User Guide: Applying Marxan with Zones

North central coast of California marine study

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Introduction

We describe the operation of the Marxan with Zones software (Watts et al. 2008 in prep, Klein et al. 2008) on a Marine planning problem for the north central coast of California, USA (Klein et al. 2008 in prep). Marxan with Zones is an adaptation of the Marxan software (Ball & Possingham 2000, Possingham et al. 2000).

Operating the software involved a series of steps, including; framing the problem definition, calibrating the input parameters, validating the correct operation of the software, and generating robust results. These steps were performed for each of our planning scenarios, illustrating best practices for Marxan with Zones.

The software used for running Marxan with Zones and performing calibration, validation, results analysis and explorative data analysis was Zonae Cogito (Watts et al. 2008 in prep).

Marxan with Zones, and Zonae Cogito can be downloaded free of charge from the Marxan website;

http:/www.uq.edu.au/Marxan

Software Validation

We adopted a hybrid approach to validation, incorporating qualitative and quantitative tests. This allowed us to ensure that the software was reliable, as well as being usable, useful, consistent and intuitive.

Qualitative testing

We determined that the results from the system were intuitive, corresponded to our expectations, and were consistent with the underlying spatial information for our study region.

Over a period of three years, we worked continually with users around the world through a series of courses, workshops and meetings, and through email correspondence. We gathered information from users, course participants, and workshop participants in the form of questionnaires, surveys and informal feedback. Based on this feedback, we progressively enhanced the experience of users and improved the usability of our software tools.

The cities and countries around the world where we conducted courses, workshops and meetings on software usability are shown in table 1.

Country	City
Australia	Brisbane, Broome, Canberra, Fremantle, Hobart, Melbourne, Perth, Sydney
Brazil	Brasilia
Canada	Vancouver
South Africa	Port Elizabeth, St Lucia
USA	Portland, San Jose

Table 1: We conducted meetings and workshops in many places around the world.

We were primarily concerned with ensuring the needs of users as planners were met, and also concerned with enhancing the quality of user experience and the level of usability to users.

Quantitative testing

A powerful quantitative technique for testing complex software systems is to implement key algorithms of the software being testing in an alternate programming language. This is an extremely flexible and robust technique that we adopted to ensure the correct operation of Marxan with Zones.

Marxan with Zones used the C++ programming language. We developed an alternate implementation of its objective function evaluation routines in the Zonae Cogito decision support system (Watts, Stewart and Kircher 2008) which used the Object Pascal programming language and the MapWindow GIS ActiveX map component (Ames 2007).

This validation system allowed us to perform quantitative tests for any nominated subset of steps in a simulated annealing process generated by Marxan with Zones. A report was then generated indicating the success or failure of each step, allowing us to validate the operation of Marxan with Zones as reliable for a series of scenarios. We executed this validation system for a series of steps of the Marxan with Zones simulated annealing algorithm for each of our scenarios.

Scenario 1a	Cost	Boundary	Shortfall
Marxan with Zones	56.555795000	903,950.8966490	0.294003000000000
Zonae Cogito	56.555795273	903,950.8966489	0.294003300000004
difference	-2.731E-07	1.00001E-07	-3E-07

Table 2: Example output from the quantitative testing software.

Table 2 shows and example of the test output for a step in one of our scenarios. The values for cost, boundary and shortfall that were evaluated by the two software systems and the differences between the two software systems were calculated. The values shown are the components of the Marxan with Zones objective function score.

Scenarios

We constructed 12 scenarios, varying the costs and targets of each scenario. Below, we outline the cost constraints and target objectives used to construct our 12 scenarios. These are just a few of many possible scenarios and were all system tested for robustness using Marxan with Zones.

Scenario	Cost	Overall Target	Reserve Zone target	Fishery Zone Target
1a	Ex-vessel value	30%		
1b	Ex-vessel value	30%	10%	
1c	Ex-vessel value	30%	15%	
1d	Ex-vessel value	30%	20%	
2a	Relative importance	30%		
2b	Relative importance	30%	10%	
2c	Relative importance	30%	15%	
2d	Relative importance	30%	20%	
3a	Ex-vessel value	30%	15%	90%
3b	Ex-vessel value	30%	15%	80%
3c	Ex-vessel value	30%	15%	70%
3d	Ex-vessel value	30%	15%	60%

Table 3: We constructed 12 Marxan scenarios.

