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Methods development for spatially-explicit bottom fishing impact evaluation within SPRFMO: 1. Fishery footprint estimation

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1. Abstract

We present a spatially explicit summary of estimated bottom trawl footprint in deepwater fishing areas of the SPRFMO Convention Area, using an impact assessment framework developed for CCAMLR bottom impact assessment of longline fishing gear (e.g., Sharp *et al.* 2009; Sharp 2010; Webber 2012). Under this framework the 'footprint' is defined as the area of the sea floor potentially contacted by bottom fishing gear. The 'footprint index' is a measure of the size of the footprint per unit of fishing effort (i.e. per linear km of trawl). 'Impact' is defined as the proportion of vulnerable benthic taxa that are damaged or destroyed by contact with bottom fishing gear within the area of the footprint. The 'impact index' is a measure of what proportion of vulnerable benthic organisms are damaged or destroyed with the area of the footprint per fishing effort. The impact index ranges 0 to 1 and varies depending on the fragility of the taxa in question. In practice impacts are often only estimated for the most fragile taxa.

Cumulative footprint and *cumulative impact* are defined to include the total footprint and impact of all individual fishing events over time. Because many deepwater VME taxa are very slow growing, this implementation of the method adopts the precautionary assumption that all impacts are permanent (i.e no recovery.)

Proportional footprint is the cumulative footprint of each cell divided by cell area. To estimate the effects of repeated fishing events in the same location, the method assumes random spatial overlap of subsequent trawl footprints within a spatial cell, and applies subsequent impacts only to the remaining un-impacted proportion of the vulnerable taxa, so that impacts are not double-counted (i.e. impact in a particular location can never exceed 100%).

Because the extent to which subsequent trawls are estimated to overlap previous trawls depends on cell size, cumulative footprint and impact will vary as a function of cell size. Here we illustrate the shape of this scale dependence by re-estimating cumulative footprint from individual trawl positions summarized at different spatial scales.

We also map spatially explicit estimates of proportional footprint at different cell sizes for all historical New Zealand fishing effort targeting orange roughy *Hoplostethus atlanticus*, and summarise the results separately for fishing patterns on different habitat types, i.e. underwater topographic features (UTFs, i.e. hills, knolls and seamounts). Finally we present the results of an impact assessment expert workshop characterizing the likely effect of individual orange roughy trawls on vulnerable benthic taxa in different topographic settings in the SPRFMO area, to inform the estimation of the *impact index*, and apply these results to generate a spatially comprehensive estimate of cumulative historical bottom fishing impact on vulnerable benthic taxa across the western SPFMO area.

This paper represents progress toward a spatially-explicit bottom impact evaluation for all deepwater fisheries in the western SPRFMO Area. When combined with the results of spatial habitat mapping or applied within defined habitat zones (e.g. depth ranges) spatially explicit impact assessments of this nature can be used to estimate the current *intact status* (i.e. proportion of the taxon or habitat remaining undamaged, analogous to current biomass in fisheries) for VME taxa. Even in the absence of spatial distribution layers for VME taxa, a spatially explicit impact layer is useful to inform the design and evaluation of spatial management strategies, for example

by showing which locations are already too heavily impacted to provide conservation benefit, and by making explicit the consequences of preventing or allowing future fishing in different locations.

Next steps include the incorporation of non-New Zealand data, and incorporation of impact index results into quantitative analyses so far applied only to footprint. It is intended that this work will inform the transparent design and evaluation of effective spatial management measures for bottom fishing in the SPFMO Area.

2. Methods

Data

Commercial catch and effort data from all bottom trawl fishing events carried out by New Zealand and New Zealand-chartered vessels in the SPRFMO region outside the New Zealand EEZ boundaries for years 1989 to 2016 were extracted from the fishery statistics database managed by the Ministry for Primary Industries (MPI, Replog no. 10889). Standard grooming was carried out as per Roux et al. (2017). Over 98% of tows targeted orange roughy but other species such as cardinalfish (0.4%) and oreos (0.2%) were also targeted.

Trawl tracks were defined as straight line distances between start and end vessel positions recorded in logbooks, recorded at a resolution of 0.002 degrees. At these latitudes, 0.002 degrees varies from 233 m to 243 m. Trawl width was assumed 150 m (door to door) for all tows since most tows targeted orange roughy following Baird et al. (2011). This assumption corresponds to a *footprint index* of .015 km^2 of footprint per 100 m of linear trawl length. (Note that discussions in the impact assessment stage, below, suggest that in subsequent implementations the footprint index should be modified to .0135 for tows on slope habitats, and .0115 for tows on UTF habitats). Tows were assigned to UTFs listed in the Seamounts database managed by NIWA (Rowden *et al.* 2008), based on tow start position (at the vessel) relative to UTF summit position, UTF category (hill, knoll or seamount) and tow duration (see Roux *et al.* 2017 for details).

The start position of tows used for the analysis is shown in Figure 1. Fewer than 0.1% of tows had trawl track distances greater than 156km based on latitude and longitude; these were dropped from the analysis, as they were likely to be position recording errors. Visual analysis of outputs suggests some positional errors may remain (i.e. the prevalence of long tows oriented directly N-S or E-W suggests positional start and end position errors); the database may benefit from additional grooming. Because the Seamounts database does not extend as far as the South Tasman Rise (south-west corner of Figure 1), all tows in that region were assumed to be continental slope tows although in reality these tows are expected to represent a mixture of UTF and slope habitat.

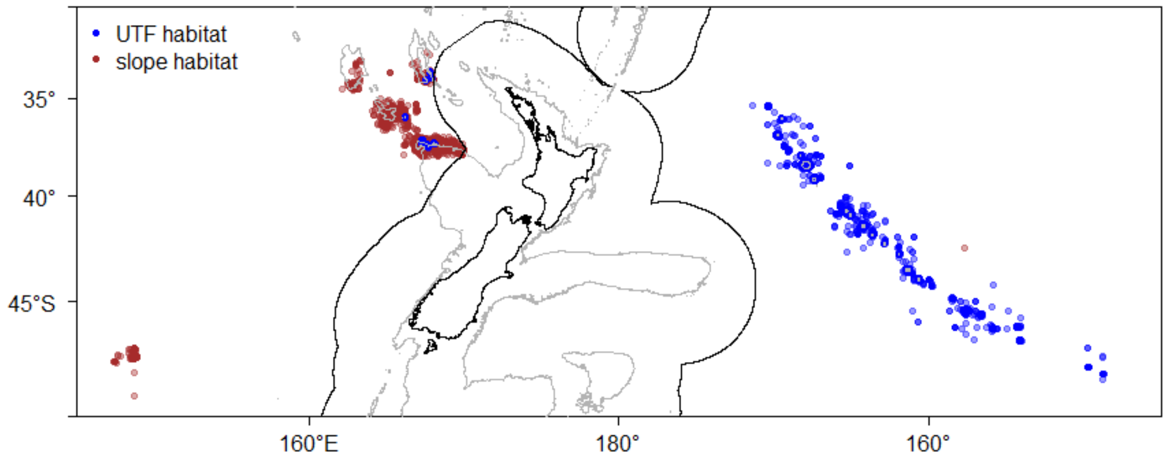

Figure 1: Start position of the tows used in analysis split by UTF (Underwater Topographic Feature) or slope habitat. The 1000m depth contour is shown in grey and the NZ EEZ in black.

Horizontal offset

Because start and end positions are recorded at the position of the vessel not the fishing gear, the position of each trawl footprint was corrected by first determining the direction of travel of the vessel (end position minus start position) and then offsetting the start and end positions backward by a distance of 1.7 times the recorded fishing depth. Geometrically this corresponds to the length of the warp being 2 times the fishing depth, which was the approximation recommended by fishers familiar with the operation of the SPFMO fishery.

For UTF tows for which the recorded start and end positions were identical, we offset the start location in the direction of the seamount summit, on the assumption that fishers fish down-slope, and applied an estimated trawl length of 100 m.

Rounded position recording offset

Reported fishing effort locations in the SPRFMO database are generally rounded to the nearest minute, corresponding to roughly 1 nm; fewer than 1% of tows are not rounded to the nearest minute. To account for positional rounding, we incorporated a random directional offset (jitter) of 0.5 minutes applied to both the start and end positions (as in Penney 2013).

Estimation of the fishery footprint

Individual trawl footprint were estimated by splitting each tow into sections of approximately 100 m long, and assigning the corresponding footprint area to the geographic location of the segment midpoint. Cumulative proportional footprint per cell is then a function of the number of segment midpoints within each cell, assuming subsequent trawls overlapped with previous trawls in the same cell in a random manner. This methodology allows the estimation of cumulative footprint at a range of cell sizes without having to carry out a full GIS analysis of the trawl path polygons intersecting grid cells, such as that in Baird et al. (2011).

Where fishers repeatedly target features or favored fishing locations at scales smaller than the scale of a cell, the assumption of random spatial tow orientations within the cell is increasingly violated at larger cell sizes. This results in a precautionary (impact-maximising) bias in the estimation of cumulative footprint and impact as individual footprints become increasingly non-overlapping at larger cell sizes.

We report 1) the *proportional footprint* per cell (areal proportion of each cell encompassed by at least one trawl footprint); and 2) the *cumulative footprint* (summed area of all footprints in all cells) as a function of cell size. To illustrate the bias effect of estimating footprint and impact at different cell sizes, estimates were generated independently at six spatial grid resolutions (assuming random overlap of individual trawl footprints with the cell at that resolution). The 200 m scale grid corresponds to the finest possible grid resolution, considering the assumed tow width of 150 m; however it is evident that that positional reporting is accurate to this scale. Sensitivities were performed to assess the effects of increasing cell sizes on the estimation of local and overall footprint (at 200 m, 1 km, 2 km, 5 km, 10 km and 20 km).

