), over bryozoan turf / thicket habitat off the West Coast of TAS.

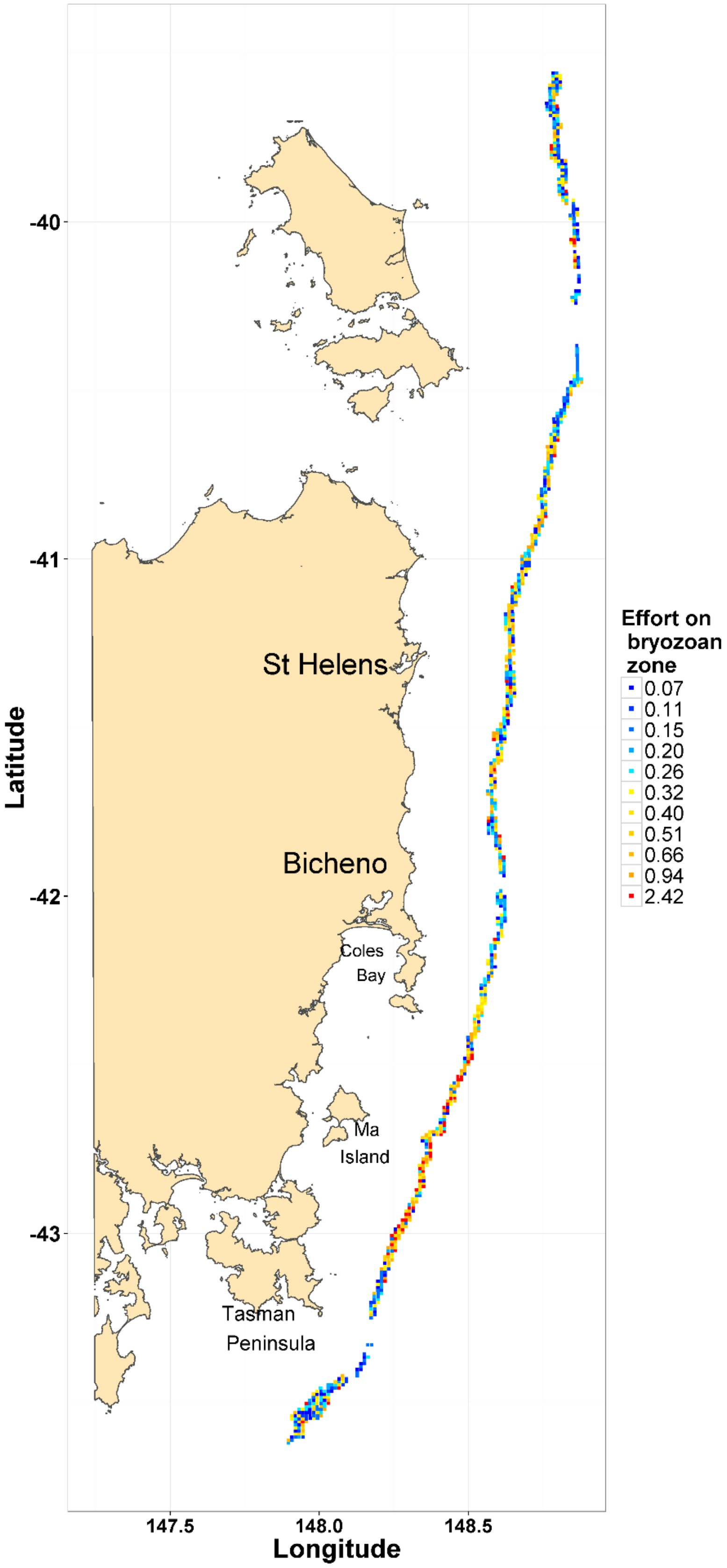

Figure 17. Spatial distribution of BT effort, trawled area per unit of surface (km^2/km^2) over bryozoan turf / thicket habitat off the East Coast of TAS.

Total BT effort over the bryozoan thicket changed significantly relative to the arbitrary baseline of 2008 (Table 4). Effort off the West Coast peaked in 2012 at ~469 km^2, dropping to ~230 km^2 in 2015. BT effort over bryozoan turf / thicket habitat was highest in three areas on the West Coast, between (i) south of King Island and Arthur River, (ii) Sandy Cape and Strahan, and (iii) south Low Rocky Point (Fig. 19).

In the East, BT effort over bryozoan turf / thicket peaked in 2009-2010 (Fig. 18). Highest effort occurred between Freycinet Peninsula and Tasman Peninsula (Fig. 20). BT effort was also high between North St Helens and Bicheno in 2010 (Fig. 20).