Three ways of using socioeconomic information

We used socioeconomic information on fishing in three ways when zoning for marine protected areas. First, we focused on two different ways of using costs (scenarios 1 and 2) while varying overall and zone-specific targets. We then explicitly targeted the revenue of 7 fisheries as spatial features (scenario 3).

Four types of human use zones

Scenarios 1 and 2 used 3 zones; available, reserve and conservation. Scenario 3 used 4 zones; available, reserve, conservation and fishing.

In the available zone, activities were not restricted. The reserve zone restricted all fishing activities, and the conservation zone restricted some fishing activities. The fishing zone restricted no fishing activities, and explicitly targeting fishing features for inclusion.

Scenario 1

The cost information used is the economic value of fisheries, that is, the amount of money made by each fishery in each planning unit. The objective was to design Marine Protected Areas (MPA's) that achieved conservation targets and minimized the total lost economic value.

Setting conservation targets for scenarios 1 and 2

Here, we outline the parameter settings for scenarios 1b and 2b. The parameter setting for scenarios 1c, 2c, 1d and 2d were equivalent to this, apart from the different proportion of the conservation features that was targeted in the reserve zone. The parameter setting for scenarios 1a and 2a were equivalent to this, apart from the omission of targets for conservation features in the reserve zone.

We wished to capture 30% overall of all conservation features in the reserved zone and the conservation zone, with at least a third of that amount in the reserved zone and the other two thirds allocated between the reserved zone and the conservation zone according to the efficient allocation of resources by our optimizing algorithm. To implement this objective we;
- set an overall target of 30% for all conservation features in spec.dat file (prop field, value 0.3).
- set the contribution of the reserved zone and the conservation zone to 1, and set the contribution of the available zone and the fisheries zone to 0 in the zonecontrib2.dat file.
- set a zone target of 10% for the reserved zone in zonetarget.dat (target 0.1, targettype 1 to indicate proportional target).

The targets specified in the spec.dat file work in concert with the contribution weightings in the zonecontrib file. Only those zones with a positive contribution weighting in zonecontrib file contribute towards meeting targets specified in the spec.dat file.

Scenario 2

The cost information uses is the social value of fisheries, that is, we normalized the economic value of fisheries to show the relative importance of each planning unit to each fishery. If 1 is the maximum value for the halibut fishery, we know that it is the most important planning unit to the halibut fishery. The objective was to design MPA's that achieved conservation targets while minimizing the loss of areas relatively important to each fishery. A similar approach was used in Klein et al. 2008a, Klein et al. 2008b.

This approach is preferable if we want to try and more evenly impact each fishery, which is sensible if fishermen generally participate in only 1 fishery. Planning units that are proportionally more important to fishermen in a particular fishery are given a higher value regardless of total economic value.

Scenario 3

As with scenario 1, the cost information used is the economic value of fisheries. For each of the scenario 3 variations, conservation zone targets were constant (capturing 15% in a reserve) and fishery zone targets varied (retaining from 90% of the revenue is 3a to 60% of the revenue in 3d). We targeted the revenue of 7 fisheries features in addition to the conservation features from the previous scenarios. The cost for the fishery zone was equal to the area of planning units.

We allowed any of these zones to be adjacent to any other zone. Fishermen like fishing the edge of reserves and we did not attempt to spatially buffer the reserve zone with the conservation zone or spatially bias the fishing zone away from or towards the reserve zone (although an alternative formulation of the ZONEBOUNDCOST file could facilitate this objective). We simply let Marxan find the most cost-effective areas to spatially allocate zones.

Setting conservation targets for scenario 3

Here, we outline the parameter settings for scenario 3a. We wished to capture 30% overall of all conservation features in the reserved zone and the conservation zone, with at least half of that amount in the reserved zone and the other half allocated between the reserved zone and the conservation zone according to the efficient allocation of resources by our optimizing algorithm. To implement this objective we;
- set an overall target of 30% for all conservation features in spec.dat file (prop field, value 0.3).
- set the contribution of the reserved zone and the conservation zone to 1, and set the contribution of the available zone and the fisheries zone to 0 in the zonecontrib2.dat file.
- set a zone target of 15% for the reserved zone in zonetarget.dat (target 0.15, targettype 1 to indicate proportional target).

The targets specified in the spec.dat file work in concert with the contribution weightings in the zonecontrib file. Only those zones with a positive contribution weighting in zonecontrib file contribute towards meeting targets specified in the spec.dat file.