- Spatial grids definition
  - The study domain (145°W to 145°E longitude and 28°S to 50°S) was projected using the Mercator projection and super-imposed on the spatial grids; for example, the 1 km scale split the domain in 2379 rows and 5797 columns.
  - Because a single projection was used over a large area, cell size changed through the domain, with the third quartile of cell size +/- 8 % of the mean cell size (at the 1 km scale, the interquartlie range was 0.97 to 1.11 km with a mean at 1.03 km).

- Cumulative proportional footprint estimation.
  - Each tow was split into equal distance segments of about 100m length (the integer closest to the value of tow distance divided by 100 m),
  - segment length was calculated based on the total length of the tow and the number of segments,
  - each segment was then assigned a mid-point latitude and longitude,
  - tows with equal start and end positions (19% of tows) represent short UTF tows; these were assigned to a single segment with a nominal length of 100m (see sensitivity below),
  - tows with no end positions (0.5% of tows) were assigned to a single segment and a nominal distance of 100 m,

- at each scale, each tow segment was assigned to a cell,
- at each scale, each segment length was multiplied by the assumed trawl width (150 m, see Baird *et al.* 2011) to calculate the footprint area of each segment, then divided by the average cell area to estimate segment contribution to proportional footprint,
- the proportional footprint of each cell (F) was calculated assuming random overlap between trawl segments, whereby:
  $F = F_1 + F_2 - (F_1 * F_2)$ for two segments *1* and *2*,
  then looped over all segments *x*:
  $F = F + F_x - (F * F_x)$.
- For example, if 50% of the cell has already been footprinted, a new segment of 10% proportional footprint will overlap by 50% with the existing footprint, and the cumulative proportional footprint will be $0.5 + 0.1 - (0.5 * 0.1) = 0.55$,
- the cumulative footprint was calculated as the proportional footprint value times the area of the cell, summed across all cells
- the *fished envelope* at each scale was defined as the area of cells with some non-zero level of proportional footprint, and reported as a percentage of the fished envelope at the 20 km scale,
- each cell was defined as 'UTF habitat' if all tows carried out in the cell were associated with a UTFs as defined in the "Data" section above, 'slope habitat' if none of the tows carried out in the cell were associated with a UTF, or 'mixed'.
- Histograms of the distribution of estimated proportional footprint were generated. Spatial plots of estimated proportional footprint by cell were also created, scaled 0-1.

- Analytical assumptions
  - A number of assumptions were made for tows which did not have suitable start and end positions for the method: either missing, of equal values, or resulting in unrealistic length trawl tracks (156 km was chosen as it represents the maximum distance derived from speed and duration of tow). A summary of the assumptions on the length of trawl tracks included in the analysis is given in Table 1 with comparison with trawl lengths based on speed and duration of tow.

Table 1: Impact of the assumptions on trawl lengths included in the analysis.

Type of tow	Percentage of all tows	Mean tow length used in the analysis (km)	Mean tow length based on speed and duration of tow (km)	Sum of tow length used in the analysis (km)	Sum of tow length based on speed and duration of tow (km)
Greater than 156km long	0.6	0.0	9.5	0	295
No end position recorded	0.5	0.1	NaN	16	0
Same start and end positions	18.2	0.1	1.8	618	10928
All other tows	81.4	9.5	9.7	263425	268126

3. Results

At the 200 m scale

The distribution of the proportional footprint at the scale of 200 m cells is shown in Figure 2. Each tow segment is (approximately) 100m long and 150m wide. Therefore, at the 200 m scale, a single tow segment midpoint assigned to a cell equates to 37.5% proportional footprint ($100 * 150/200^2$). Figure 2 shows that approximately 9% of cells were affected by one or fewer trawl segment midpoints as represented by a strong peak at 35-40% proportional footprint; 40% by two or fewer midpoints; and 27% of cells had a proportional footprint greater than 95% (equating to three or greater tow segments in that cell).

When separated by habitat type, a smaller proportion of UTF had a proportional footprint greater than 95%, relative to slope cells: 14% for UTFs habitat vs 30% for slope habitat (Figure 3). The histograms are discontinuous because of the small scale of the cells.

Note that the histograms in Figures 2-6 depict only cells with non-zero fishing effort, but the total area of all cells with non-zero footprint increases with increasing cell size (Figure 7). The estimated proportional footprints apparent in Figures 2-6 cannot be compared for different cell sizes without reference to a single 'fished envelope' that is constant across all scales. For this reason, above each histogram we indicate what proportion of the 20-km-scale fished envelope is represented by non-zero cells in that figure. To illustrate, the total area of non-zero footprint cells at the 1 km scale (Figure 4) is just 16% of the fished envelope at the 20 km scale; the remaining 86% of 1 km cells have had no fishing effort (zero footprint) but are not included in the figure.

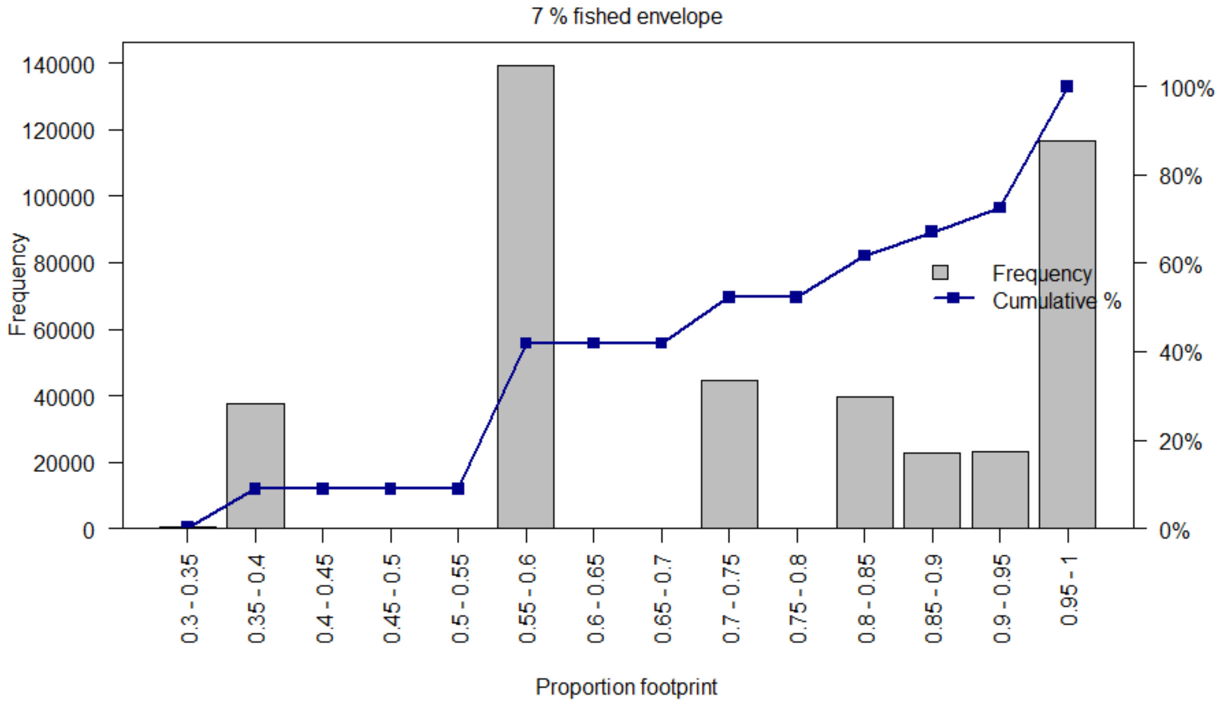

Figure 2: Histogram of the proportion of fished cells with different levels of estimated proportional footprint at 200 m scale. Note that relative to the area of the fished envelope at the 20 km scale, only 7% of cells at the 200 m scale are fished; the remaining 93% of cells have zero footprint.

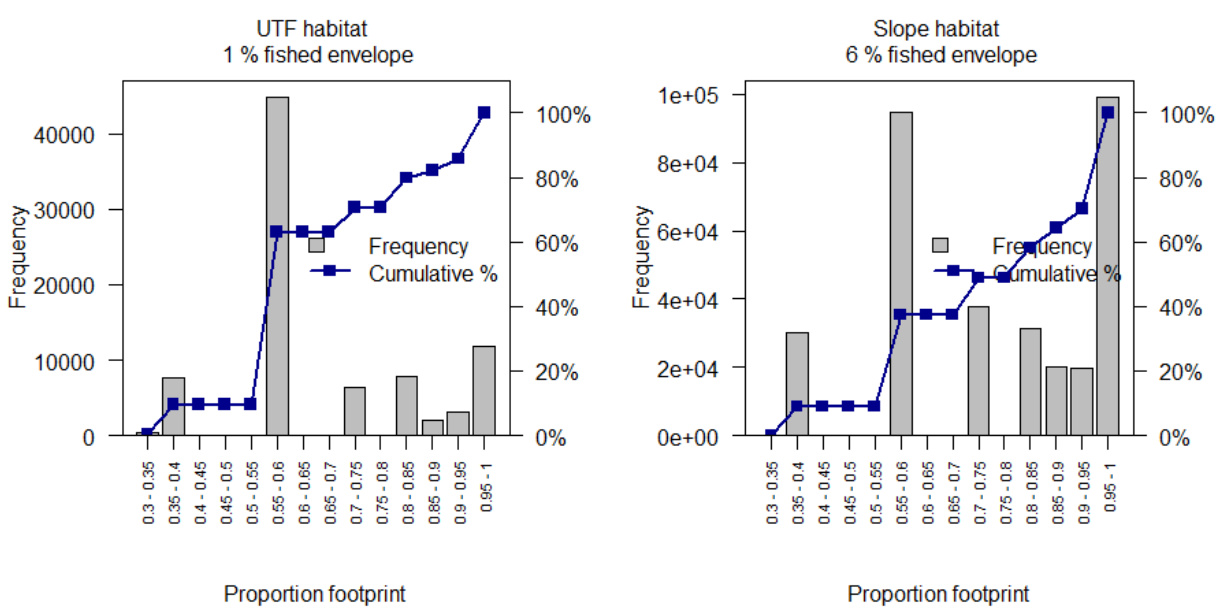

Figure 3: Histogram of the footprint at 200 m scale for UTF habitat (left) or slope habitat (right). Relative to the fished envelope at the 20 km scale, 1% of cells are UTF habitat; 6% of cells are slope habitat, and 93% of cells have zero footprint.