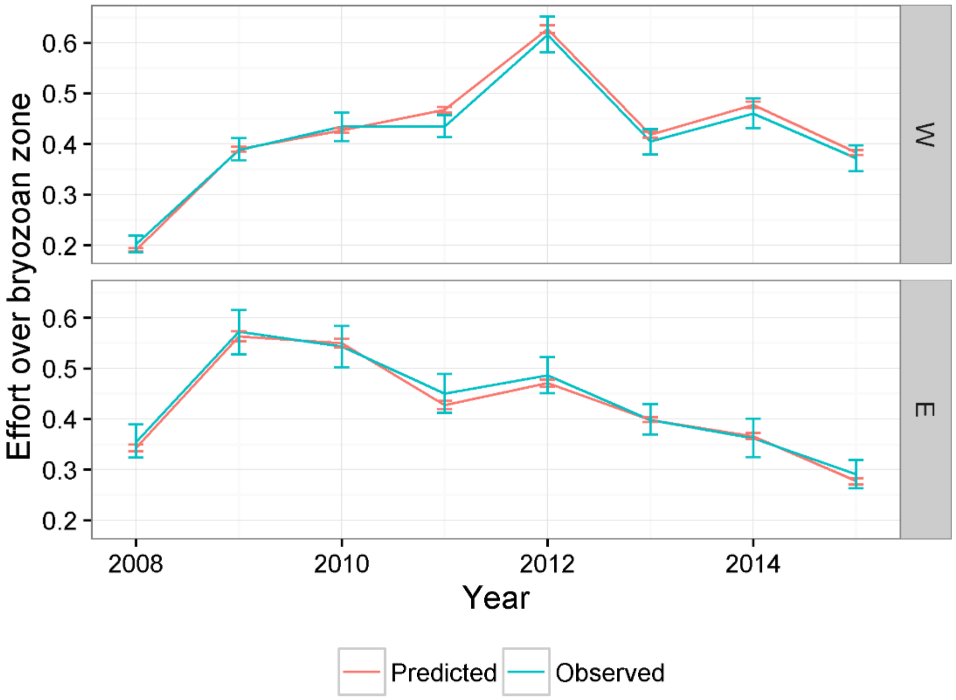

Figure 18. Mean change in BT effort per unit of surface over bryozoan turf / thicket habitat measured as trawled distance per area of habitat (km^2/km^2). Bars are confidence intervals.