Setting fishery targets for scenario 3

Here, we outline the parameter settings for scenario 3a. The parameter setting for scenarios 3b, 3c and 3d was equivalent to this, apart from the different proportion of the fishing features that were targeted.

We wished for the fisheries zone to capture 90% of the fisheries features. To implement this objective we;

- set a zone target of 90% for the fisheries zone in zonetarget.dat (target 0.9, targettype 1 to indicate proportional target).

The zonetarget.dat file is unrelated to overall targets in the spec.dat file and their related contributions in the zonecontrib file, although zone targets can be used in concert with overall targets for some problem definitions (as in our example above with conservation targets).

Calibration

There are four key parameters that require calibration in order for the simulated annealing to run efficiently and produce valid, robust results for the problem specified. These parameters are;

NUMITNS - Number of iterations of simulated annealing.

NUMREPS – Number of runs, or number of zone configurations to generate.

FPF – Feature Penalty Factor.

ZONEBOUNDCOST - Spatial compactness, or zone boundary relationships.

The calibration of FPF should be performed before ZONEBOUNDCOST, and then the calibration of FPF and ZONEBOUNDCOST should be repeated. We repeat these calibration steps as the parameters interact with each other, and changing one will affect the behavior of the other. This ensures the FPF in use is not too high, and also ensures the ZONEBOUNDCOST parameters in use are not too high. Failure to repeat the calibrations may lead to the calibrated values being higher than desired for best operation.

Number of iterations

An appropriate value for NUMITNS was determined in the following way. Note that we used the same number of iterations for all twelve of our planning scenarios. Figure 1 shows the tradeoff between the number of iterations of simulated annealing (execution speed) and the objective function score (efficiency). A value of 10 million iterations gave an acceptable tradeoff.

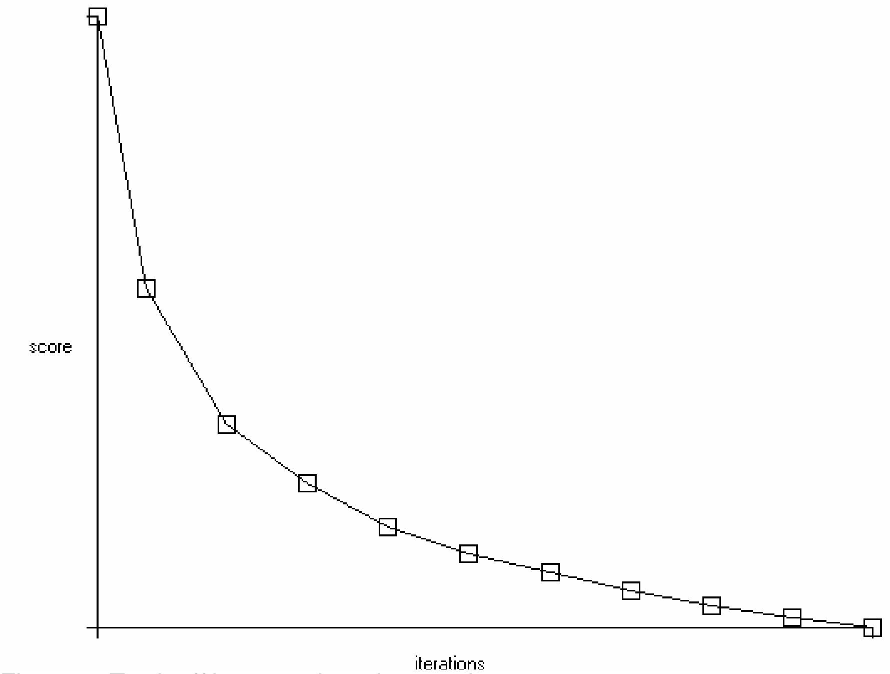


Figure 1: Tradeoff between iterations and score.

We use 1 million iterations for our calibration of our ZONEBOUNDCOST and FPF parameters to save execution time. This does not change the dynamics of our problem and allows us to rapidly determine appropriate parameter values.

Number of runs

An appropriate value for NUMREPS was determined in the following way. We generated two sets of summed solution results for each number of runs under consideration, and then generated a tradeoff curve between the number of runs of Marxan and the dissimilarity of the pairs of summed solutions (the robustness of summed solution). A value of 100 gave an acceptable tradeoff between robustness and execution speed.