At the 1 km scale

The distribution of the proportional footprint at the scale of 1km cells is shown in Figure 4. About 40% of cells were crossed by a tow once or less as represented by a strong peak at 10-15% proportional footprint ($1000 * 150/1000^2$). Conversely, 9% of cells had a proprtional footprint greater than 95%, which would take on average 66 tow segments, or roughly 6 tows crossing the cell.

When separated by habitat type, a higher proportion of UTF cells had a proportional footprint of a single tow or less (over 60%) and a smaller proportion of UTF habitat had a proportional footprint with 95% or more (4%). In contrast, slope tows showed the general pattern (Figure 5). The spatial plot of proportion footprint at 1, 5, 10 km and 20 km cell sizes are shown in Appendix A.

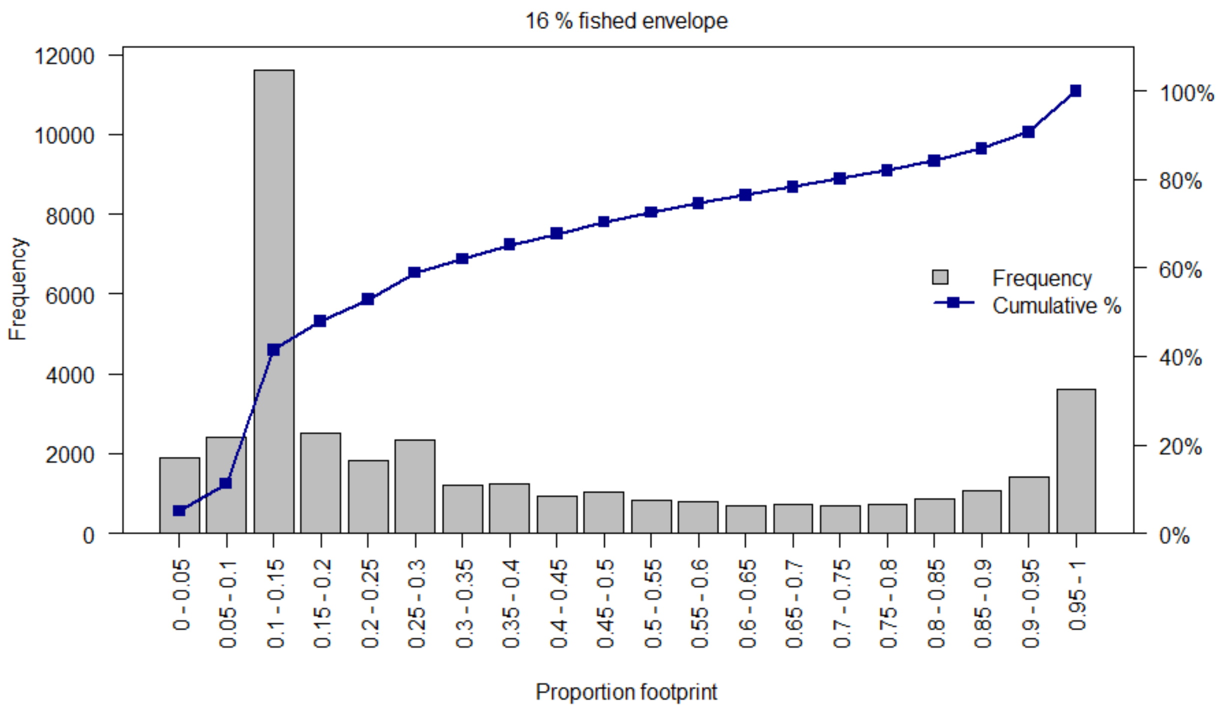

Figure 4: Histogram of the proportional footprint at 1 km scale, with the fished envelope. Note that relative to the area of the fished envelope at the 20 km scale, only 16% of cells at the 1 km scale are fished; the remaining 84% of cells have zero footprint.

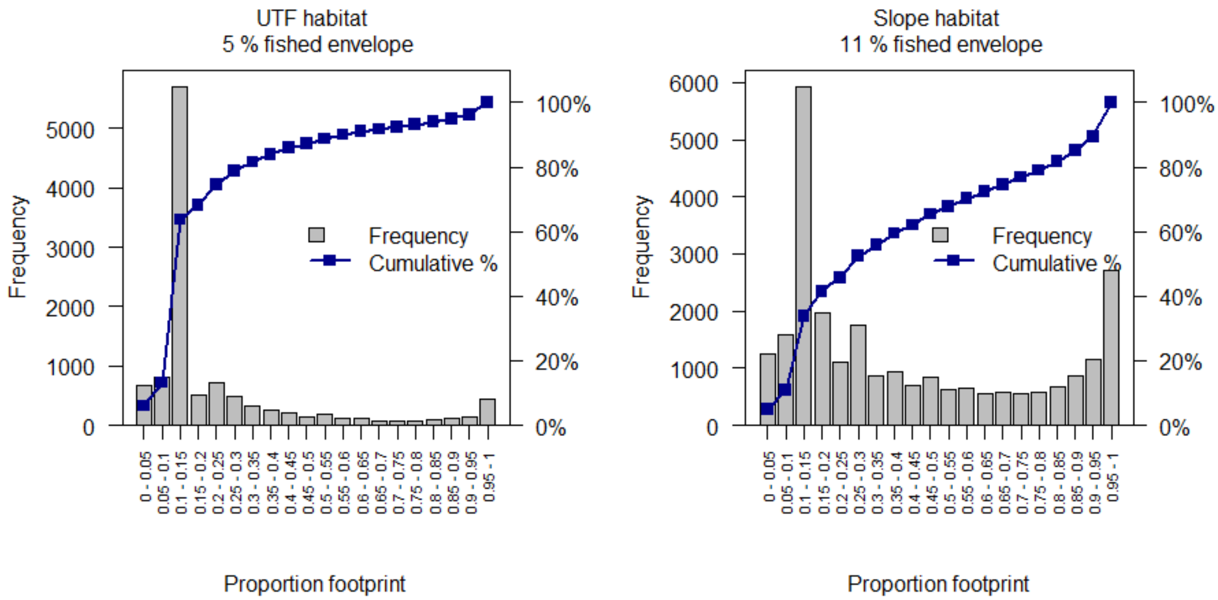

Figure 5: Histogram of the proportional footprint at 1 km scale for UTF habitat (left) or slope habitat (right). Relative to the fished envelope at the 20 km scale, 5% of cells are UTF habitat; 11% of cells are slope habitat, and 84% of cells have zero footprint..

Effect of scale

The effect of spatial scale on proportional footprint is shown in Figure 6. As the cell size increases, the proportional footprint is effectively "diluted" (i.e. the number of cells with high footprint reduces as cell size increases and values are averaged out but the fished envelope increases). Sample spatial plots of the proportional footprint at 1, 5, 10, and 20 km scales are shown in Appendix I .

The estimate of cumulative footprint increases with increasing cell size (Table 2). The cumulative footprint is a function of the number of tow segments, and assumed overlap of multiple trawl footprints within cells calculated at each scale, hence the increase with increasing scale: within larger cells there is less random overlap between individual tows. If we were to assume no overlap between tows (i.e. methodologically equivalent to estimating impacts at infinite cell size), then the cumulative footprint would equal the sum of all segment areas (~ 39600^2).

Note that estimates at the 200 m scale are likely to be spurious because at that scale even a single tow segment constitutes a large proportion of the area of an individual cell, but this cell size is considerably smaller than the positional accuracy with which individual tow paths are reported. Ingoring the 200 m scale, estimates of the total cumulative footprint vary only slightly from the 1 km to 5 km scale, but at the infinite scale the estimate is 2.6 times higher than at the 1 km scale, reflecting highly non-random fishing patterns at least down to the 5 km scale. These patterns have implications for the scale at which effort data should be reported and analysed to accurately understand bottom fishing impacts

