MixFishSim: highly resolved spatiotemporal simulations for exploring mixed fishery dynamics

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Abstract

[Guidance: A concise and factual abstract is required. The abstract should state briefly the purpose of the research, the principal results and major conclusions. An abstract is often pnresented separately from the article, so it must be able to stand alone. For this reason, References should be avoided, but if essential, then cite the author(s) and year(s). Also, non-standard or uncommon abbreviations should be avoided, but if essential they must be defined at their first mention in the abstract itself. Graphical abstract: Although a graphical abstract is optional, its use is encouraged as it draws more attention to the online article. The graphical abstract should summarize the contents of the article in a concise, pictorial form designed to capture the attention of a wide readership. Graphical abstracts should be submitted as a separate file in the online submission system. Image size: Please provide an image with a minimum of 531 X 1328 pixels (h X w) or proportionally more. The image should be readable at a size of 5 x 13 cm using a regular screen resolution of 96 dpi. Preferred file types: TIFF, EPS, PDF or MS Office files.]

Fishing exploits spatially and temporally hetergenous fish populations, using species-unselective gear that can result in unintended, unwanted catch of

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low quota or protected species. Reducing these unwanted catches is crucial for biological and economic sustainability of 'mixed fisheries' and implementation of an ecosystem approach to fishing.

To implement effective spatial measures to reduce discards a good understanding of spatiotemporal fishery dynamics is required. However, traditional scientific advice is limited by a lack of highly resolved knowledge of population distribution, movement and how fishers interact with different fish populations. This reflects that data on fish location at high temporal and spatial resolutions is expensive and difficult to collect and therefore proxies inferred from either scientific surveys or commercial catch data are often used to model distributions, often with limited spatial and temporal resolution.

To understand how resolution impacts mixed fisheries inference, we develop a highly resolved spatiotemporal simulation model incorporating: i) delay-difference population dynamics, ii) population movement using Gaussian Random Fields to simulate patchy, hetergenously distributed populations, and iii) fishery dynamics for multiple fleet characteristics based on targetting via correlated random walk movement and learned behaviour.

We simulate 20 years of exploitation of the fish populations and use the results from the fishing model to draw inference on the underlying population structures. We compare this inference to i) a simulated fixed-site sampling design commonly used for fisheries monitoring purposes, and ii) the true underlying population structures input to the simulation, to establish the potential and limitations of fishery-dependent data - an inherently biased sampling method due to fisher's targeting- to provide a robust picture of spatiotemporal distributions. [We simulate a closure based on areas defined from commercial catch data and assess its effectiveness on reducing catches of a fish population.]

We conclude that...

[233 words]

Keywords: Some, keywords, here. Max 6

2010 MSC: 00-01, 99-00

1. Introduction

[Guidance:: State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.]

Fishers exploit fish populations that are heterogenously distributed in space and time with verying knowledge of species distributions using species-unselective fishing gear. Fisheries that catch an assemblage of species, known as mixed fisheries, when managed by single-species quotas can end up discarding overquota catch leading to overexploitation of fish populations. Reducing discarding is crucial to ensure biological and economic sustainability of fisheries and implementation of an ecosystem approach to fisheries. As such there is increasing interest in technical solutions such as gear and spatial closures as ways of avoiding discards.

Use of spatial management as a tool has been proposed as a method to reduce discards. However, its implementation is hampered by lack of knowledge of fish and fishery spatiotemporal dynamics and understanding of the scale at which processes are important for management. Understanding the correct scale for spatial management is crucial in order to implement measures at a resolution that ensures effective management[1] while minimising economic impact. For example, a scale that promotes species avoidance for vulnerable or low quota species while allowing continuance of sustainable fisheries for available quota species.

Ensuring measures are implemented at an appropriate scale has been a challenge in the past that has led to ineffectual measures with unintended consequences such as limited impact towards the management objective or increased benthic impact on previously unexploited areas (e.g. the cod closure in the North Sea[2, 3]). Since then more refined spatial information has become available through the combination of logbook and Vessel Monitoring System (VMS) data[4, 5, 6, 7] and more real-time spatial management has been possible (e.g. [8]). Such information is, however, patchy and derived from an inherently biased sampling programme (i.e. targeted fishing). Further, fishers generally only recorded landings (not catch) on a daily basis. This leads to questions about the validity of inference that can be drawn from landings data assigned to VMS activity pings.

In order to understand challenges that face VMS-linked landings to draw inference on the underlying population structure we develop a simulation model where population dynamics are highly-resolved in space and time and are known rather than inferred from sampling or commercial catches. Population movement is driven by a random (diffusive) and directed (advective) process and we incorporate characterisation of a number of different fisheries exploiting four fish populations with different spatial and population demographics.

Using our model we simulate 20 years of exploitation of the fish populations and use the results from the fishing model to draw inference on the underlying population structures. We compare this inference to: i) a stratified fixed-site sampling survey design commonly used for fisheries monitoring purposes, otherwise know as a fisheries-independent survey, and ii) the underlying population structures input to the simulation.

[Could fit a geostatistical model (e.g. VAST) to the fisheries-dependent and fisheries-independent data, though may be overkill...]

We simulate a fishery closure to protect one species based on the fishery-dependent inferred distributions at a spatial and temporal scale typical in fisheries management, and assess a theoretical "benefit" to the population, and effect on the other three populations. Further, we extend our analysis to a range of spatial and temporal scales to assess the impact of these processes on the success of the management measure.

2. Materials and Methods

[Guidance: Provide sufficient details to allow the work to be reproduced by an independent researcher. Methods that are already published should be summarized, and indicated by a reference. If quoting directly from a previously published method, use quotation marks and also cite the source. Any modifications to existing methods should also be described.]

We develop a simulation model with a modular event-based approach, where modules are implemented on independent time-scales appropriate to capture the characteristic of the process modelled (Figure 1). The fishing model operated on a tow-by-tow basis, while population dynamics (fishing and natural mortality, growth) operate on a daily time-step. Population movement occurs on a weekly time-step, while recruitment occurs periodcally each year for a set time period (e.g. 3 weeks) at at specified point individual to a species. The simulation framework is implemented in the statistical software package R [9]; available as an R package from the authors github (`www.github.com/pdolder/MixFishSim`).

Here we describe each of the model components; 1) Population dynamics, 2) Recruitment dynamics, 3) Population movement, 4) fishery dynamics.