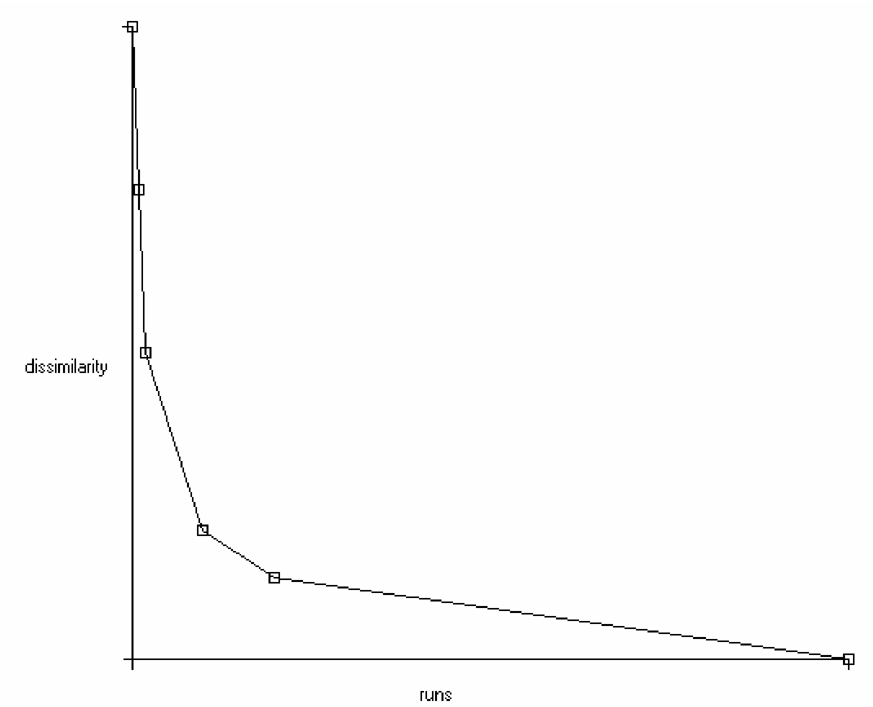


Figure 2: Tradeoff between number of runs and dissimilarity of pairs of summed solution results.

We used 10 runs for our calibration of our ZONEBOUNDCOST and FPF parameters to save execution time. This does not change the dynamics of our problem and allows us to rapidly determine appropriate parameter values.

Feature Penalty Factor, Scenarios 1 and 2

We used two alternate automated methods for determining FPF values to use for our scenarios 1 and 2.

Method 1: We performed calibration on FPF between 0 and 1, generating a tradeoff curve showing the tradeoff between FPF and target gap. The upper bound varies according to the dataset, and was set as a point larger than that which would reliably meet the targets for all our features. The upper bound ranged between 1 and 100 for our datasets.

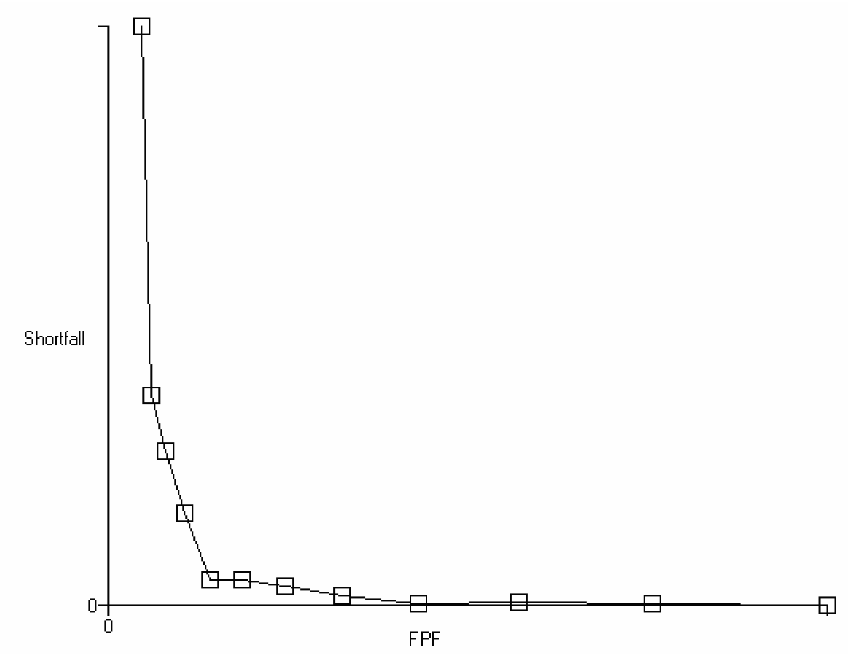


Figure : Tradeoff between FPF and target gap.