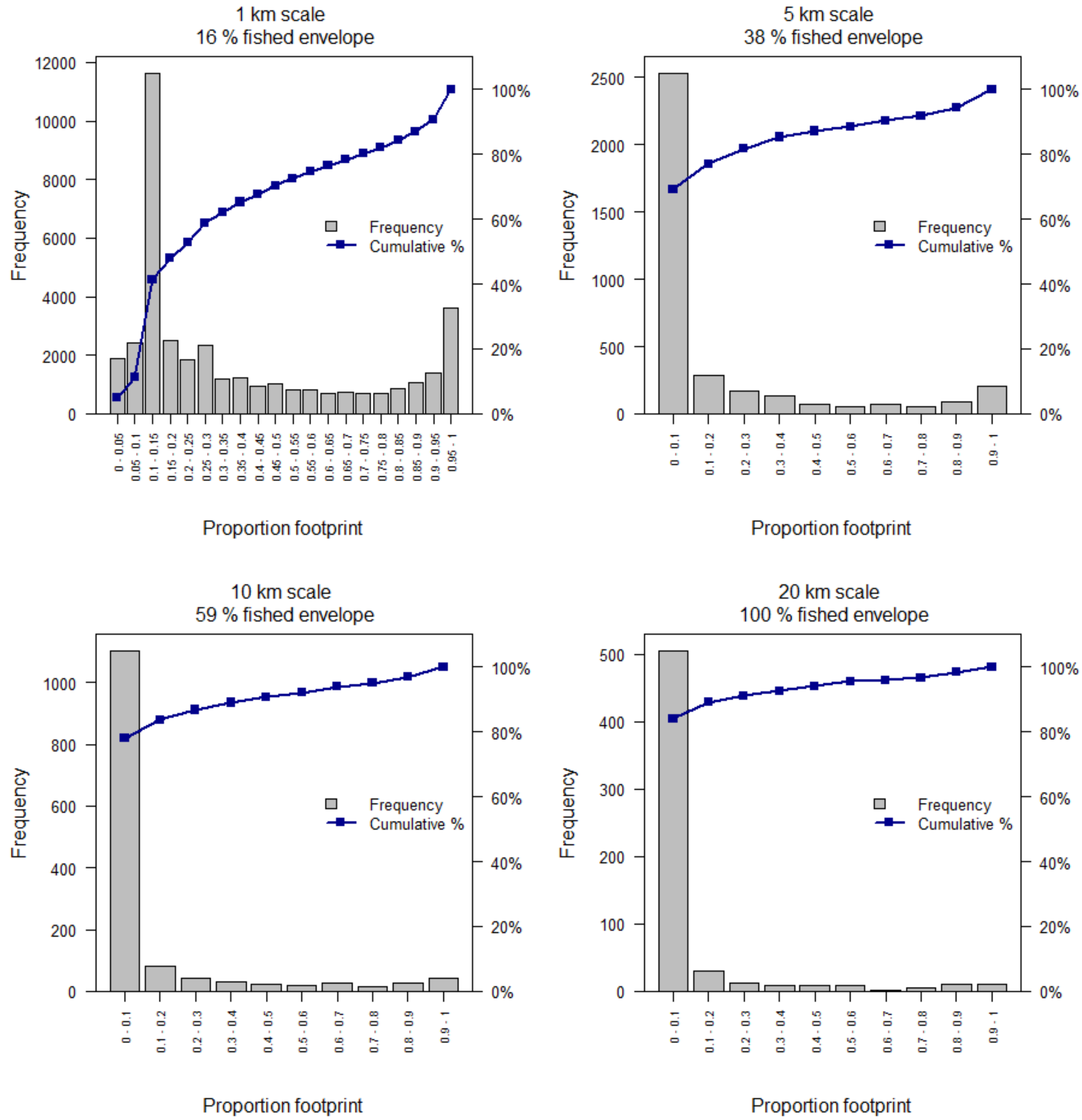

Figure 6: Histogram of the proportional footprint at 1km, 5km, 10km and 20 km scale, with the fished envelope (as a proportion of the 20 km scale fished envelope). Note that relative to the area of the fished envelope at the 20 km scale, only 16%, 38%, and 59% of cells at the 1 km, 5 km, and 10 km scales, respectively, are fished; the remaining cells have zero footprint.

Table 2: Summary of the proportional and cumulative footprint at various scales. The infinite scale (Inf) shows the cumulative footprint assuming there is no overlap of tows.

Size of cells (km per side)	Cumulative footprint (km2)	Mean proportional footprint	Fished envelope (km2)	Area of cells with over 50% proportional footprint (km2)	Area of cells with over 95% proportional footprint (km2)
~~0.2~~	~~13402~~	~~0.75~~	~~17945~~	~~16338~~	~~4933~~
1.0	15232	0.37	40634	12062	3803
2.1	15777	0.27	57895	11939	3824
5.1	16730	0.17	96641	12454	3940
10.3	18275	0.12	149549	13961	3596
20.6	20993	0.08	253831	15230	2961
Inf	39567	NA	NA	NA	NA

Combined effect of scale and habitat type

The distribution of the extent of the proportional footprint at different scales for UTF and slope habitat are shown in Figure 7. UTF habitats have a lower mean proportional footprint than slope habitats (horizontal lines in Figure 7) as well as a more discrete mode. The numerous modes at the 200 m resolution indicates that this scale is too small to adequately capture patterns. As the size of cells increases, the mean proportional footprint is decreases (see also Table 2). Although the mean footprint drops as the size of the cell increases, the fished envelope (summed area of cells that have had some degree of fishing) increases for both UTF and slope habitat (the blue line in Figure 7).

Sensitivity to assumptions on short tows

For very short tows, start and end positions can be identical and assumptions made in the analysis might impact on the results; they represent 18% of tows. We have assumed a 100 m impact for each of those tows, consistent with the segment size chosen for the analysis, but this grossly under-estimates the actual average trawl distance (1.8km, see Table 1) and might impact on the proportional footprint. A further analysis was carried out at the 1 km resolution for UTF habitat only whereby tows with the same start and end positions were given their actual distance calculated from speed and duration (capped at 2 km to avoid outliers). Results show that the analysis of proportional footprint is insensitive to this assumption (Table 3), which is likely due to the high overlap of fishing on UTF habitat. Analyses of annual proportional footprint or of fishery impact might however be sensitive to this assumption.

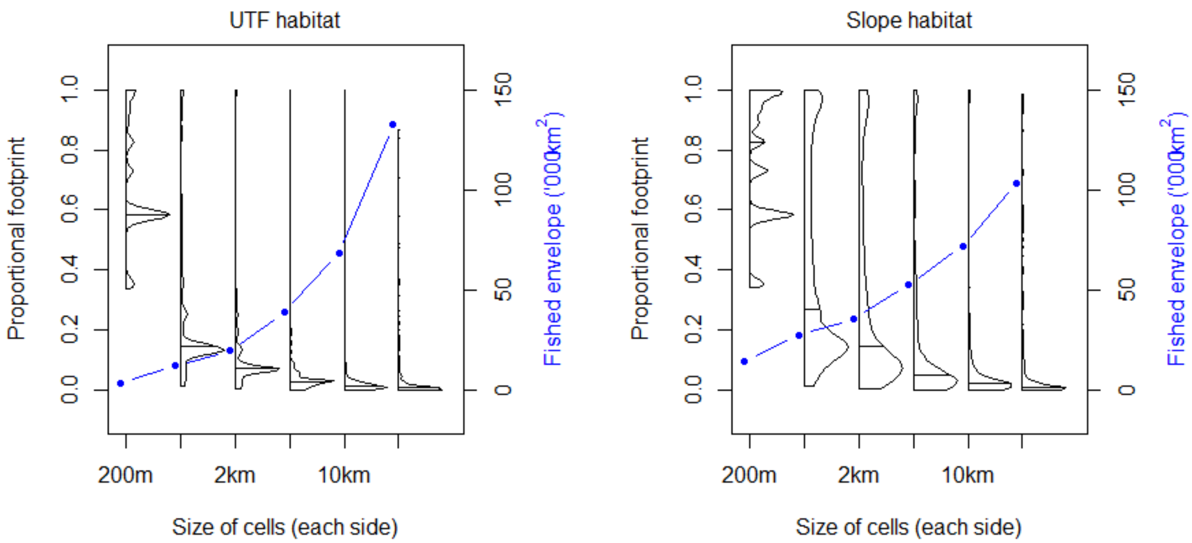

Figure 7: Distribution of the proportional footprint at various scales for UTF habitat (left) or slope habitat (right). Mean is shown as a horizontal line. Also shown in blue is the fished envelope (summed area of cells with some proportional footprint) at each resolution.

Table 3: Summary of the distribution of the proportional footprint for UTF habitat using two assumptions for tows with the same start and end positions: assuming they are 100 m long (based on segment length), or calculating their distance based on tow speed and duration (capped at 2 km).

Proportional footprint	Percentage of cells using 100 m assumption	Percentage of cells using actual distance
0 - 0.1	13.2	12.6
0.1 - 0.2	55.0	54.9
0.2 - 0.3	10.7	10.8
0.3 - 0.4	5.1	5.2
0.4 - 0.5	3.2	3.2
0.5 - 0.6	2.8	2.8
0.6 - 0.7	1.8	1.8
0.7 - 0.8	1.4	1.4
0.8 - 0.9	1.9	2.0
0.9 - 1	5.0	5.2

From footprint to impact

An initial version of this analysis presented to a SPRFMO bottom fishing technical working group (in Hobart, June 2017) estimated only footprint (the area potentially contacted by bottom fishing gear) without reference to *impact*, i.e. the actual level of damage or mortality sustained by benthic habitats or organisms. Consistent with the recommendations of that working group, and following Sharp et al. (2009) subsequently we convened a technical subgroup of experts and scientists to estimate *impact indices* associated with bottom fishing gear and practices in SPRFMO bottom trawl fisheries. To achieve this, experts with practical knowledge of fishing operations and fishing gear, along with benthic ecologists and fishery scientists were directed to produce estimates via the following sequence.

First, fishing industry experts and fishers with practical knowledge of fishing operations described in detail the fishing gear and the operation of the fishing gear in a standard fishing event, with an emphasis on factors affecting the way in which the fishing gear will contact and damage vulnerable benthic organisms, with discussion aided of photographs and diagrams. The workshop agreed that fishing impacts should be characterized separately for:

- Slope fishing: characterized by longer tows for disaggregated fish, often on muddy or sandy habitats, with the doors generally in contact with the bottom; vs
- Features (UTFs): characterized by shorter tows targeting identified fish aggregations, often on steep features with rocky or hard bottom, where the objective is to minimize bottom contact except in the location of the aggregation, and for much of the tow the doors are flown in midwater.