2.1. Population dynamics

The basic population level processes are simulated using a modified two-stage Deriso-Schnute delay difference model [10, 11, 12] occurring at a daily

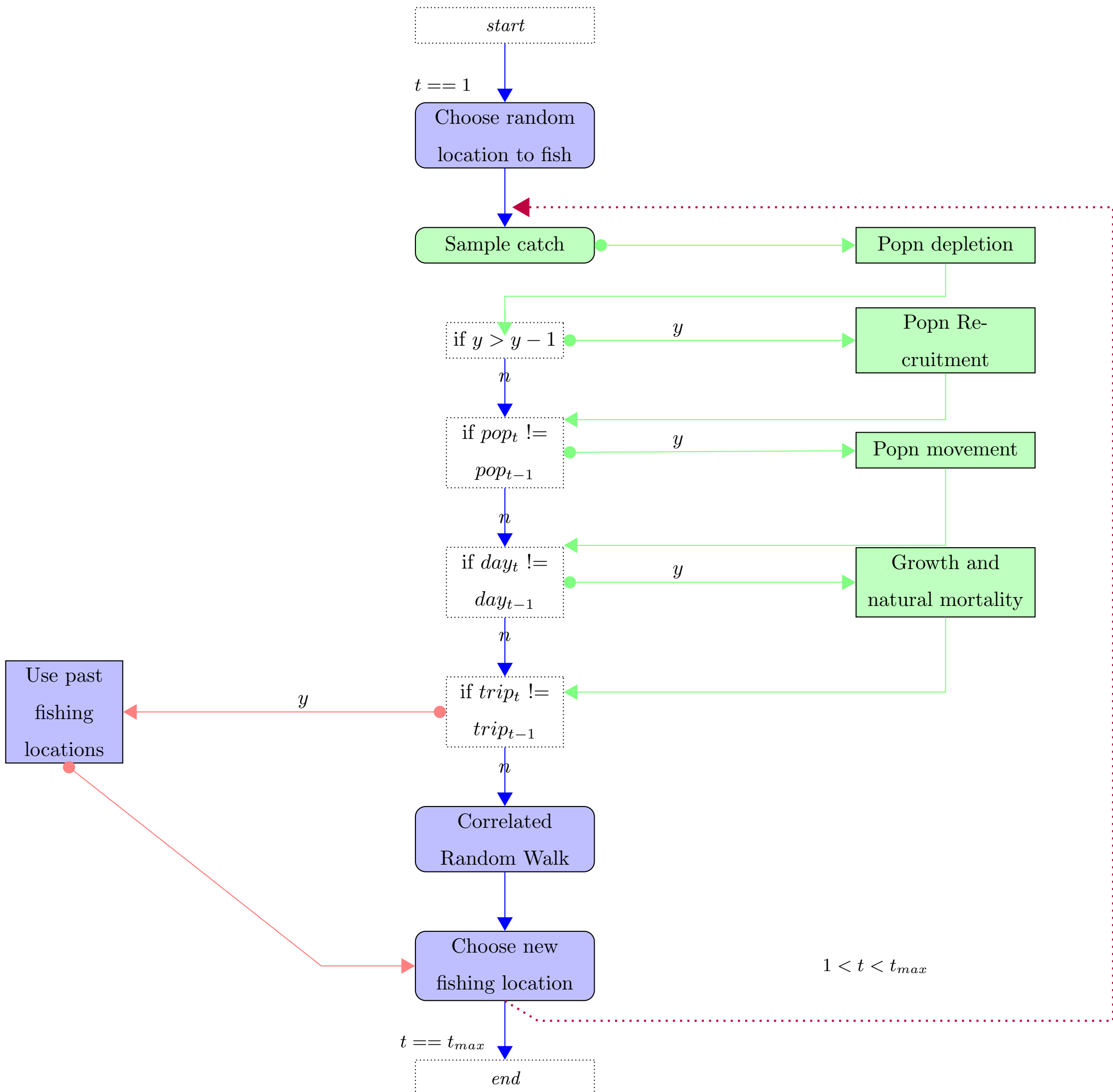

Figure 1: Overview Schematic of simulation model. The blue boxes indicate fleet dynamics processes, the green boxes population dynamics processes while the white boxes are the timesteps at which processes occur; t = tow, $tmax$ is the total number of tows, y = year, pop_t is time of population movement, day is a day timestep, $trip$ is a trip time step.

time-step. Here, population biomass growth and depletion for pre-recruits and fish recruited to the fishery are modelled separately as a function of previous recruited biomass, intrinsic population growth and recruitment:

$$
\begin{aligned}
B_{y,d+1} = & \\
& (1+\rho)B_{y,d} \cdot e^{-Z_{y,d}} - \rho \cdot e^{-Z_{y,d}} \quad \times \\
& (B_{y,d-1} \cdot e^{-Z_{y,d-1}} + Wt_{R-1} \cdot \alpha_{d-1} \cdot R_{\tilde{y}(y,d-1)}) \quad + \\
& Wt_R \cdot \alpha_d \cdot R_{\tilde{y}(y,d)}
\end{aligned}
$$

where ρ is Brody's coefficient, shown to be approximately equal to $exp(-K)$, where K is the growth rate from a von bertalanffy logistic growth model [11]. Wt_{R-1} is the weight of fish prior to recruitment, while Wt_R is the recruited weight. α_d represents the proportion of fish recruited during that day for the year, while $R_{\tilde{y}}$ is the annual recruits.

Mortality Z can be decomposed to natural mortality, M, and fishing mortality, F, where both M and F are instantaneous rates with M fixed and F calculated by solving the Baranov catch equation [13] for F:

$$C_d = \frac{F_d}{F_d + M_d} * (1 - e^{-(F_d + M_d)}) * B$$

where C is the summed catch from the fishing model across all fleets and vessels for the population during the day, and B the daily biomass for the species. [link F to effort and catchability - as I think we have F as an emergent property of the fleets rather than something we solve for (I could be wrong though!) - catch for a vessel is a product of catchability and biomass, i.e. C = qB, but this catch is summed to solve for F. So its both really]

2.2. Recruitment dynamics

Recruitment is modelled through a function relating the mature biomass to recruits at time of recruitment. In *mixfishsim*, it can be modelled either either as a stochastic Beverton-Holt stock-recruit form ([14]):

$$\bar{R} = \frac{(\alpha * B)}{(\beta + B)}$$

$$R \sim N[(\bar{R}, \sigma^2)]$$

[better to use lognormal variability to avoid negative recruitment events at low biomasses.] Where α is the maximum recruitment rate, β the spawning stock biomass (SSB) required to produce half the maximum, and B current SSB;

or a stochastic Ricker form [15]

$$\bar{R} = B * e^{(\alpha - \beta * B)}$$

$$R \sim N[(\bar{R}, \sigma^2)]$$

where α is the maximum productivity per spawner and β the density dependent reduction in productivity as the SSB increases.

2.3. Population movement

To simulate how fish populations might be distributed in space and time, we employed a Gaussian spatial process to model habitat suitability for each of the populations, with an advection-diffusion process to control how the populations moved over time. [say why - balance between realism and practicalities of IBMs for the fish population]

For the habitat we define a Gaussian random field process, $\{S(x) : x \in \mathbb{R}^2\}$, that is a stochastic process where any collection of locations $x_1, \ldots, x_n$ where for each $x_i \in \mathbb{R}^2$, the joint distribution of $S = \{S(x1), \ldots S(x_n)\}$ is multivariate Gaussian. The distribution is specified by its *mean function*, $\mu(x) = E[S(x)]$ and its *covariance function*, $\gamma(x, x') = Cov\{S(x), S(x')\}$ [16].

The covariance structure affects the smoothness of the surfaces which the process generates, and we used the *Matérn* family of covariance structures, one where the correlation strength weakens the further the distance apart (i.e. the correlation between $S(x)$ and $S(x')$ decreases as the distance $u = ||x - x'||$ increases). The *Matérn* correlation is a two-parameter family where:

$$\rho(u) = \{2^{\kappa-1}\Gamma\kappa\}^{-1}(u/\phi)^{\kappa}K_{\kappa}(u/\phi)$$

$K_{\kappa}(.)$ is a modified Bessel function of order κ, $\phi > 0$ is a scale parameter with the dimensions of distance, and $\kappa > 0$, called the order, is a shape parameter which determines the smoothness of the underlying process.