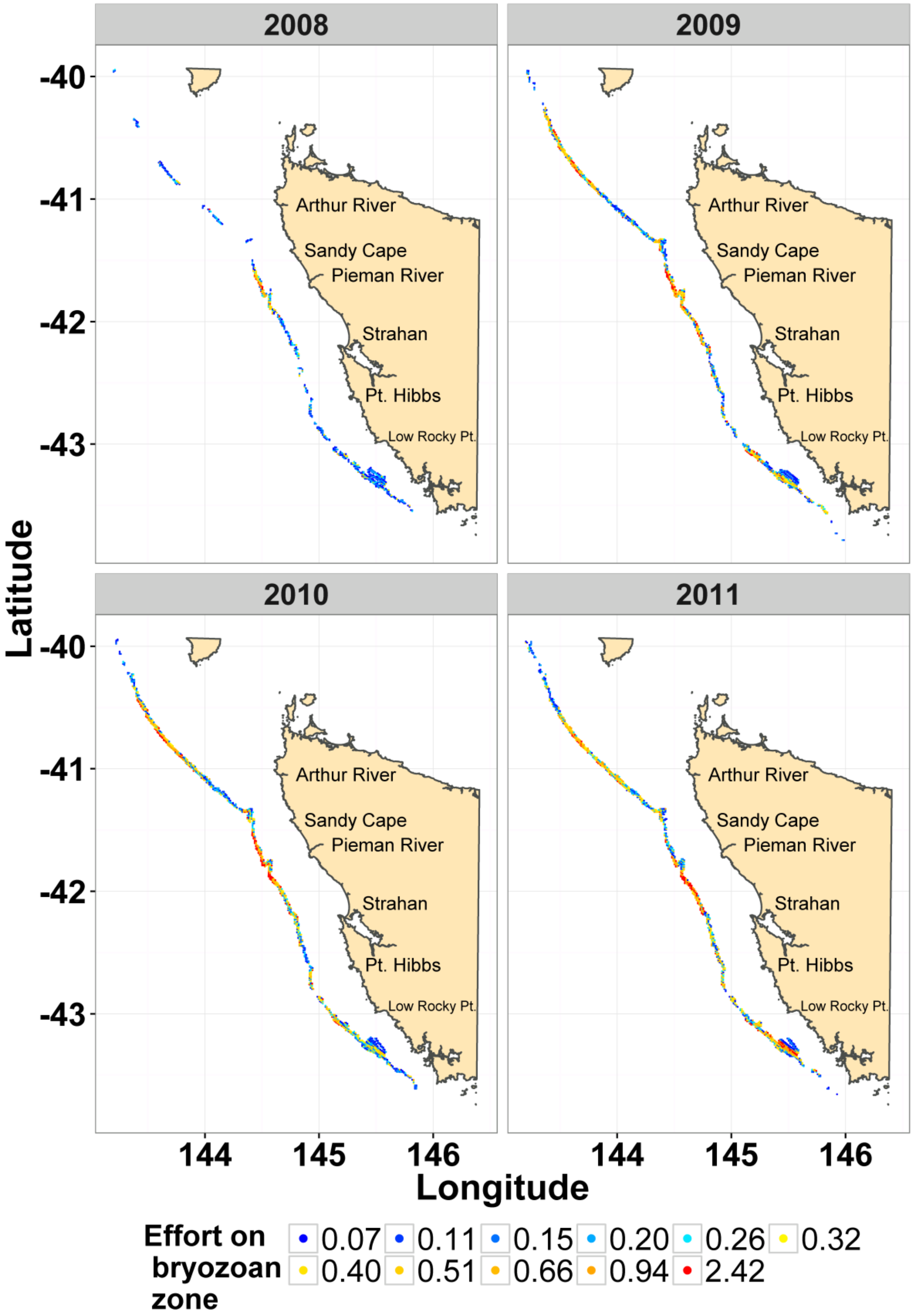

Figure 19. Latitudinal and temporal changes (2008 to 2011) of BT effort per unit of surface over bryozoan turn habitat off the West Coast of TAS. Effort was measured as trawled area per unit of surface of habitat (km^2/km^2) (*Continued*).