Next the workshop characterized and estimated footprint widths for different components of the trawl gear which are expected to have distinct levels and types of impact on vulnerable benthic organisms. The workshop identified the following:

- Door furrows: 1-2 m wide (x2); heavy impact, some penetration of soft sediments
- Ground gear: 15 – 22 , wide; rockhoppers followed by net and codend; heavy contact but minimal penetration; some spaces between rockhoppers
- Sweeps/bridles: remainder of width (varies for slopes vs. UTFs); no penetration of sediment but strong lateral impacts; sweeps at variable height; bottom contact discontinuous

Next the workshop estimated what proportion of vulnerable benthic taxa within the footprint of each sub-component is damaged or destroyed in a single passage of a bottom trawl *in specific locations where the gear is in contact with the bottom*. Separate estimates were made for three different generic functional groups of VME organisms, with different levels of fragility. Note that these impacts were in the first instance estimated without reference to what proportion of the time the gear is actually in contact with the ocean bottom within area of the component footprint (this is the subsequent step).

Next the workshop estimated over what areal proportion of the footprint component that component of the gear is actually in contact with the ocean floor, as a function of both the amount of time the gear is in contact (i.e. because sweeps can bounce, or because in UTF fishing, fishers aim to fly the doors and sweeps clear of the bottom) and also the configuration of the gear (i.e. there are gaps between rollers on the ground gear, and sweeps contact doors and bridles at some height above the ocean floor so that when the sweep is taut its full length is not in contact with the ocean floor simultaneously). These estimates involved detailed discussion of the operation of the trawl gear under different scenarios and considered the geometry of the gear configuration relative to different growth forms of VME organisms. The impact index was then calculated as a simple arithmetic combination of the individual gear component impacts, proportional to the relative area of their respective footprints. Where the workshop estimated a range, midpoints were used.

For slope habitats, these component-disaggregated impact estimates and resulting aggregate impact indices were as follows:

		Percent impact, by VME taxa functional groups			
Footprint component	**Width of footprint**	**Large, erect, hard sessile**	**Small, flexible/ encrusting**	**Deep burrowing infauna**	**Percent time/ area in bottom contact**
Door furrow	2-4 m	100%	100%	50-80%	100%
Sweep/bridle	103-124	100%	30-60%	0-5%	75-85%
Ground gear	15 – 22 m	90-100%	30-50%	0-10%	100%
Aggregate impact index (midpoint)		**0.82**	**0.38**	**0.04**	

For UTF habitats, these component-disaggregated impact estimates and resulting aggregated impact indices were as follows. Note the estimated reduced total width of the footprint on UTF habitats, due to shortened sweeps, and estimated low proportion of time that the doors and furrows are actually in contact with the ocean floor (because fishers attempt to fly the doors in mid-water).

		Percent impact, by VME taxa functional groups			
Footprint component	**Width of footprint**	**Large, erect, hard sessile**	**Small, flexible/ encrusting**	**Deep burrowing infauna**	**Percent time/ area in bottom contact**
Door furrow	2 -4 m	100%	100%	50-80%	5-15%
Sweep/bridle	73 – 104 m	100%	30-60%	0-5%	5-15%
Ground gear	15 – 22 m	90-100%	30-50%	0-10%	100%
Aggregate impact index (midpoint)		**0.24**	**0.09**	**0.01**	

Note that impact indices are different for VME taxa with different levels of fragility; as expected, tall erect brittle taxa are more fragile than encrusting taxa or burrowing infauna.

The impact indices were applied at the scale of every 100 m segment, proportionally reducing (relative to the footprint) the amount of damage associated with each fishing event, prior to the step at which the cumulative effect multiple events in the same location are considered. Because the spatial distribution of footprints and impacts from sequential fishing events are assumed to be random at the scale of the cell, for a particular cell size the effect of applying an impact index less than 1 is mathematically equivalent to proportionally reducing the width of the footprint and assuming 100% damage within the footprint.

The impact layer was generated at the 1 km scale in the first instance, for visual comparison with the corresponding footprint layer at spatial scale at which the positional effort data was thought to be reliable. Impacts are only shown for the most fragile taxa. See Appendix B. Visual examination reveals some pertinent conclusions, i.e.

- Unsurprisingly, for the most fragile taxa (iimpact index = 0.81) estimated impacts in slope habitats are very similar to estimated cumulative footprints.
- There are large areas of slope habitat, especially on the Challenger Plateau, that are nearly 100% impacted. Protection of these areas from bottom fishing methods would yield little benefit from the perspective of conserving VME taxa (except for example as an opportunity to monitor recovery)
- In contrast, in seamount habitats, impact estimates are much lower than the estimated cumulative footprint (impact index = 0.24 for the most fragile taxa) such that many areas within the fished footprint are only lightly impacted. Nonetheless, fishing effort at repeatedly fished locations near the summit of preferred seamounts is still sufficiently concentrated that the cumulative impact approaches 100%, but over a much smaller area than appears in the footprint maps.

4. Discussion

The cumulative fishing footprint and impact of commercial bottom trawl fishing effort in the SPRFMO area were estimated using start and end tow positions, assuming straight line tows. Individual tows were split in 100 m segments in order to enable footprint estimation at cell sizes smaller than individual tow lengths; footprints were assigned to segment midpoints so that all segment could be assigned unambiguously to individual cells. Footprint was estimated by assuming random spatial orientation and overlap of individual tows within cells, at six different cell sizes, i.e. 200 m, 1 km, 2 km, 5 km, 10 km or 20 km per side.

Results suggest that the 200 m scale is too small to accurately represent patterns and distributions of footprint and impact, given that tow segments were 100 m long and trawl width was 150 m; furthermore this is smaller than the positional accuracy of the effort data. At scales larger than 1 km cells, estimates of cumulative footprint increase, because smaller-scale spatial fishing effort patterns are lost, and cumulative footprint and impact in the same locations are estimated as if overlap between subsequent tows is lower than is apparent in the data. These results demonstrate that fishing effort patterns in SPRFMO bottom fisheries are non-random at scales down to (at least) 1 km, and analyses at larger scales are likely to be positively biased (i.e. they will over-estimate fishery footprint and impact). The fished envelope (i.e. total area of all cells contacted by fishing effort, irrespective of footprint width) is a very poor indicator of footprint and impact at larger cell sizes.

Penney and Guinotte (2013) calculated the footprint based on GIS mapping. Matching the data used in that study, the footprint calculated using the 1km grid and random overlap assumption was

92% of that calculated by Penney and Guinotte (2013). Part of the difference could be due to the treatment of the 18% of tows with identical start and end positions, which was not detailed in that paper. Part of the difference could be due to the randomization of the start position they implemented, or the assumption of random overlap within the scale of the cell. Nevertheless, the close results show this approach is robust to assumptions of random overlap at the 1km scale. That paper estimated only footprint not impact.

Limitations

In any spatial impact assessment, the quality of the spatial data is critical, as any erroneous positions will affect the results, as illustrated by very long tows in the Appendix B plots. Additional data grooming may be useful.

Assumptions made on the length of tows carried out on UTF habitat with identical start and end position were shown not to affect the results when calculating the proportional footprint over the entire duration of the fishery, but might become relevant if investigating impact rather than footprint, or annual footprint. These kinds of small-scale patterns, if they exist, are likely to be obscured by the positional error arising from data rounding, for which a random offset jitter was required. In future, use of higher-precision start and end position to investigate the existence of smaller-scale patterns may be productive; such patterns are unlikely on slope habitats where fishing is already widely dispersed, but may be relevant on UTFs, where fishers may target small-scale features or seek to avoid rough ground.

Other limitations of this analysis include at a very small scale the disconnect between the recorded location of the tow and the actual position at which fishing gear contacts the bottom, which is affected by factors such as depth, for which a positional correction was required based on depth and the assumed geometrical relationship between vessel position and gear position in contact with the sea floor.

Next steps

At present the estimated cumulative impact layer has only been analysed visually, in comparison with footprint. The more rigorous quantitative analyses for footprint above could be repeated also for impact.

At present these analyses only include New Zealand fishing effort data and a subset of Australian effort data. Additional Member data could be groomed and incorporated into the analyses.

At present these data include only bottom trawl fisheries targeting orange roughy. For completeness, the analyses could be expanded to also include mid-water trawls (which occasionally contact the bottom) and bottom longline fisheries (as in Sharp et al. 2009, Webber 2012) but extremely low impact indices and low effort levels will likely indicate that impact levels are negligible relative to bottom trawl fisheries.

Impact can be represented as cumulative proportional impact in a spatially explicit layer representing the cumulative damage associated with all historical fishing effort as in Appendix B.

Alternately it can be represented as a 'naturalness' or 'intact status' layer (where 'status' = (1 – impact)). The latter representation, especially when multiplied by a habitat map or modelled spatial distribution for a particular vulnerable taxon, yields spatially explicit estimates of current status (analogous to current biomass in fisheries) which can be summed at the scale of particular features or sub-regions or across the full domain to estimate current status at a biogeographic or population level, analogous to stock status in fisheries. Progressing this work may be useful.

Spatially explicit impact estimates generated using this method may be useful to inform spatial management. Even in the absence of spatial distribution models for VME taxa, the status layer (1 – impact) can also be used in systematic conservation planning, to prioritize the protection of locations where benthic organisms remain intact and down-weight the protection of areas where VMEs are already heavily impacted.