In the simulation model, the habitat for each of the populations is generated through the *RFSimulate* function of the *RandomFields* R package [17], implementing different parameter settings to affect the patchiness of the populations. Each population is initialised at a single location, and subsequently moves according to a probabilistic distribtion based on habitat suitability and distance from current cell.

$$Pr(B|A) = \frac{e^{-\lambda * d_{AB}} \cdot Hab_B^2}{\sum_{c=1}^{C} e^{-\lambda * d} \cdot Hab_B^2} \tag{1}$$

Where d_{AB} is the euclidean distance between cell A and cell B, λ is a given rate of decay and Hab_B^2 is the squared index of habitat suitability for cell B.

During specified weeks of the year, the habitat quality is modified for spawning habitats, meaning each population has a concentrated area where spawning takes place and the population moves towards this in the weeks prior to spawning.

2.4. Fleet dynamics

The fleet dynamics can be broadly categorised into three components; fleet targeting - which determines the fleet catch efficiency and preference towards a particular species; trip-level decisions, which determine the initial location to be fished at the beginning of a trip; and within-trip decisions, determining movement from one fishing spot to another within a trip.

2.4.1. Fleet targeting

Each fleet of n vessels is characterised by both a general efficiency, Q, and a population specific efficiency, Q_p. Thus, the product of these parameters affects the overall catch rates for the fleet and the preferential targeting of one population over another. This, in combination with the parameter choice for the step-function (as well as some randomness from the exploratory fishing process) determines the preference of fishing locations for the fleet. All species prices are kept the same, across fleets, though can be made to vary seasonally.

2.4.2. Trip-level decisions

Several studies (e.g.[18, 19, 20]) have confirmed past activity and past catch rates are strong predictors of fishing location choice. For this reason, the fleet dynamics sub-model includes a learning component, where a vessel's initial fishing location in a trip is based on selecting from previously successful fishing locations. This is achieved by sorting all previous fishing events in the previous trip as well as the previous time periods in past years, and choosing randomly from the top x % of fishing events in value. Simulation testing indicated that this learning increased the mean value of catches for the vessels, over just relying on the correlated random walk function.

2.4.3. Within-trip decisions

Fishing locations within a trip are determined by a modified random walk process. A random walk type was chosen as it is the simplest assumption commonly used in ecology to describe animal movement which searching for homogeneously distributed prey about which there is uncertain knowledge. In a random walk, movement is a stochastic process through a series of steps that can either be equal in length or take some other functional form. The direction of the random walk can be correlated, a characteristic known as 'persistence', providing some overall location of directional movement [21] or uncorrelated.

A *lévy walk* is a particular form of random walk characterised by a heavy-tailed distribution of step-length and has received a lot of attention in ecological theory in recent years as having shown to have very similar characteristics as those observed by animals in nature, and being a near optimum searching strategy for predators pursuing patchily distributed prey [22, 23]. [24] showed that Peruvian anchovy fishermen have a stochastic search pattern similar to that observed with a lévy walk. However, it remains a subject of debate, with the contention that search patterns may be more simply characterised as random walks [25] with specific patterns related to the characteristics of the prey field [26].

We use a modified random walk where directional change is based on a correlated circular distribution where a favourable fishing ground is likely to be "fished back over" by the vessel returning in the direction it came from and step length (i.e. the distance travelled from the current to the next fishing location) is determined by relating recent fishing success, measured as the summed value of fish caught,

$$Rev = \sum_{s=1}^{\infty} C_s \cdot Pr_s$$

where C_s is catch of a species, and Pr_s price of a species, to step distance. Here, when fishing is successful vessels remain in a similar location and continue to exploit the local fishing grounds. When unsuccessful, they move some distance away from the current fishing location. The movement distance retains some degree of stochasticity, which can be controlled separately.

The step function takes the form:

$$StepL = e^{log(\beta_1)+log(\beta_2)-(log(\frac{\beta_1}{\beta_3}))} * Rev$$

So that, a step from (x1,y1) to (x2, y2) is defined by:

$$
\begin{aligned}
(x2, y2) =& x1 + StepL \cdot \cos(\frac{\pi \cdot Br}{180}), \\
& y1 + StepL \cdot \sin(\frac{\pi \cdot Br}{180}) \\
with \quad & Br_{t-1} < 180, Br_t = 180+ \sim vm[(0, 360), k] \\
& Br_{t-1} > 180, Br_t = 180- \sim vm[(0, 360), k]
\end{aligned}
$$

with k the concentration parameter from the von mises distribution which we correlate with the revenue so that $k = (Rev + 1/RefRev) * max_k$, where max_k is the maximum concentration value, k, and RefRev is parameterised as for β_3 in the step length function.

2.4.4. Local population depletion

Where several fishing vessels are exploiting the same fish population competition is known to play an important role in local distribution of fishing effort [27]. If several vessels are fishing on the same patch of fish, local depletion and interference will affect fishing location choice of the fleet as a whole [28, 29]. In order to account for this behaviour, the fishing sub-model operates spatially on a daily time-step so that for future days the biomass available to the fishery is reduced in the areas fished. The cumulative effect is to make heavily fished areas less attractive as future fishing opportunities.

2.5. Fisheries independent survey

A fisheries-independent survey is simulated where fishing on a regular grid begins each year at the same time for a given number of stations (a fixed station survey design). Catches of the populations present are recorded but not removed from the population. This provides a fishery independent snapshot of the populations at a regular spatial distribution each year, similar to scientific surveys undertaken by fisheries research agencies.

3. Calculation

[Guidance: A Theory section should extend, not repeat, the background to the article already dealt with in the Introduction and lay the foundation for further work. In contrast, a Calculation section represents a practical development from a theoretical basis.]

3.1. Simulation settings

To illustrate the capabilities on *MixFishSim*, we investigate the influence of ... [expand]. To do so, we first set up with simulation to run for 20 years based on a 100 X 100 square grid, with five fleets of 20 vessels each and four fish populations. Fishing takes place four times a day per vessel and five days a week, while population movement is every week.

3.2. Population parameterisation

We parameterised the simulation model for four populations with differing habitat preference (Figure 2), population demographic and recruitment functions; each of the populations also has two defined spawning areas and movement rates (Table 1).

3.3. Fleet parameterisation

The fleets were parameterised to reflect five different characteristics based on targeting preference and exploitation dynamics (Table 2). This ensures that different fleets have different spatial dynamics, preferentially targeted different fish populations. The stochasticity in the random walk process ensures that different vessels within a fleet have slightly different spatial distributions based on individual experience, while the step function was parameterised dynamically so that vessels take smaller steps where the fishing location yields in the top X [??]quartile of the value available in that year (as defined per fleet in Table 2).

Each fleet was set so that, after the first year, fishing locations were chosen based on experience built up in the same month from previous years and from past trip fishing success. 'Success' in this context was defined as the locations where the top 75 % of revenue from was found in previous trips.

3.4. Survey settings

The survey simulation was set up with follow a fixed gridded station design with 49 stations fished each year, starting on day 92 with same catchability parameters for all populations (Q = 1).

4. Results

Need to consider what best to present here as 4 / 5 figures:

- Spatial dynamics: e.g. Figure 14. showing the population movement across weeks, including a spawning period.
- Overall population trends: e.g. Figure 3, showing the population dynamics at play.
- Realised step function: e.g. Figure 13, showing how the movement and turning angle responds. This could be combined with Figure 7 for a more complete visualisaiton.
- Catch composition and spatial clustering: e.g. Figure 10, showing the importance of spatial resolution.
- Some measure of temporal trends/changes in spatial composition - could pick a certain cell and show how the proportions change over time ? An example is Figure 15, though there is little variation here. I think this is because the static habitat with population movement is far more stable than the previous directly affected population distributions (where there was an advective-diffusive process from the SPDE). Might need to consider how to change this? Could include a spatiotemporally changing habitat

suitability covariate, e.g. temperature ?? [temperature would be very interesting and cover varying spatial fields]

- Comparison of population structure from i) commercial sampling, ii) fisheries independent survey, iii) real population. This should be some statistical measure...not sure best approach here.

ether this is also a seasonal closure.