We took care not to set the FPF values too high for our features, ensuring efficient operation of the simulated annealing algorithm. We chose FPF values that gave an acceptable tradeoff between penalty and efficiency, and ensured our solutions captured at least 99% of targets for all features in use.

Method 2: We applied an adaptive calibration algorithm to select FPF values robust for a large number of runs of Marxan. The adaptive calibration algorithm is a systematic and repeatable way of generating FPF values. The graph below illustrates how the adaptive calibration algorithm systematically searches from low values of FPF to higher ones, then progressively narrows its search until converging to the most efficient FPF value that ensures 99% of targets for all our features are met.

Note that this adaptive calibration technique only works for scenarios where all target objectives are simultaneously achievable, such as scenarios 1 and 2. For scenario 3 (described in detail below), all target objectives are not simultaneously achievable, so applying this technique leads to the FPF value continuing to increase exponentially until stopped by the user.

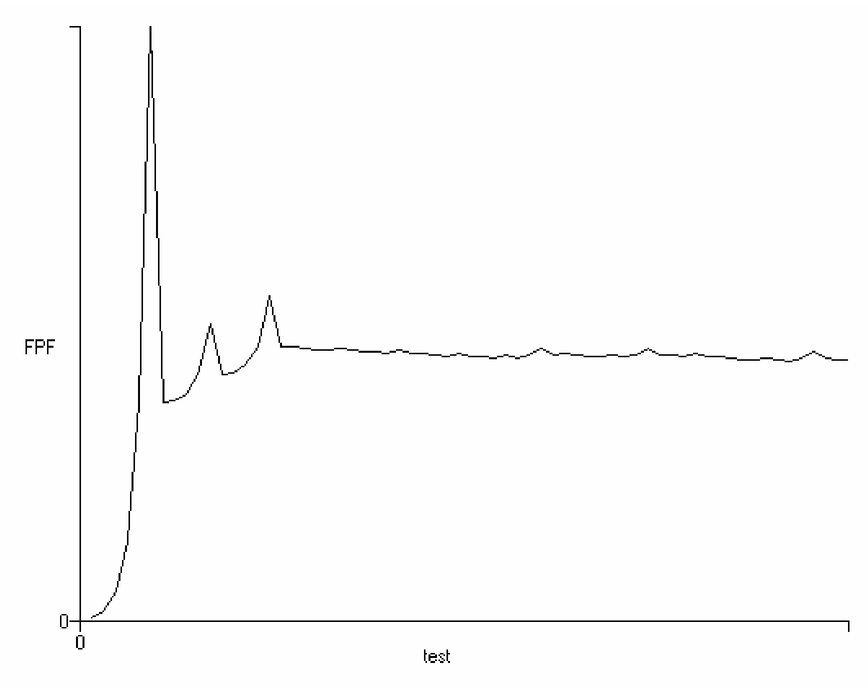


Figure : Fluctuations of FPF during the course of adaptive calibration.

We adaptively calibrated FPF by following these steps;

1) Start off with a very small number for FPF (eg. 0.00001).
2) Run the system and view the minimum proportion of targets met (MPM) for all solutions.
3) If the MPM is less than the desired amount, increase the FPF by an order of magnitude.
4) Run the system and view the MPM for all solutions.
5) Repeat steps 3 and 4 until MPM exceeds the desired amount.
6) Reduce the FPF value to that used in the previous run of the system.
7) Increase the FPF by a very small number (eg. 0.00001).
8) Run the system and view the MPM for all solutions.
9) If the MPM is less that the desired amount, increase the FPF by an amount one order of magnitude greater than the increase used in previous run of the system, then go to step 10. If the MPM is greater than the target amount, go to step 6.
10) Run the system and view the MPM for all solutions.
11) Go to step 9.

We followed this sequence of steps to systematically find FPF values through a process of adaptive calibration. We stopped the adaptive calibration sequence when the FPF had converged to a value that ensured 99% of targets for all our features were met with maximum efficiency.

Below are the FPF values we selected for scenarios 1 and 2.

Scenario	FPF
1a	0.0128
1b	1.97
1c	4.46
1d	3.01
2a	0.537
2b	4.31
2c	10.2
2d	4.75

Feature Penalty Factor, Scenario 3

For scenario 3, all target objectives are not simultaneously achievable, so applying the adaptive calibration technique lead to the FPF value continuing to increase exponentially as the method was applied.