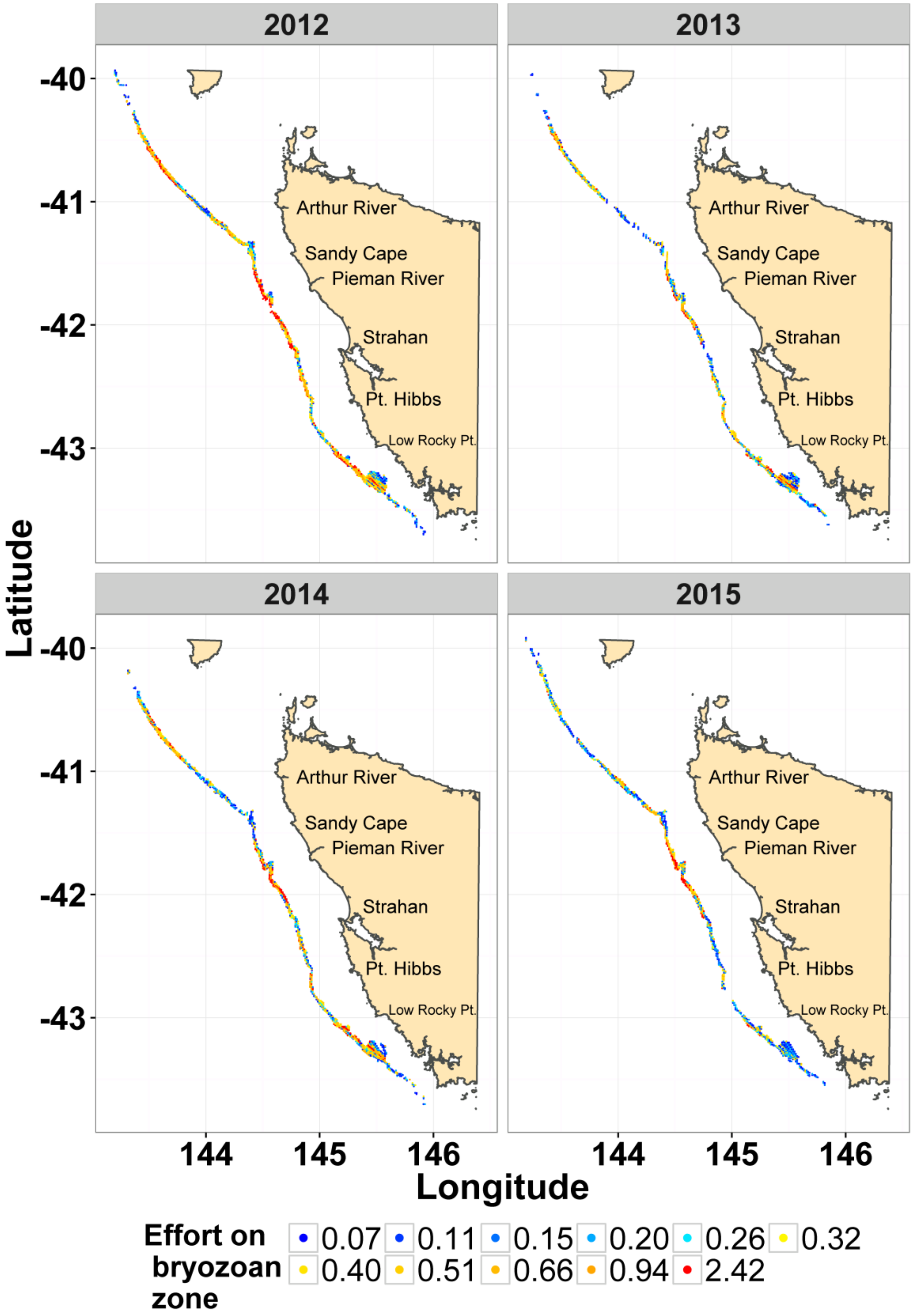

Figure 19. (*Continued*) Latitudinal and temporal changes (2012 to 2015) of BT effort per unit of surface over bryozoan turn habitat off the West Coast of TAS. Effort was measured as trawled area per unit of surface of habitat (km^2/km^2).