Present simulated closures in terms of % change in population biomass and fishery.

[Guidance: Results should be clear and concise.]

5. Discussion

[Guidance: This should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.]

6. Conclusions

[Guidance: The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.]

Appendices

[Guidance: If there is more than one appendix, they should be identified as A, B, etc. Formulae and equations in appendices should be given separate numbering: Eq. (A.1), Eq. (A.2), etc.; in a subsequent appendix, Eq. (B.1) and so on. Similarly for tables and figures: Table A.1; Fig. A.1, etc.]

Abbreviations

Detail any unusual ones used.

Table 1: Population dynamics and movement parameter setting

Parameter	Pop 1	Pop 2	Pop 3	Pop 4
Habitat quality				
Matérn ν	1/0.15	1/0.05	1/0.55	1/0.05
Matérn κ	1	2	1	1
Anisotropy	1.5,3,-3,4	1,2,-1,2	2.5,1,-1,2	0.1,2,-1,0.2
Spawning areas (bound box)	40,50,40,50; 80,90,60,70	50,60,30,40; 80,90,90,90	30,34,10,20; 60,70,20,30	50,55,80,85; 30,40,30,40
Spawning multiplier	10	10	10	10
Movement λ	0.3	0.3	0.3	0.3
Population dynamics				
Starting Biomass	1e5	2e5	1e5	1e4
Beverton-Holt Recruit 'a'	60	100	80	2
Beverton-Holt Recruit 'b'	250	250	200	50
Beverton-Holt Recruit σ^2	0.4	0.3	0.4	0.3
Recruit week	13-16	12-16	14-16	16-20
Spawn week	16-18	16-19	16-18	18-20
K	0.3	0.3	0.3	0.3
wt	1	1	1	1
wt_{d-1}	0.1	0.1	0.1	0.1
M (annual)	0.2	0.2	0.2	0.1

Acknowledgements

those providing help during the research..

Funding

This work was supported by the MARES doctoral training program; and the Centre for Environment, Fisheries and Aquaculture Science seedcorn program.

Table 2: Fleet dynamics parameter setting

Parameter	Fleet 1	Fleet 2	Fleet 3	Fleet 4	Fleet 5
Targeting preferences					
Price Pop1	100	100	100	100	100
Price Pop2	200	200	200	200	200
Price Pop3	600	600	600	600	600
Price Pop4	1600	1600	1600	1600	1600
Q Pop1	0.01	0.02	0.02	0.01	0.01
Q Pop2	0.02	0.01	0.02	0.01	0.03
Q Pop3	0.01	0.02	0.02	0.01	0.02
Q Pop4	0.02	0.01	0.02	0.05	0.01
Exploitation dynamics					
step function β_1	1	2	1	2	3
step function β_2	10	10	8	12	7
step function β_3	Q90	Q90	Q85	Q90	Q80
step function $rate$	10	20	15	25	10
Past Knowledge	T	T	T	T	T
Past Year & Month	T	T	T	T	T
Past Trip	T	T	T	T	T
Threshold	0.75	0.75	0.75	0.75	0.75