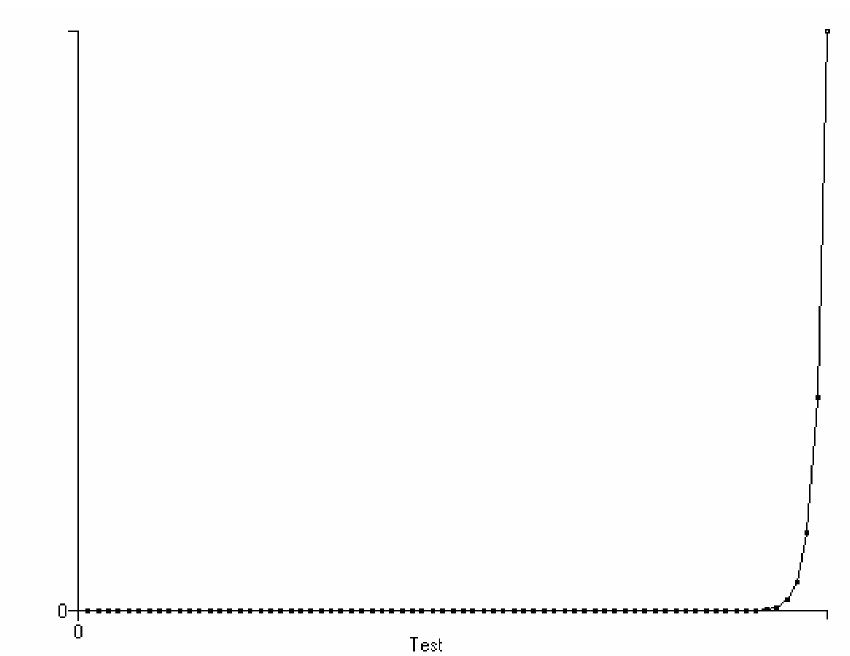


Figure : Variation of FPF during the course of adaptive calibration for a dataset that has target objectives that are not simultaneously achievable.

Instead, we used an alternative approach for setting differential FPF values for conservation features and fishing features.

1) We applied the adaptive calibration steps to only the FPF for conservation features, while holding the FPF for fishery features constant at 0.00001.

2) We applied the adaptive calibration steps to only the FPF for fishery features, while holding the FPF for conservation features constant at 0.00001.

These two steps allowed us to identify FPF values for both sets of features that consider conservation targets and fishery targets equally (neutral priority).

3) We varied the FPF for conservation features through a range above and below its neutral value, while holding the FPF for fishery features constant at its neutral value.

Priority	Conservation FPF	Fishery FPF
Conservation	1	0.1
Neutral	0.5	0.1
Fisheries	0.1	0.1

This process allowed us to find differential FPF values for conservation features (ecological objectives) and fishery features (economic objectives) to;

- Prioritize conservation targets over fishery targets.
- Prioritize fishery targets over conservation targets.
- Consider conservation targets and fishery targets equally.

We varied the FPF for conservation features between 0.1 and 1, while holding the FPF for fishery features constant at 0.1. This allowed us to explore the tradeoff between economic and ecological objectives.