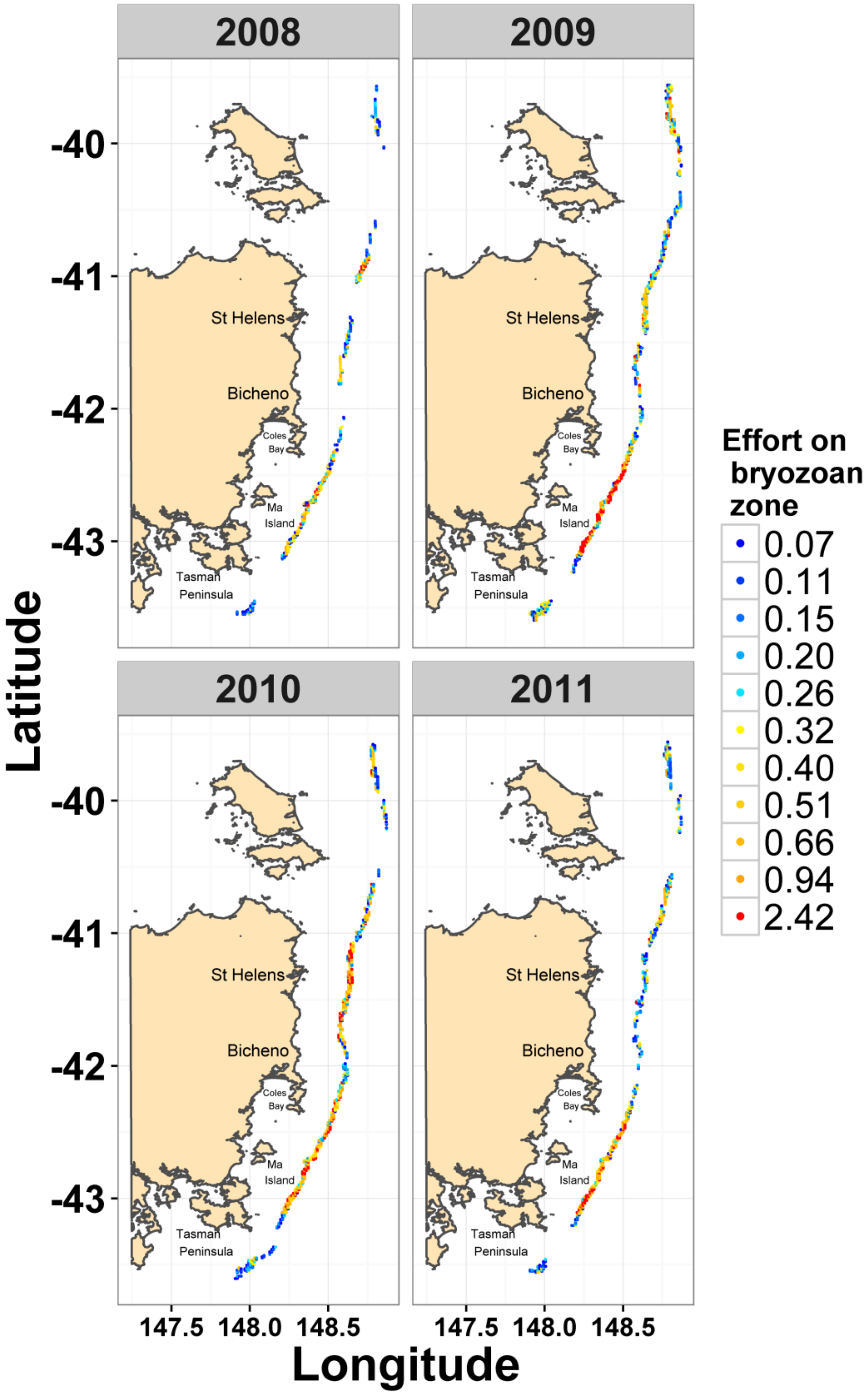

Figure 20. Latitudinal and temporal changes (2008 to 2011) of BT effort per unit of surface over bryozoan turn habitat off the East Coast of TAS. Effort was measured as trawled area per unit of surface of habitat (km^2/km^2) (*Continued*).

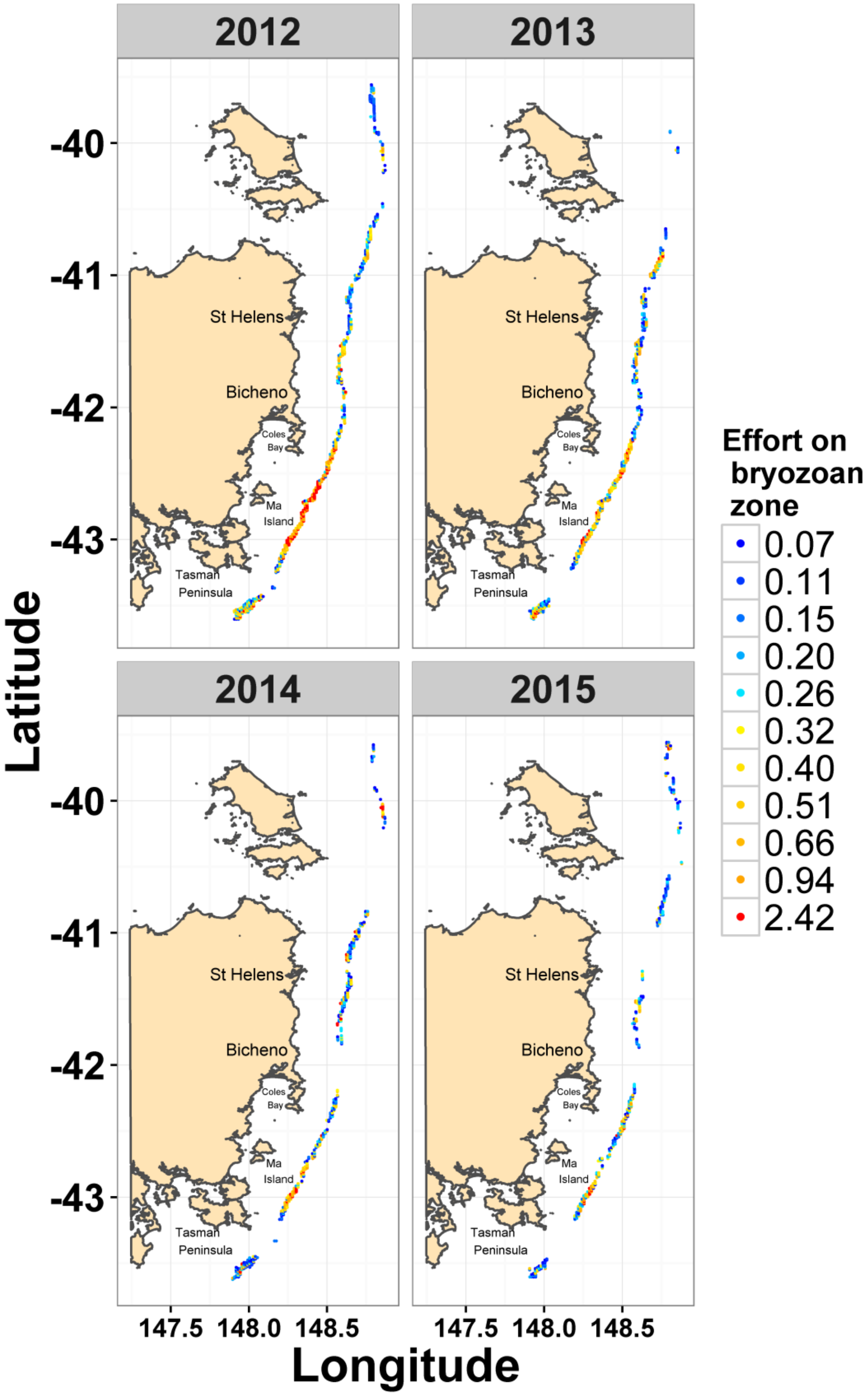

Figure 20. (*Continued*) Latitudinal and temporal changes (2008 to 2011) of BT effort per unit of surface over bryozoan turn habitat off the East Coast of TAS. Effort was measured as trawled area per unit of surface of habitat (km^2/km^2).