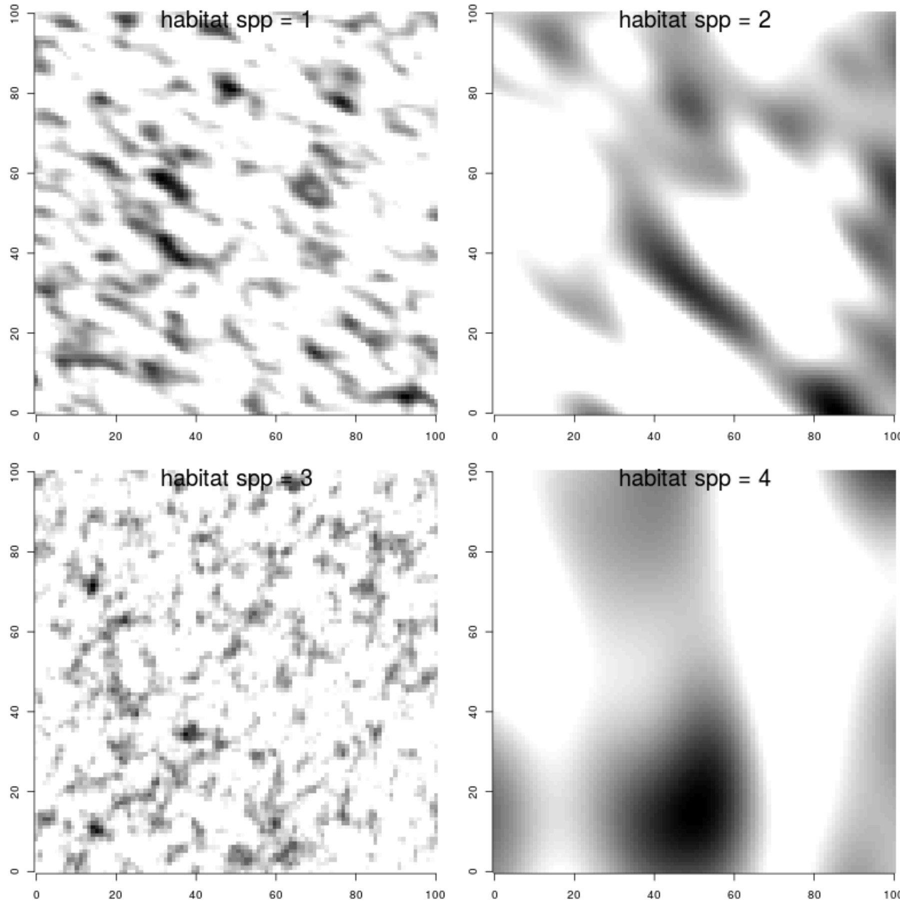

Figure 2: habitat preference

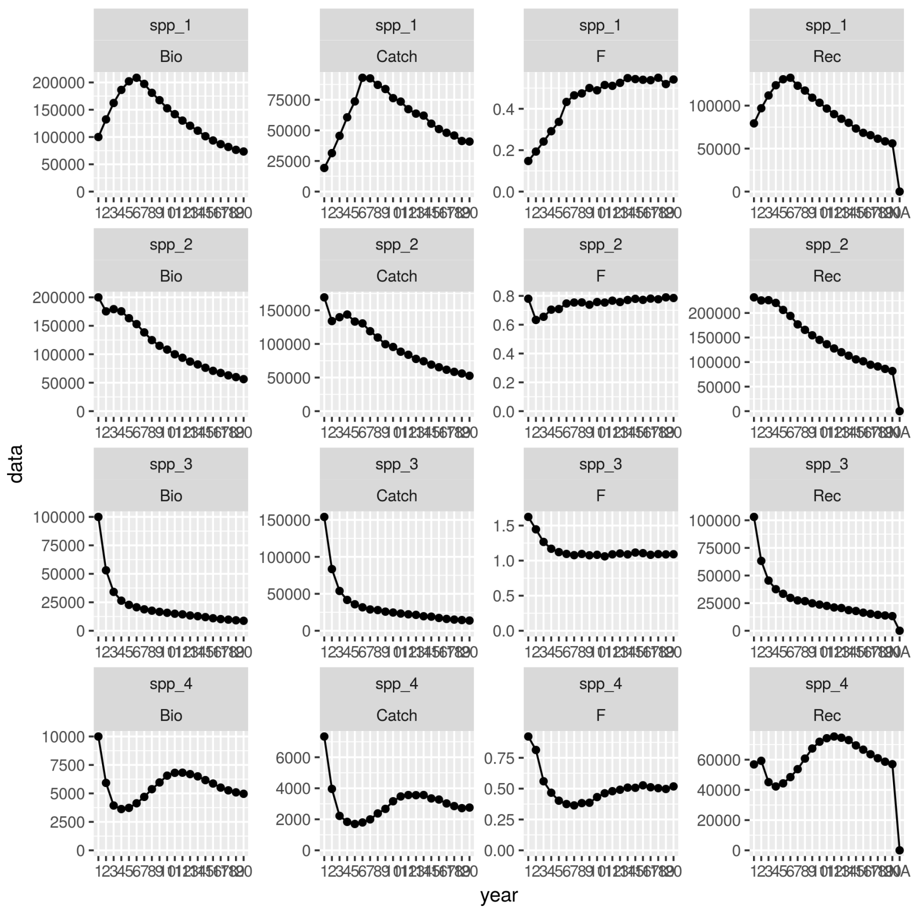

Figure 3: Summary of annualised metrics: biomass, catch, fishing mortality and recruitment. x-axis is the year, y the value

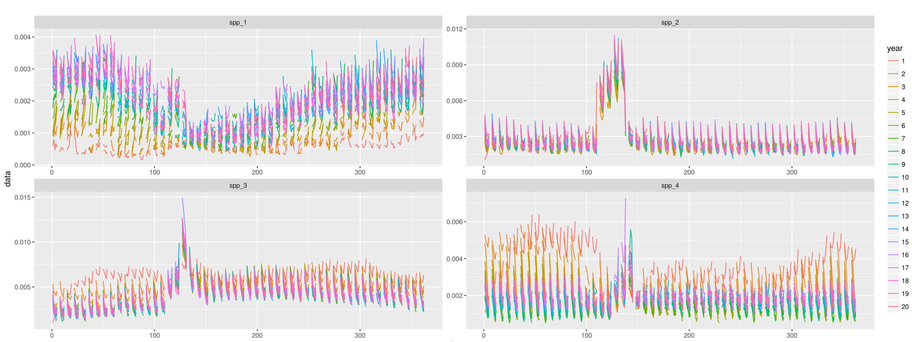

Figure 4: f dynamics - the daily fishing mortalities, each year is a different colour

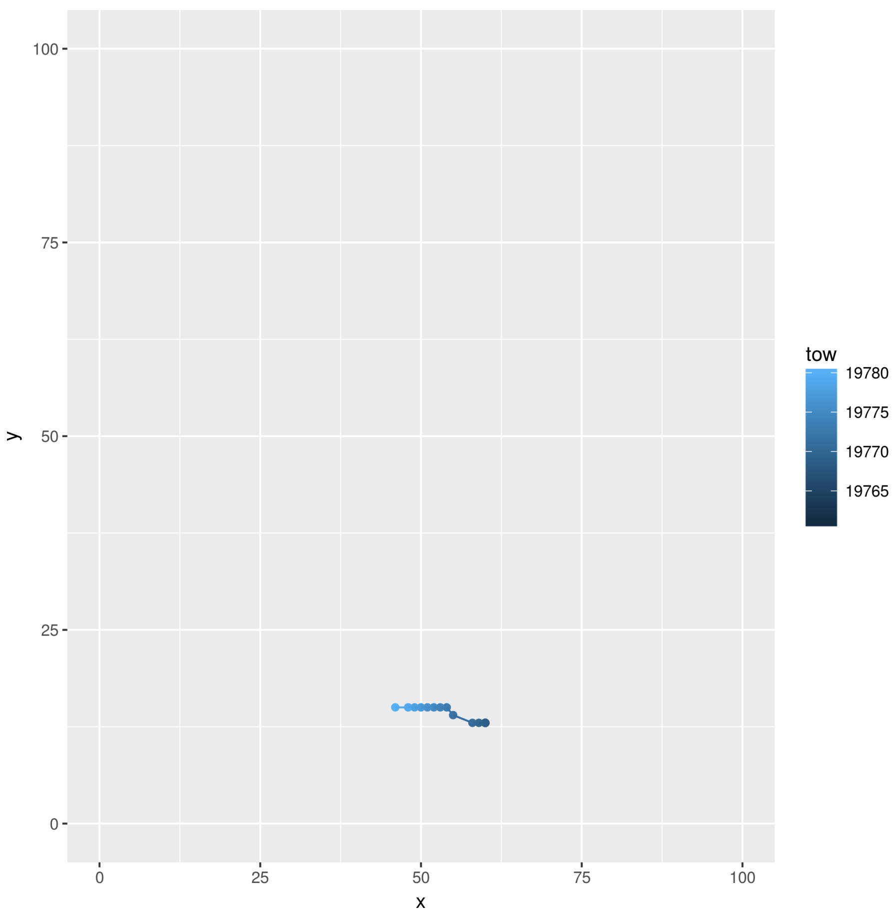

Figure 5: vessel movement - a single trip movement for one vessel

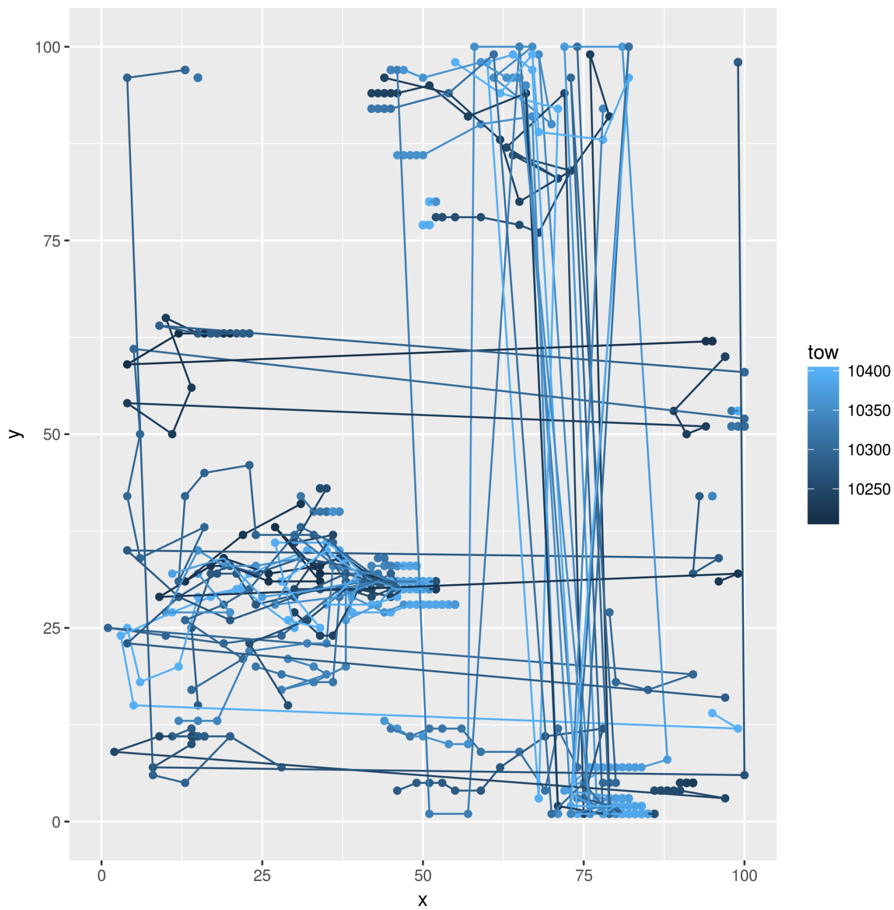

Figure 6: vessel movement for multiple trips from a single vessel. Note the movement off the side pops up the other side, but is joined by a line across the grid. This is from the torus approach rather than the edges being barriers