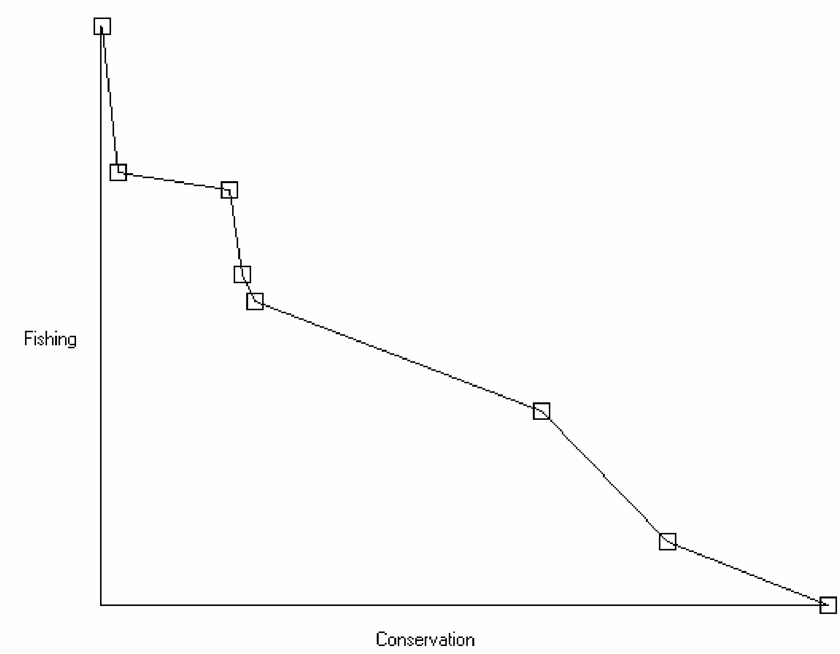


Figure : Tradeoff between conservation and fishing for scenario 3.

Zone boundary relationships

We outline the methods for calibrating zone boundary relationships for spatially clumped zones, and spatially nested zones. The zone boundary relationships are stored in the ZONEBOUNDCOST parameter file for each scenario.

For spatial clumping, we require all zones to be spatially clumped, with a tendency for planning units to be adjacent to other planning units of the same zone and not have a random spatial scattering. For spatially buffered zones, we have the same requirements as for spatial clumping, with an additional requirement that specified zones are buffered by other specified zones.

The default matrix for 3 zones ($n = 3$) for spatial clumping is a negation of the identity matrix I , shown below. ZBC is the default ZONEBOUNDCOST matrix for spatial clumping.

$$I = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$ZBC = \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix}$$

The default ZONEBOUNDCOST matrix can be computed by subtracting the identity matrix from the ($n \times n,\ n = 3$) matrix with a value of 1 for each element;

$$1 - I = ZBC$$

Or

$$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} - \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix}$$

The default matrix for four zones is shown below.

	Available	Reserve	Conservation	Fishing
Available	0	1	1	1
Reserve	1	0	1	1
Conservation	1	1	0	1
Fishing	1	1	1	0

Steps in calibrating ZONEBOUNDCOST

Each element in the matrix represents the boundary relationship between the pair of zones referencing that element. When calibrating the zone boundary matrix, we always set the relationship between any zone and itself to zero, and calibrate ZONEBOUNDCOST for spatial clumping for all other elements with the following steps;

1) Start off with the default matrix multiplied by a small number (eg. 0.00001).
2) Run the system and view spatial output of solutions.
3) Increase the multiplication factor of the default matrix by one order of magnitude.
4) Run the system and view spatial output of solutions.
5) Repeat steps 3 and 4 until at least one zone has moderate spatial clumping.
6) Increase the multiplication factor (* see notes below) for all elements referencing the zones that have not achieved moderate spatial clumping.
7) Run the system and view spatial output of solutions.
8) Repeat step 6 and 7 until all zones have moderate spatial clumping.

If the multiplication factor becomes too high for pairs of zones in the ZONEBOUNDCOST matrix, this can be observed in one of 2 ways;

1) Spatial buffering will occur between one of the pair of zones and other zones not in the pair, or;
2) One of the pair of zones will not occur in the zone configuration.

Spatial buffering of zones

Reducing the multiplication factor will reduce the spatial buffering. In some cases, spatial buffering is desired to generate spatially nested zone configurations, and it can be achieved by increasing the multiplication factors between pairs of zones that you do not want spatially adjacent to each other until the desired level of buffering occurs.

Setting ZONEBOUNDCOST matrix elements

* Note on multiplication factor: We start off by increasing the multiplication factor by an order of magnitude at a time. To fine tune the values, we reduce the magnitude of increases (and decreases) in multiplication factors until we have precisely the degree of spatial clumping required for each zone.

Note on repeated application of steps 6 and 7: We only adjust the values of elements referencing zones that have not achieved moderate spatial clumping. The number of zones still being calibrated will reduce until all zones are calibrated.