3.3. Bycatch of crabs in trawl gear

Observer data is available for only a small portion of trips and was not used other than to confirm that the reported bycatch of crabs were giant crabs and not some other species (as king crabs are also taken occasionally, although generally in much deeper water). Data on bycatch of giant crabs by the BT fishery was from fishers' logs and has remained low over the time, relative to the GC catch reported by the GC trap sector (Table 5, Fig. 21). The maximum and minimum value of GC as bycatch in TAS was 1.1 (2007) and 0.04 tonnes (2010) respectively. On the West Coast GC catch reported by BT fishers was around 1% the GC trap captures between 2007 and 209 (Fig. 21). The minimum value (0.15%) occurred in 2010 and then gradually increased to reach values around 0.6% in 2012-13. On the East Coast GC as incidental catch showed values very close to zero, except in the years 2007 and 2012 when this reached 4.3 and 2.0% respectively.

Table. 5. Giant crab catch (kg) in the crab trap fishery and as bycatch by bottom trawl as reported in logbook returns.

Year	Total TAS		West Coast		East Coast	
	Trap Catch	BT Bycatch	Trap Catch	BT Bycatch	Trap Catch	BT Bycatch
2007	56400	1101	41300	459	15100	642
2008	54900	295	31500	250	23300	45
2009	44400	327	30300	295	14100	32
2010	47100	46	28000	41	19000	5
2011	40100	117	25100	90	15000	27
2012	26400	300	16700	110	9700	190
2013	26000	134	18100	114	7800	20

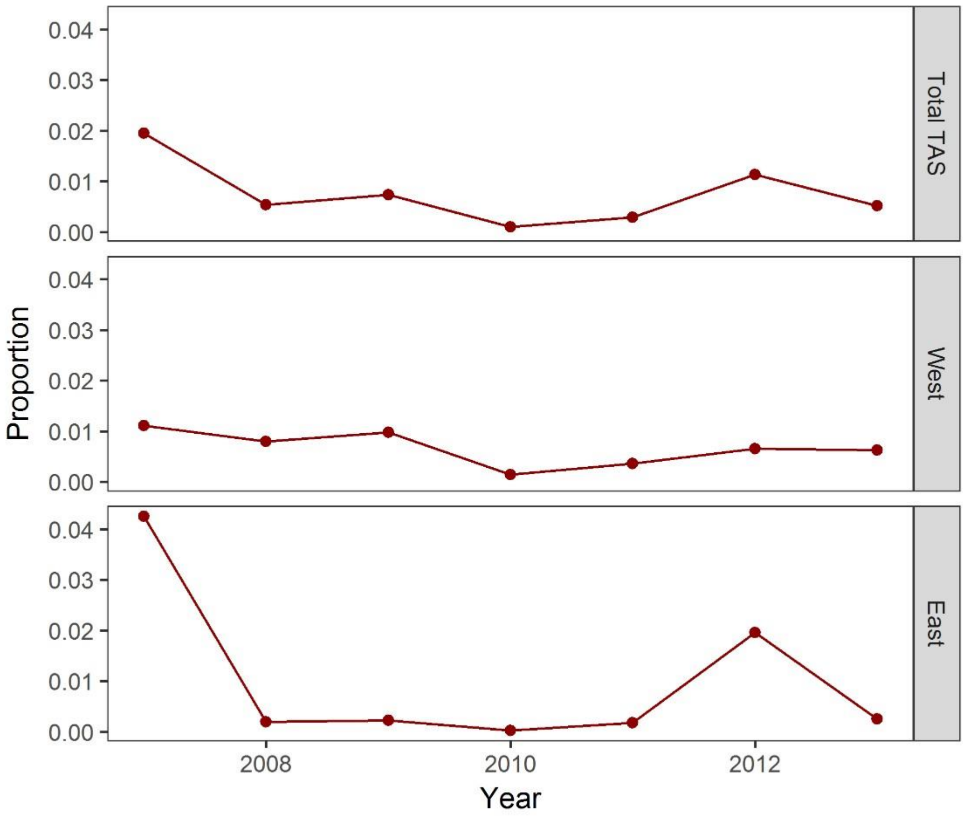

Figure 21. Giant crab as bycatch in the bottom trawl fishery as proportion of the catch in the crab trap fishery.