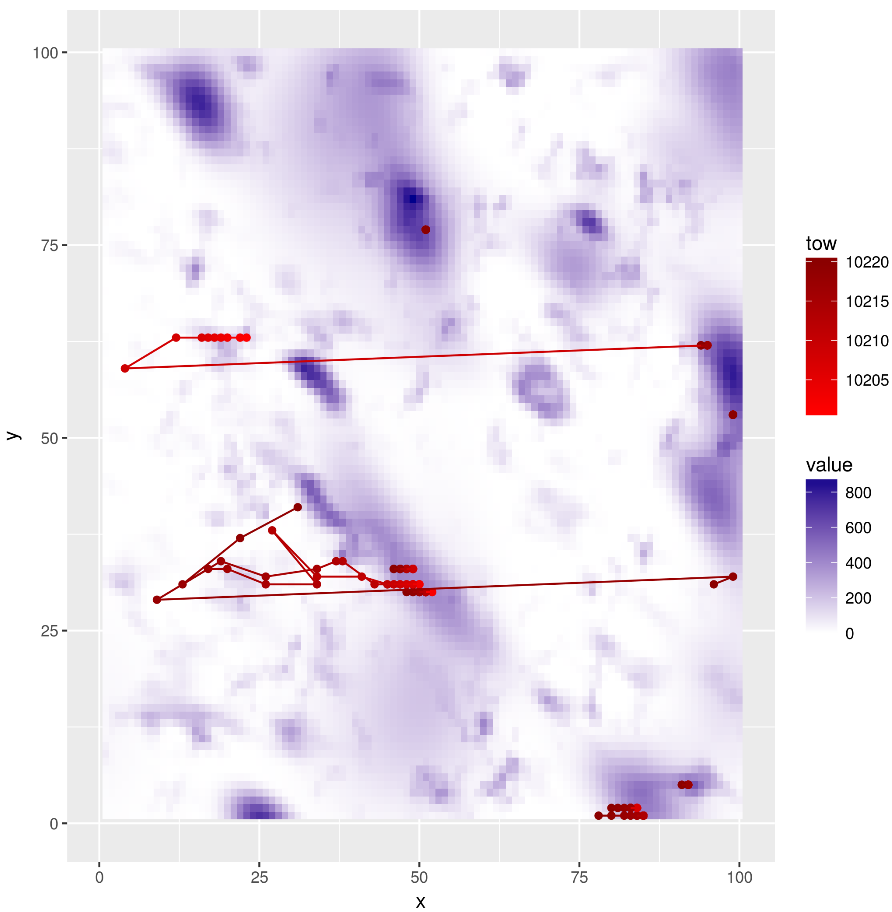

Figure 7: movement of a single vessel over a few trips overlaid on the value field (i.e. sum of the population abundance x catchability x value

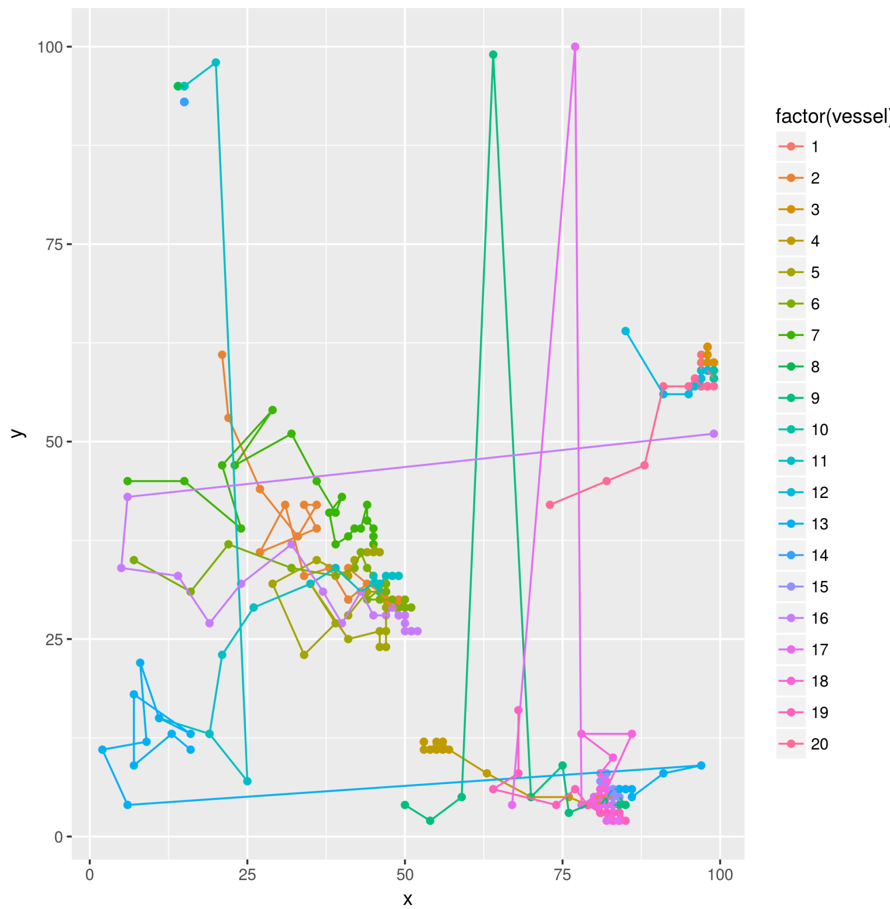

Figure 8: An entire fleets (20 vessels) movement for a single trip

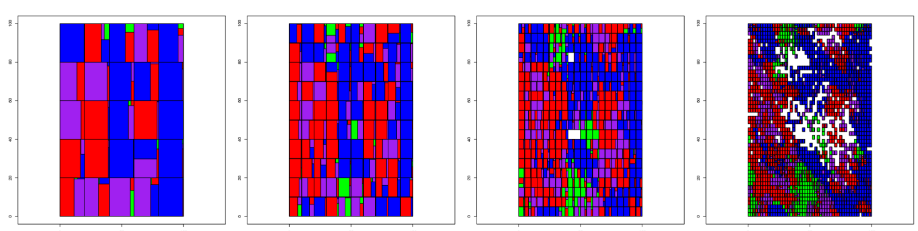

Figure 9: spatial catch composition - the raw catches per cell at 4 different spatial resolutions. Sorry, its a bit small at the moment!