Spatially explicit impact estimates of this kind are also useful to inform management strategy evaluation of the effects of spatial management measures (e.g. spatial closures or move-on rules) on modeled or simulated spatial distributions of vulnerable benthic taxa using spatial management strategy evaluation (e.g. Dunn et al. 2010, Mormede and Dunn 2013).

5. Recommendations

It is recommended that the Scientific Committee:

- **Notes** the successful application to SPRFMO bottom trawl fisheries of the spatially explicit bottom fishing impact evaluation methodology originally developed for CCAMLR bottom line fisheries
- **Agrees** that this methodology is appropriate for assessing the impacted area, intensity of impact by location, and likely impact on benthic epifauna
- **Agrees** that the methodology should be applied to develop spatially-explicit bottom impact evaluations for all deepwater bottom fisheries in the western SPRFMO Area

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Appendix A – Sample spatially explicit cumulative footprint estimated at a range of cell sizes

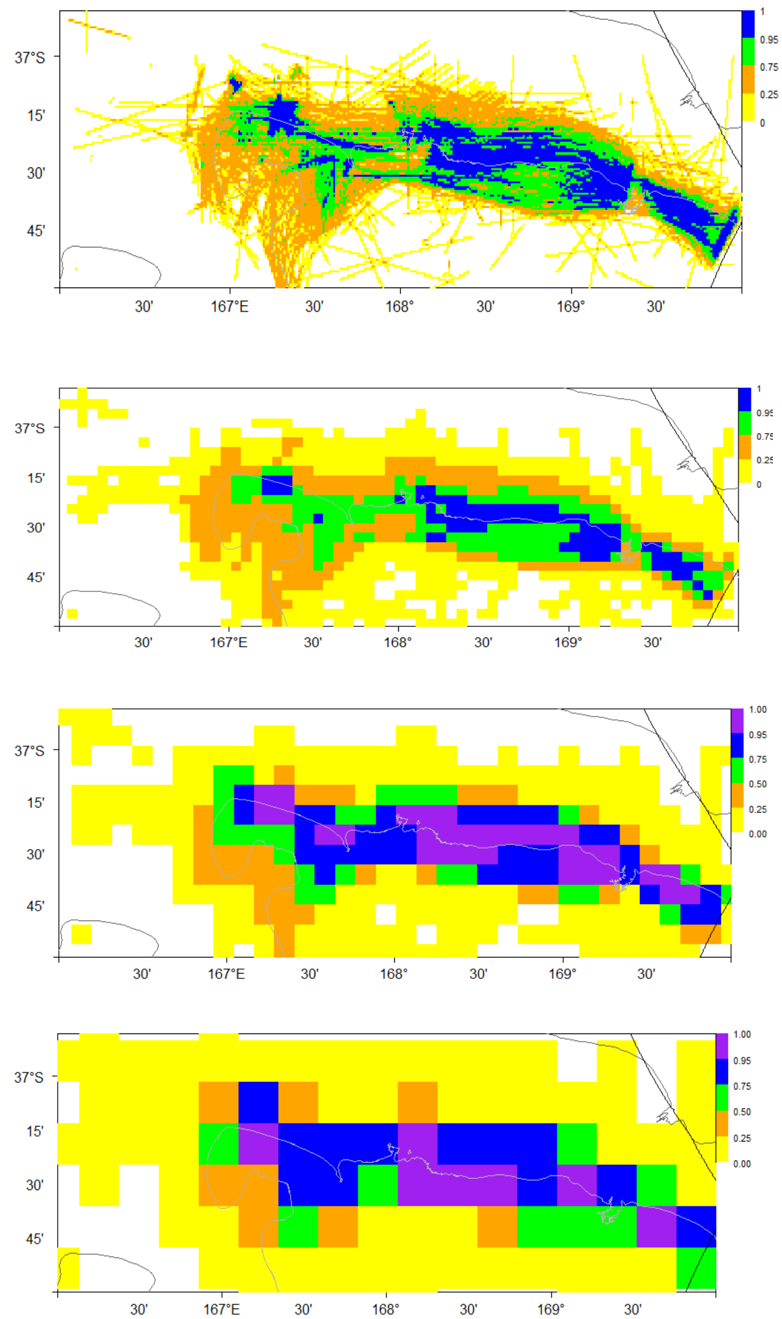


Figure A.12: Cumulative proportional footprint for the Norwest Challenger at 1, 5 10, and 20 km cell sizes.

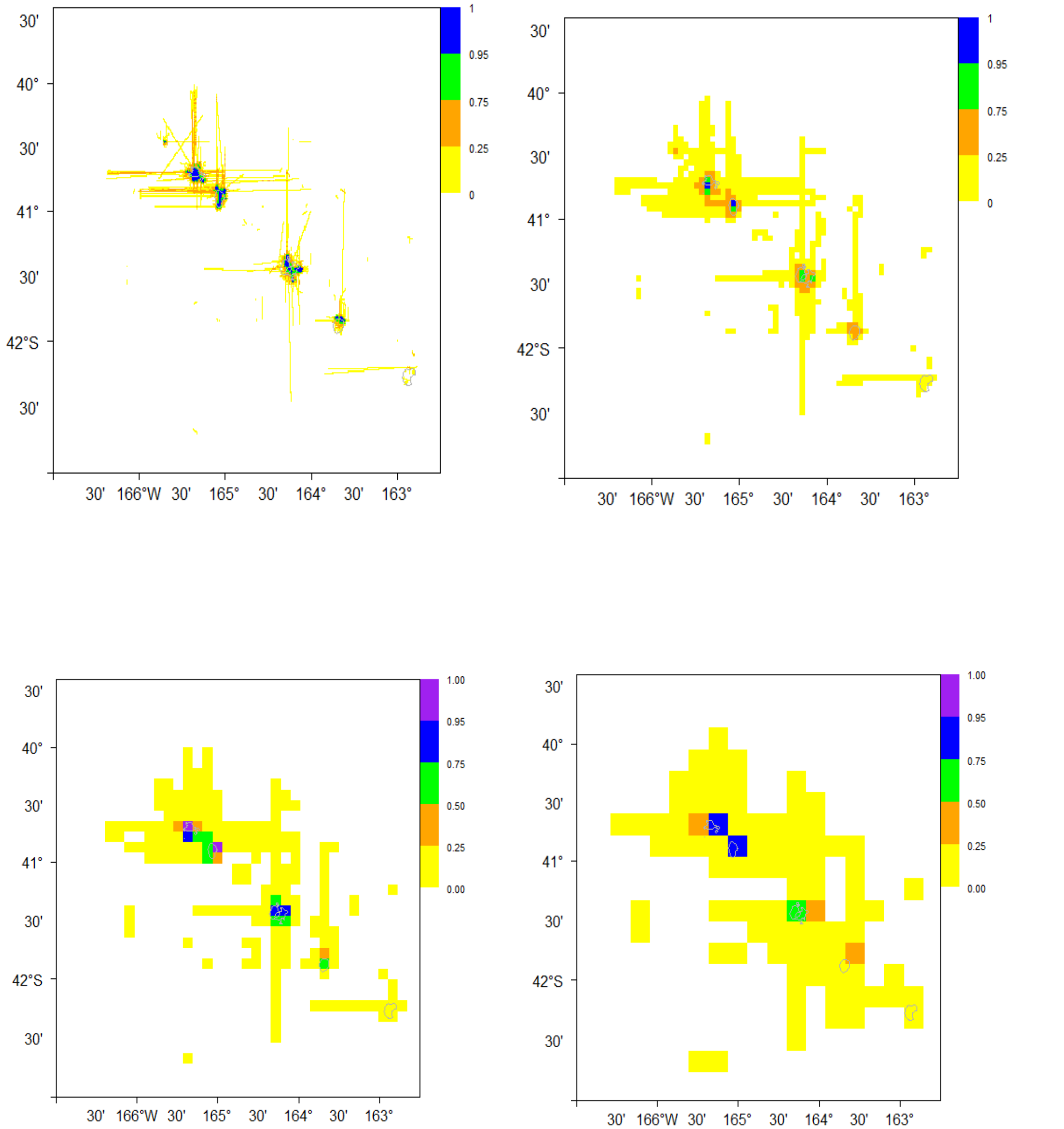


Figure A.16: Cumulative proportional footprint for the Louisville Ridge Central at 1, 5, 10, and 20 km cell sizes.