GC bycatch varied along the west coast with higher catches towards the north (Table 6, Fig. 22). There were peaks of GC as bycatch at the latitude between Pieman River and Woolnorth respectively (41.5° and 40.5° latitude South, respectively, Fig. 4, and 16) which are both locations where there was high overlap of the BT fishery and bryozoan turf / thicket habitat. On the East Coast, there were two peaks at the latitude of Bicheno and south of Flinders Island that match with mean and high values of spatial overlap between both fisheries (42.0° and 40.25° latitude South, respectively, Fig. 5 and 17). Bycatch of GC from trawl tended to be deeper than the trap fishery, peaking at 550 m (Fig. 22). Bycatch on the East coast peaked at 380 m depth.

Table. 6. Generalized additive model outputs describing changes of occurrence of GC as bycatch over time and space. Model fit assuming a Binomial distribution and log as a link.

Term	Factor	Estimate	Std. Error	z value	Pr(>|z|)
Parametric	Intercept	3.821	0.050	75.933	< 0.0001
	Year 2008	-0.778	0.056	-13.991	< 0.0001
	Year 2009	-0.933	0.055	-17.08	< 0.0001
	Year 2010	-0.690	0.049	-14.153	< 0.0001
	Year 2012	-0.164	0.047	-3.482	0.0005
	Year 2013	-0.980	0.052	-19.014	< 0.0001
	Factor	edf	Ref.df	Chi.sq	p-value
Non-parametric (smooth)	Latitude W coast	8.869	9	4049.5	< 0.0001
	Latitude E coast	7.647	9	288.3	< 0.0001
	Depth W coast	7.002	9	817.7	< 0.0001
	Depth E coast	8.374	9	241.3	< 0.0001