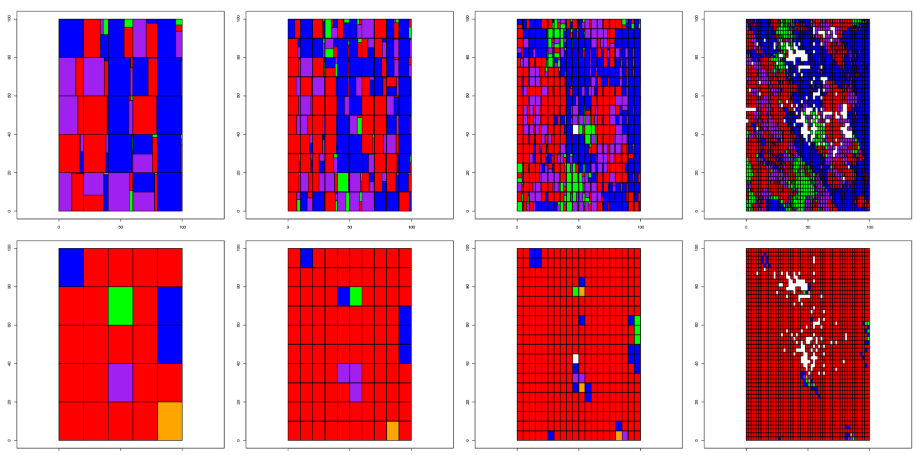

Figure 10: spatial catch composition (as above) but with clustering of cells performs on the bottom row. I'm confused as to why some entirely blue cells in the raw catch composition get allocated to the same cluster as some entirely red cells - needs investigating, it may be the clustering is not optimal

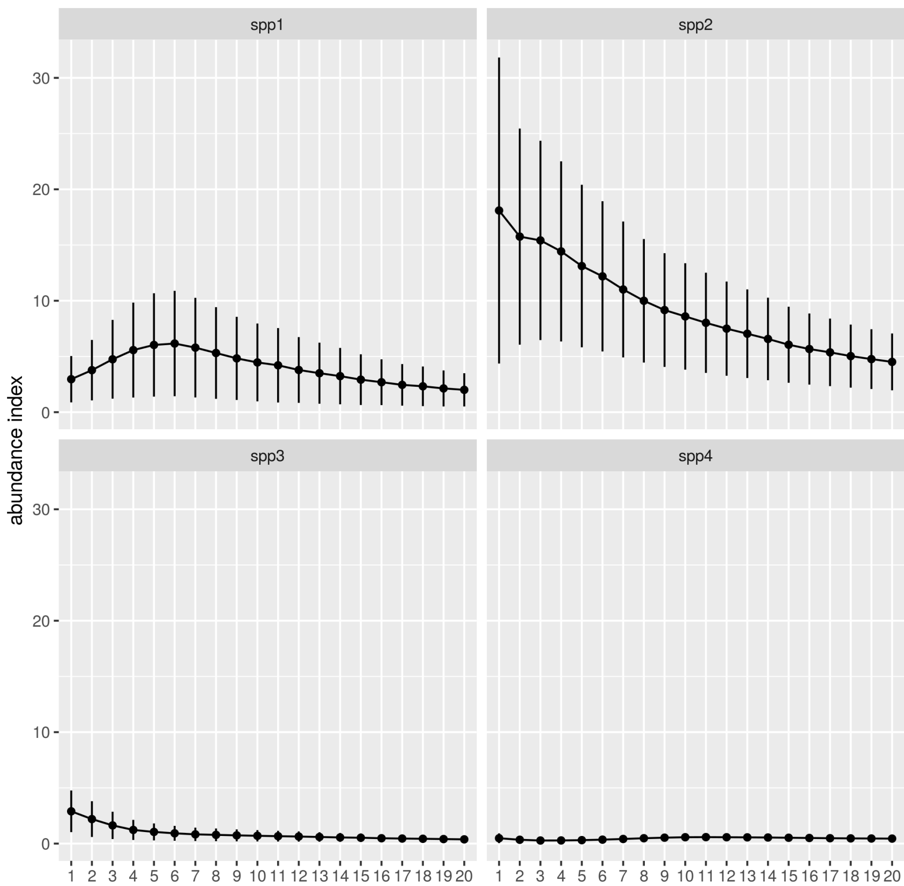

Figure 11: survey index - a non-spatial index generated from the fishery independent survey

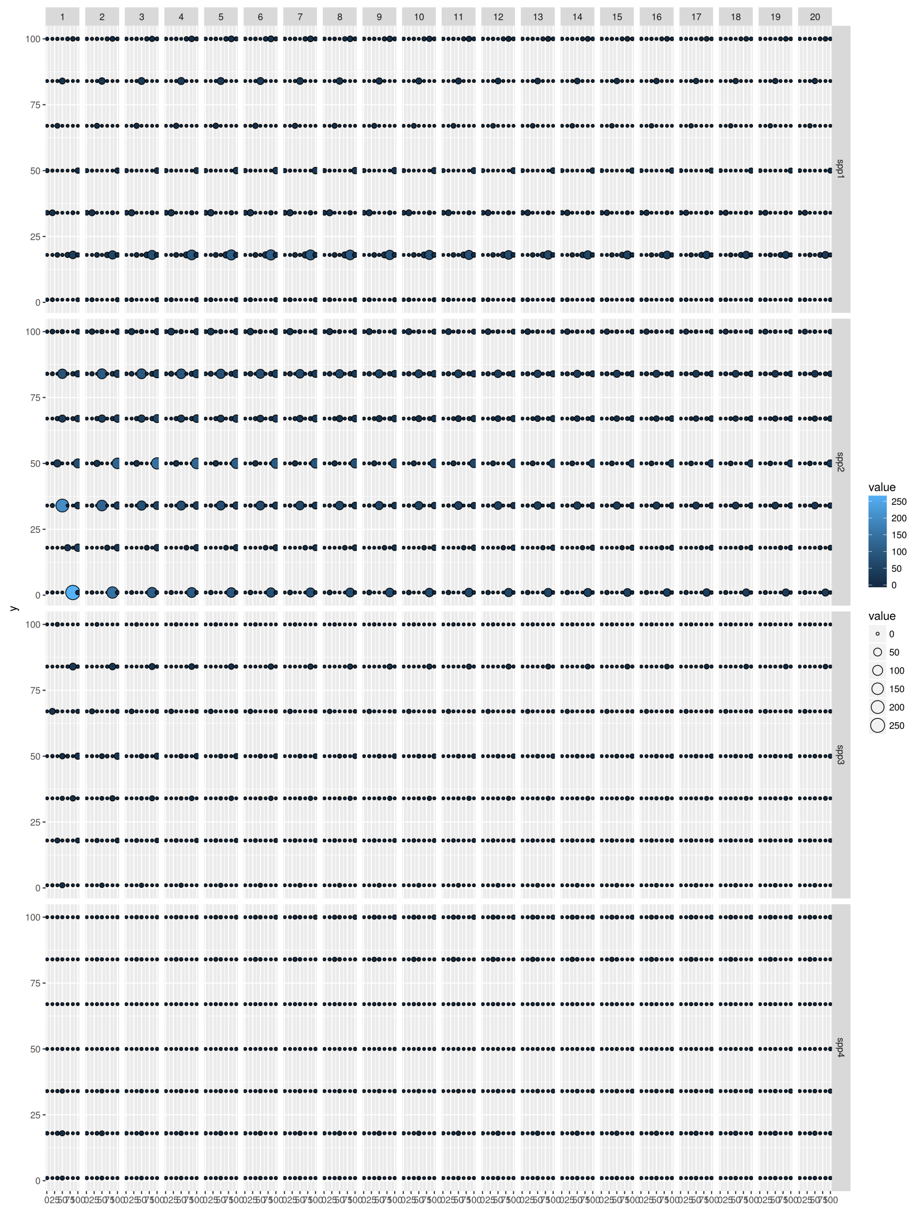

Figure 12: survey spatial abundance - a bubble plot of the survey abundances, not really useful for the paper