Appendix B – Spatially explicit cumulative footprint and impact at 1 km cell size

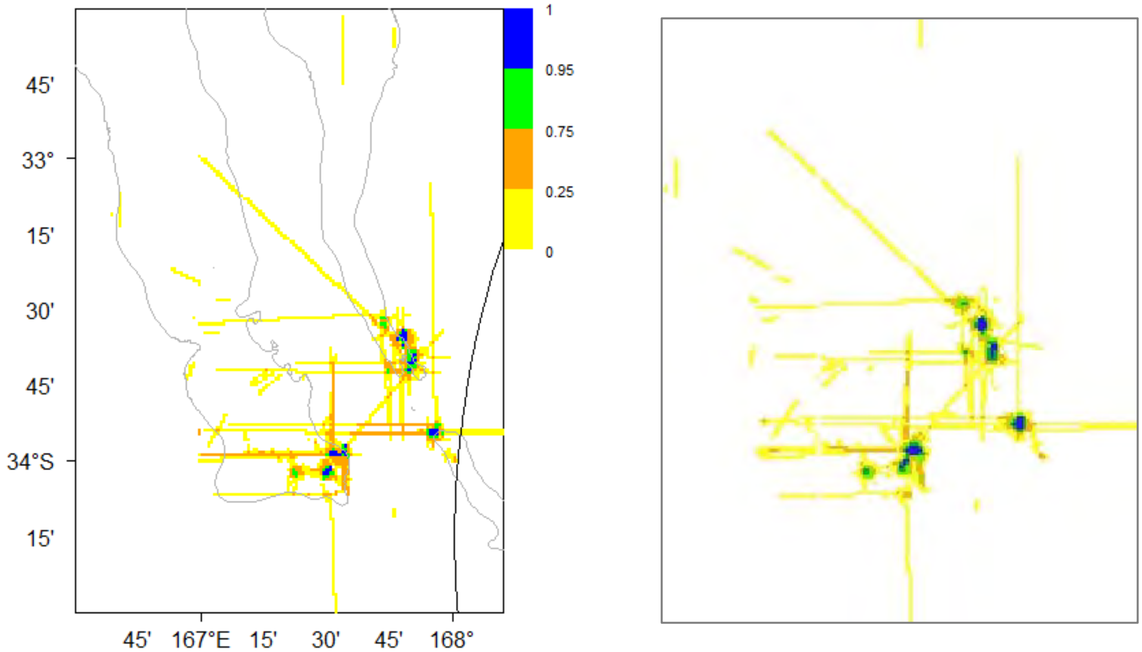


Figure B.1: Cumulative footprint (left) and impact (right) at 1km scale in the West Norfolk Ridge

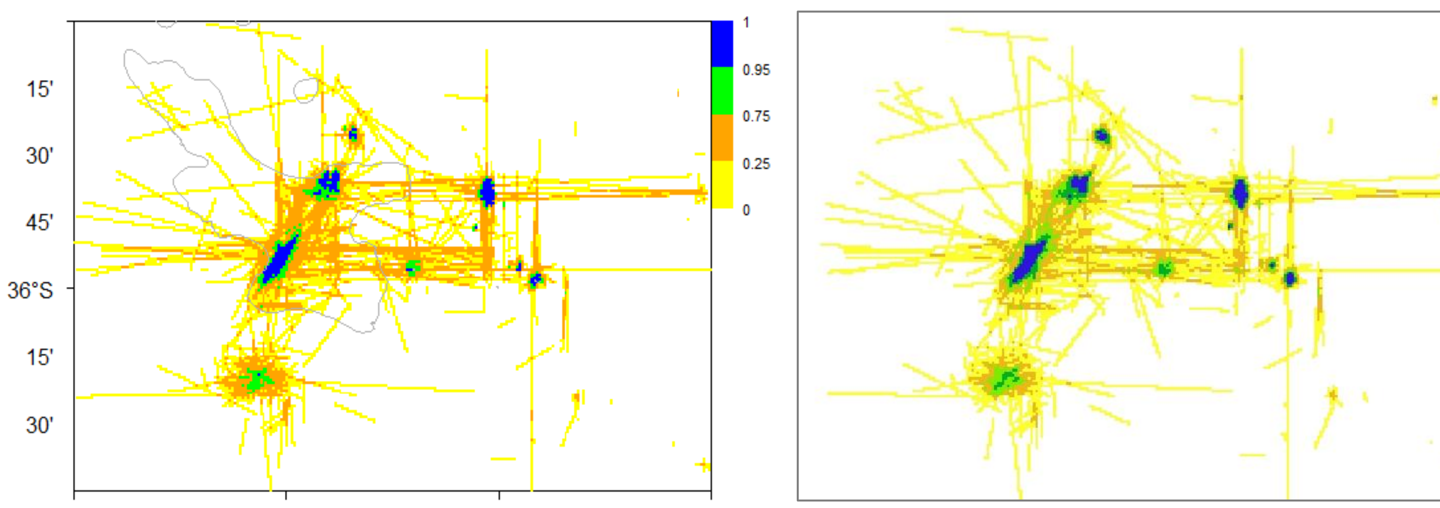


Figure B.2: Cumulative footprint (left) and impact (right) at 1km scale in the Lord Howe Rise

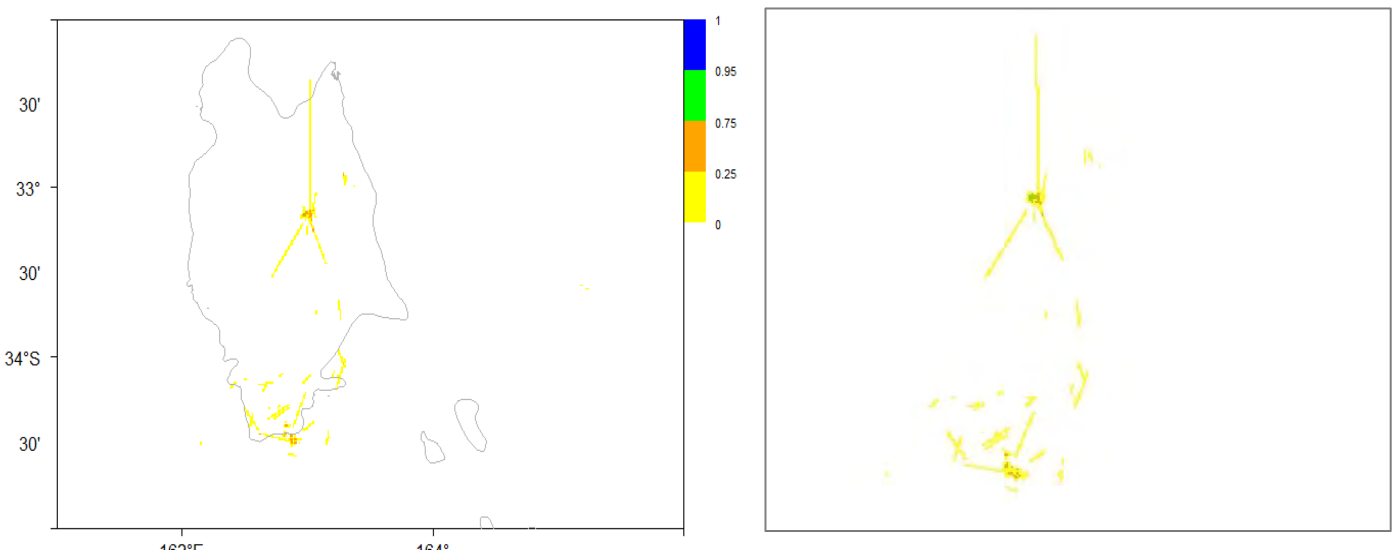


Figure B.3: Cumulative footprint (left) and impact (right) at 1km scale in the Upper Lord Howe Rise

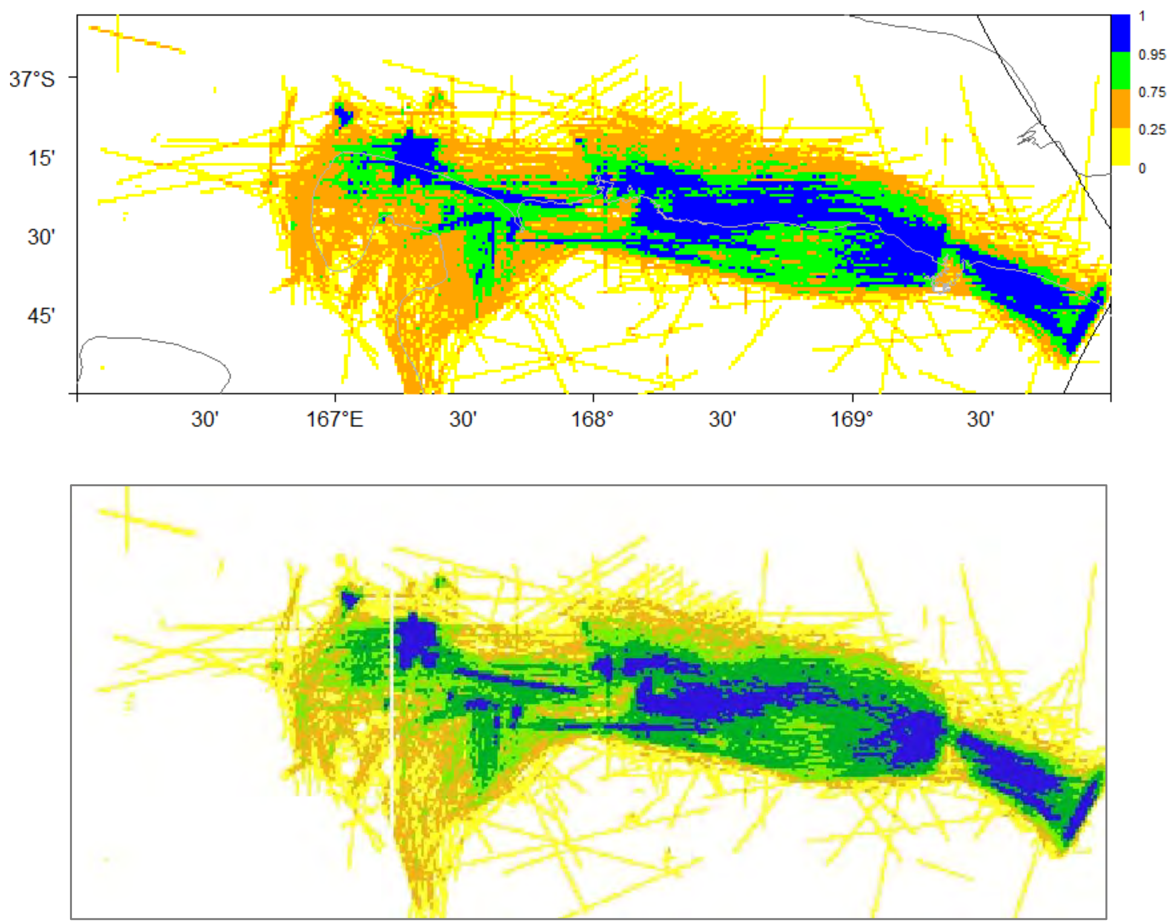


Figure B4: Cumulative footprint (top) and impact (bottom) at 1km scale in the Northwest Challenger