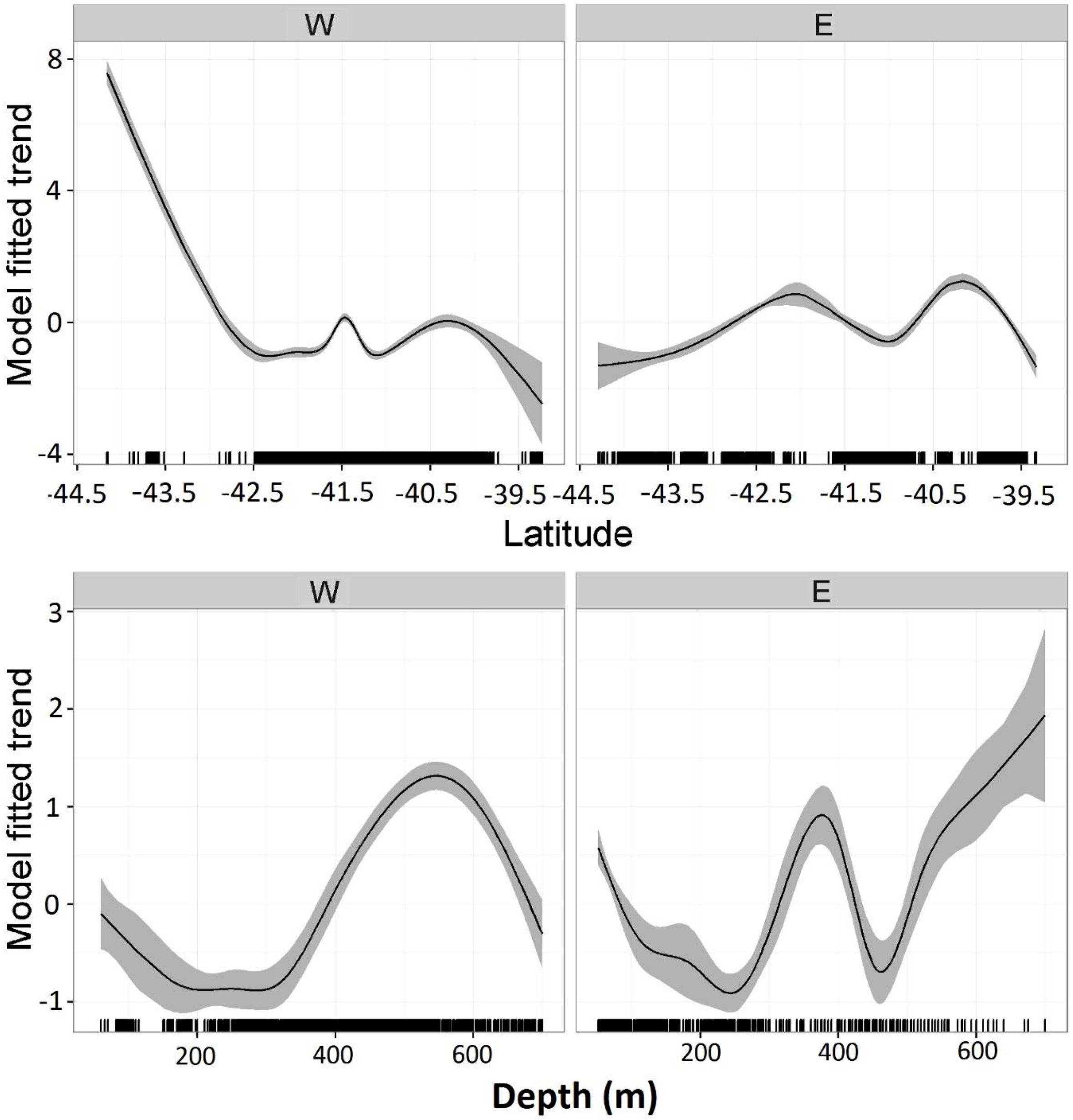

Figure 22. Latitudinal and bathymetric changes of occurrence of GC as bycatch in the West and East coast of TAS.

4. Discussion

There are several distinct issues involved in examining the interaction between the BT and GC fisheries with gear interaction the least important and most easy resolved of these. Spatial distribution of overlap of effort shows there was a higher chance of gear conflict off the West Coast than off the East Coast of TAS. In the West, 80% of the BT effort overlapped with areas used for GC effort indicated by cells with overlap. This issue can be addressed by simple changes such as the two sectors communicating with each other on the position of gear and coordinating the return of any entangled gear. Radio communication has been used to-date but web-based systems for sharing location data are also an option as these have been applied in other fisheries.

BT effort was greater in zones where BT was to be excluded in the voluntary agreement than in the zones where there was agreement that BT would continue. Effort has continued within the voluntary exclusion zones and was typically higher than in the agreed open areas of the same depth. Temporal trends in overall BT effort, BT effort overlapping GC fishing grounds, and BT effort in the voluntary exclusion zones were equivalent and appeared to be influenced by economics as the net economic return (NER) for the BT sector peaked around the same time as effort levels in 2010/11 (Georgeson et al. 2016). Collectively, these data show that the voluntary agreement did not act to regulate BT effort in areas that were critical to the crab fishery. This failure of attempted co-management suggests that alternate and regulatory approaches are required to resolve interactions between the two fisheries.

The spatial areas defined in the previous agreement cover only part of the bryozoan habitat that supports the GC fishery. Future management discussions should consider interactions between BT effort and GC habitat more widely than the zones in the agreement because of the wider scale of the interaction. This is because up to 50% of the bryozoan habitat receives BT effort in a single year, given assumptions described in methods regarding swept area.

Abundance of females and undersized crabs in the Northwest of TAS, between Arthur River and King Island was high historically indicating that this was an important area for recruitment (Williams et al. 2009). This was also supported by modelling of larval advection that showed that the Northwest of TAS was an especially important region for GC recruitment. Distribution of BT effort analysed here showed a high-level effort on the bryozoan zone to the north of Arthur River, especially when BT effort increased in 2012.

The implications of interaction between BT and the bryozoan turf / thicket habitat were summarised by Williams et al. (2009) as follows:

- the habitat has a potentially high risk of negative impact from benthic trawling, and other bottom contact methods using the same area will add (marginally) to this impact.
- Impacts include complete removal, recovery is likely to be slow (multiyear), and there is little rocky bottom to impede benthic trawling off western Tasmania.
- This habitat type makes up a large part of the depth zone (~150 to 350 m) where trawl sectors and giant crab fishing ‘interact’.
- No protection of bryozoan turf habitats occurs through formal fishery spatial management regulations.
- Some protection of bryozoan turf habitats occurs through Commonwealth MPAs (~6.5% of habitat distribution).

Giant crab catch reported by the BT sector was small and unlikely to have any impact.

The analyses presented in this report did not attempt to address two other issues raised as concerns by the GC industry. These were: (i) discard mortality of released crabs; and (ii) mortality of crabs that come in contact with BT gear but are not captured. Both of these would require further research involving field trials. This type of research has been done on other species so methods are established but values tend to be species-specific so would require new investigation for this fishery (Rose, 1999, Rose et al., 2013).

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