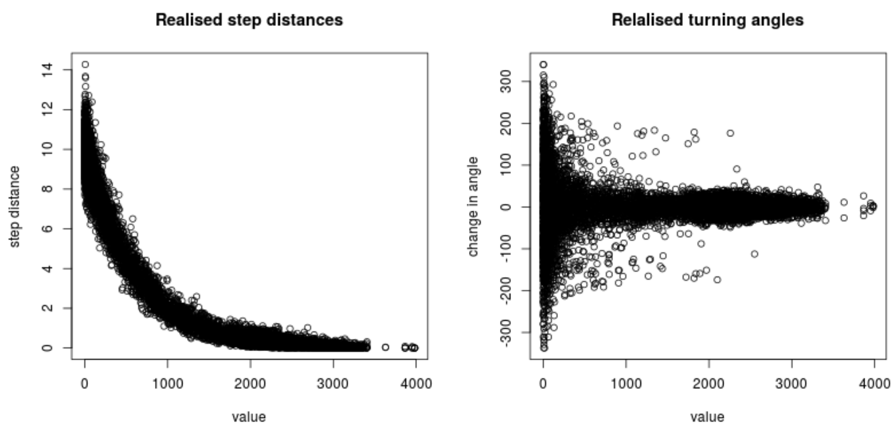

Figure 13: Realised step function - the step function as realised for a single fleet. For turning angles, it can be seen that at higher values, the turning range is less

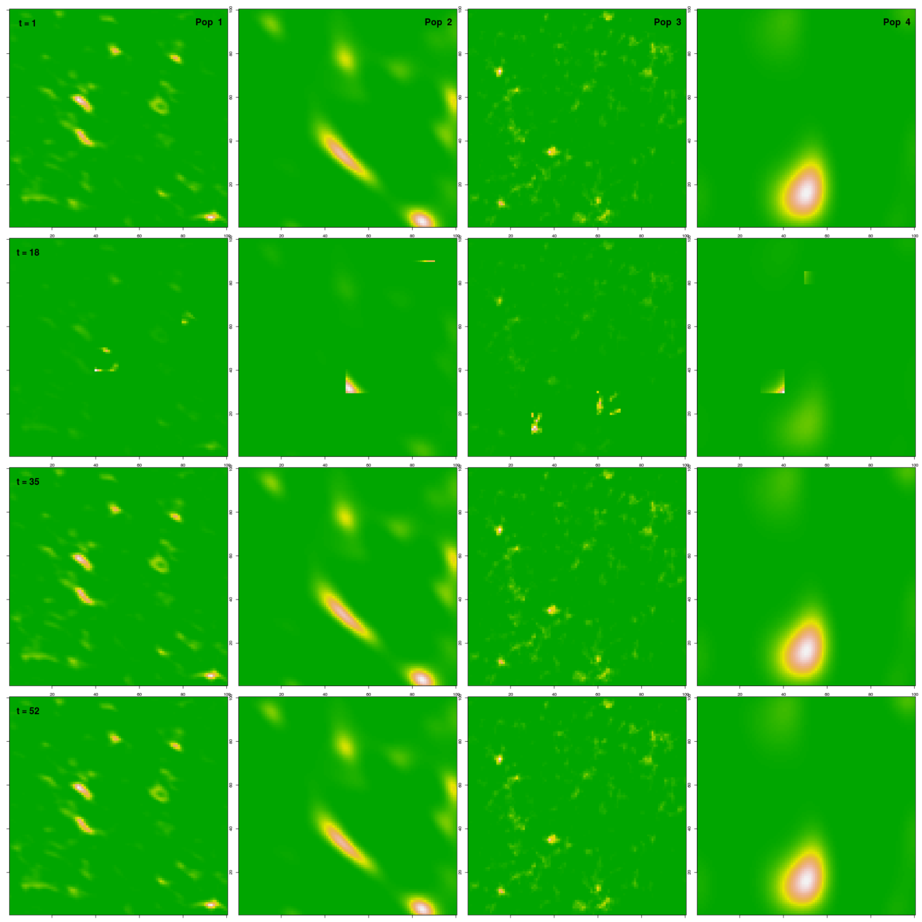

Figure 14: Spatial dynamics - the four populations at four time steps. Not really happy about the lack of dynamics here - mainly down to the static habitat leading to the populations settle in same cells over most time steps (exception: during the spawning period). Could include a temperature covariate or something to force some more temporal changes?

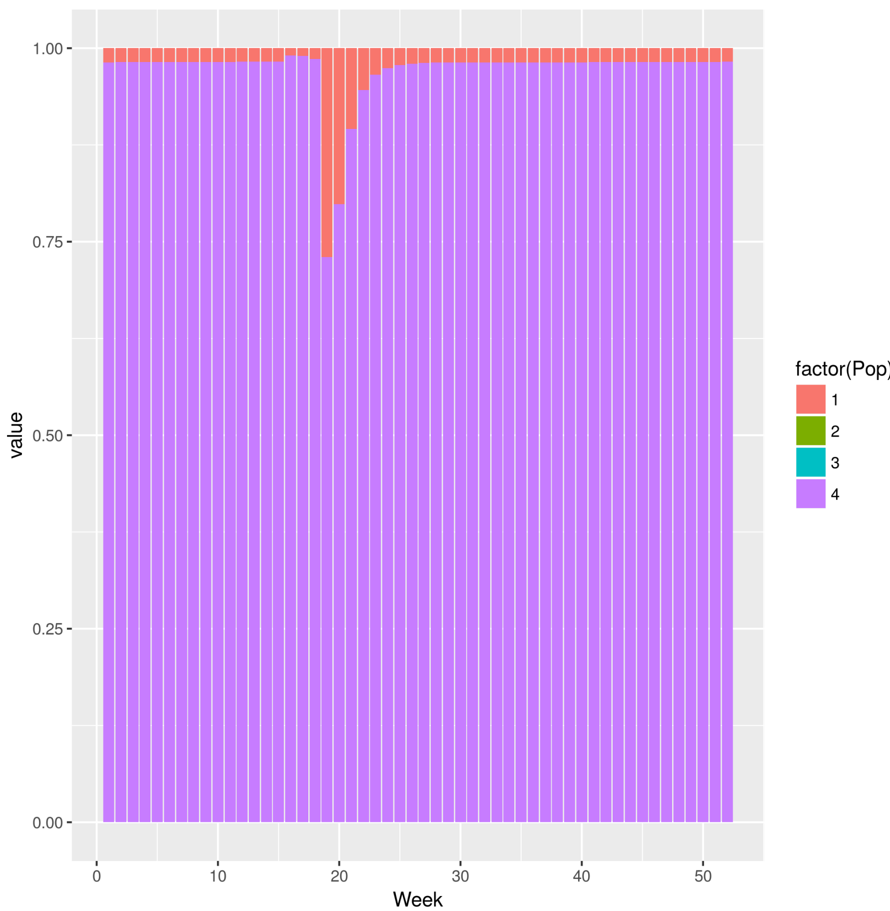

Figure 15: Temporal dynamics - the proportion of each population in a randomly chosen cell. Similar criticism as above

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