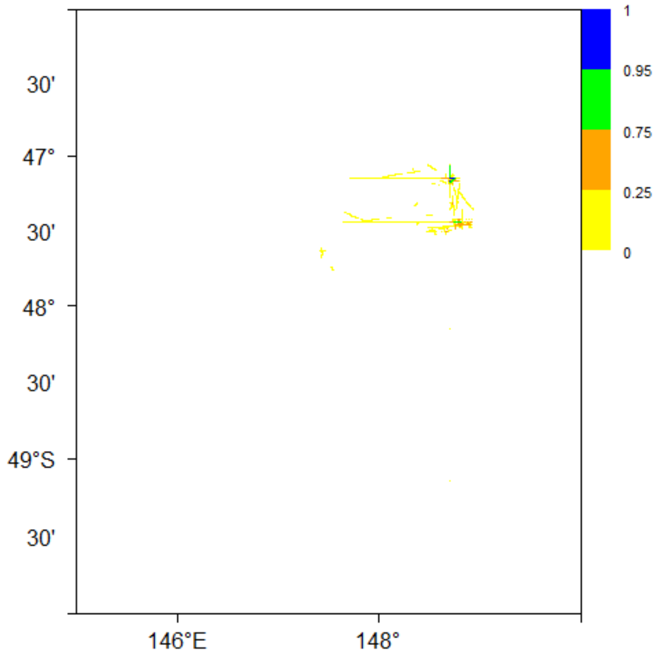
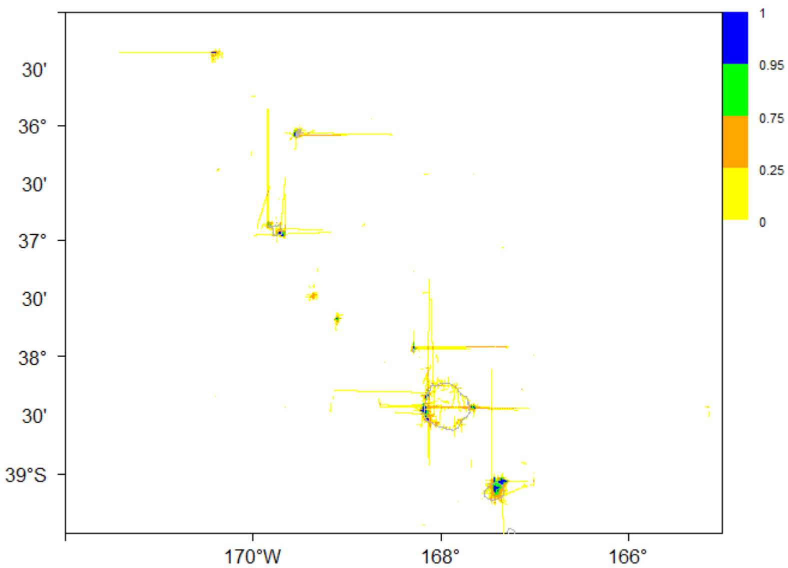


Figure B.5: Cumulative footprint (left) and impact (right) at 1km scale in the South Tasman Rise



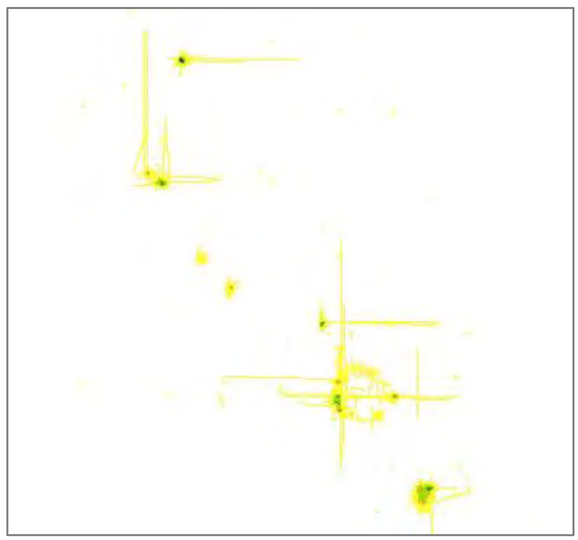


Figure B.6: Cumulative footprint (left) and impact (right) at 1km scale in the Louisville Ridge North

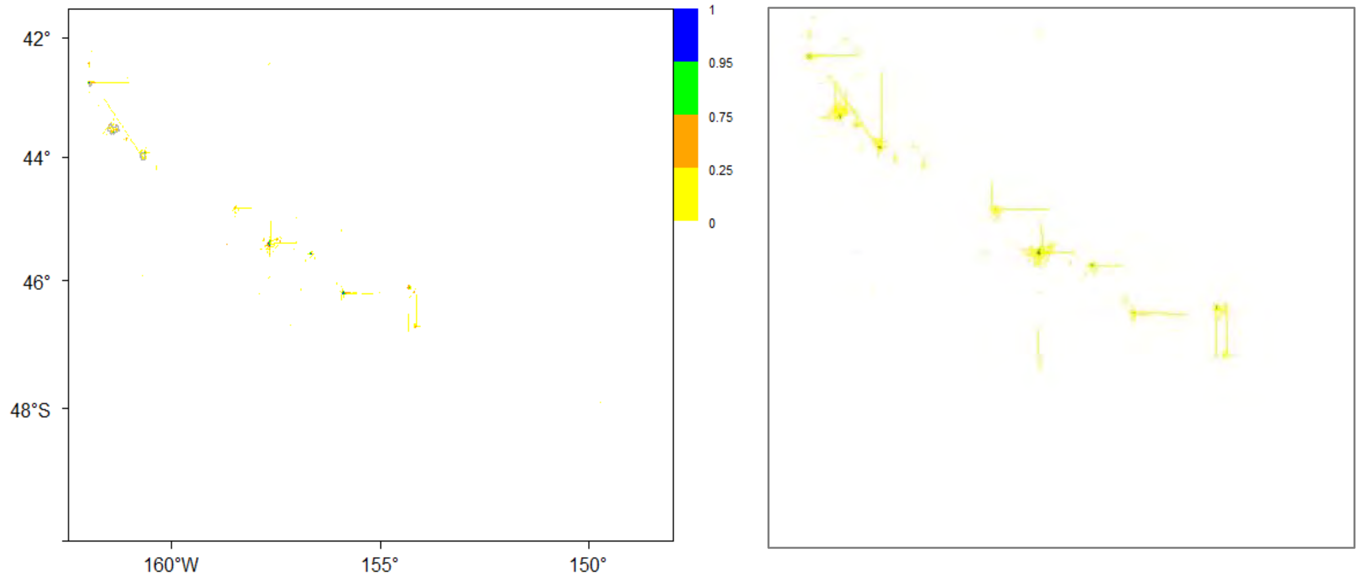


Figure B.7: Cumulative footprint (left) and impact (right) at 1km scale in the Louisville Ridge South

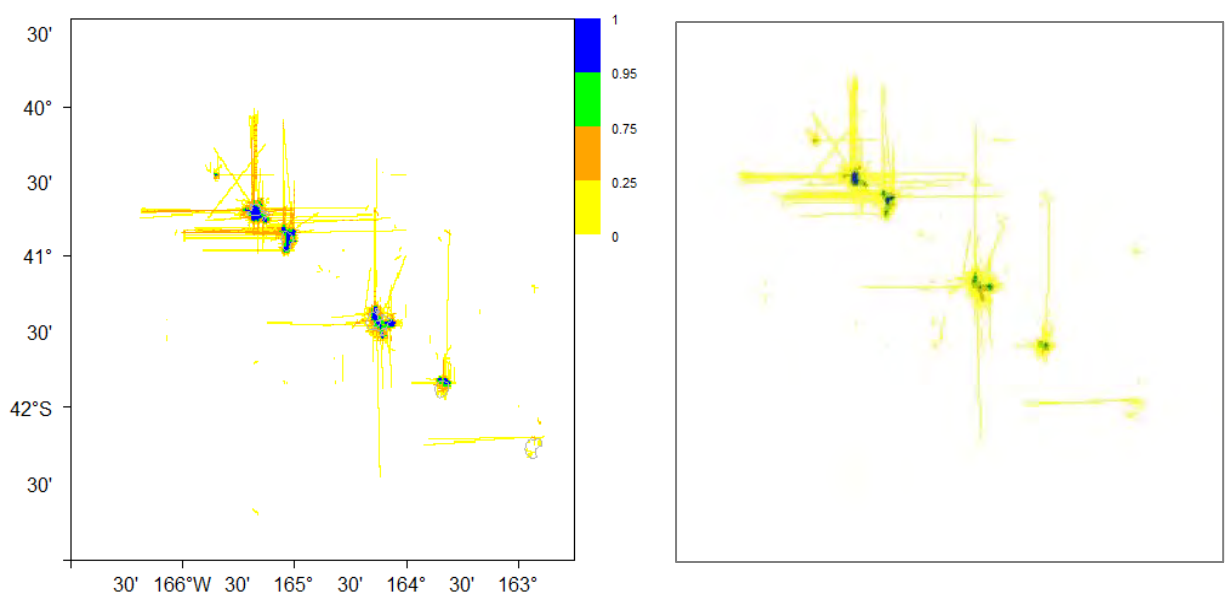


Figure B.8: Cumulative footprint (left) and impact (right) at 1km scale in the Louisville Ridge Central