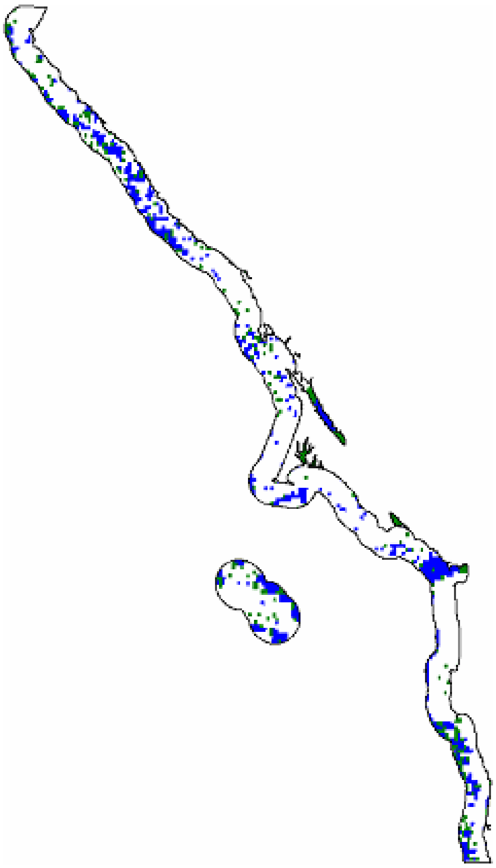
	Available	Reserve	Conservation	Fishing
Available	0	1	1	1
Reserve	1	0	1	1
Conservation	1	1	0	1
Fishing	1	1	1	0

In the default matrix above, we highlight the cells referenced by the conservation zone in green, the cells referenced by the reserve zone in blue, and the cells referenced by both the conservation and reserve zones in red.

If the reserve zone had achieved the desired level of spatial clumping, and the conservation zone had not yet achieved the desired level of spatial clumping, then only the cells referenced by the conservation zone and not referenced by the reserve zone (green) would be increased.

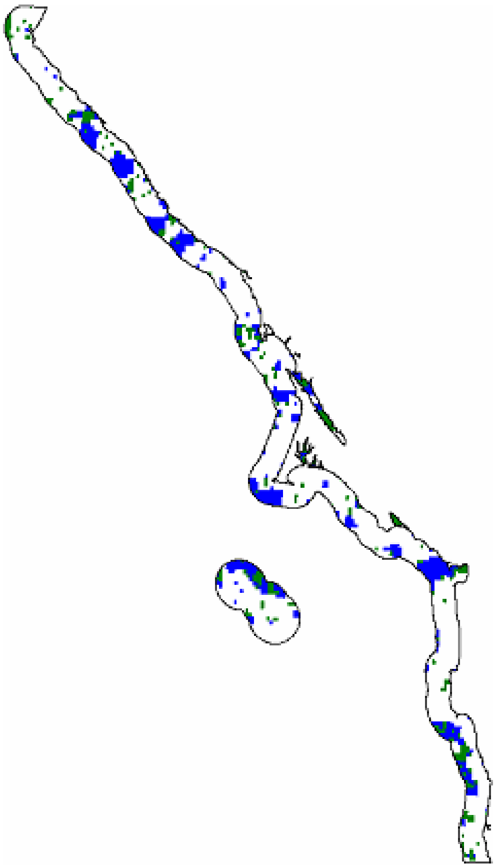
Below we follow illustrate this method for one of our scenarios that required a non-trivial calibration (scenario 2a);

First Step



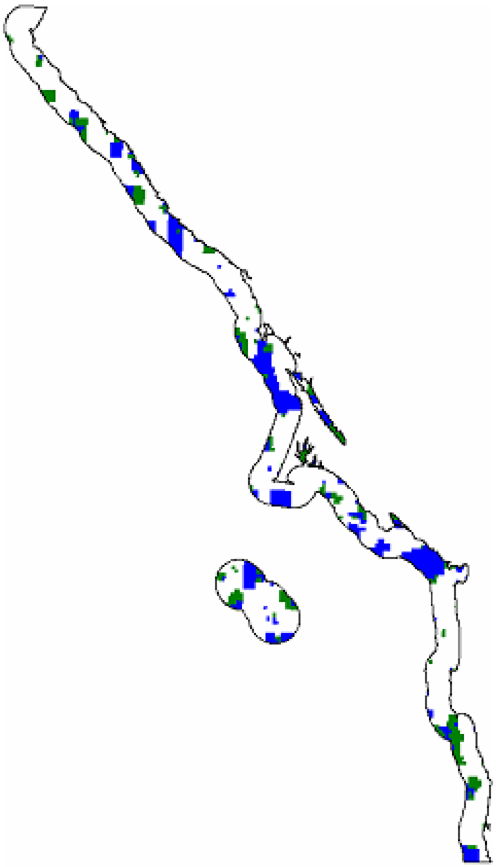
2a First Step	Available	Reserve	Conservation
Available	0	0.00001	0.00001
Reserve	0.00001	0	0.00001
Conservation	0.00001	0.00001	0

Second Step



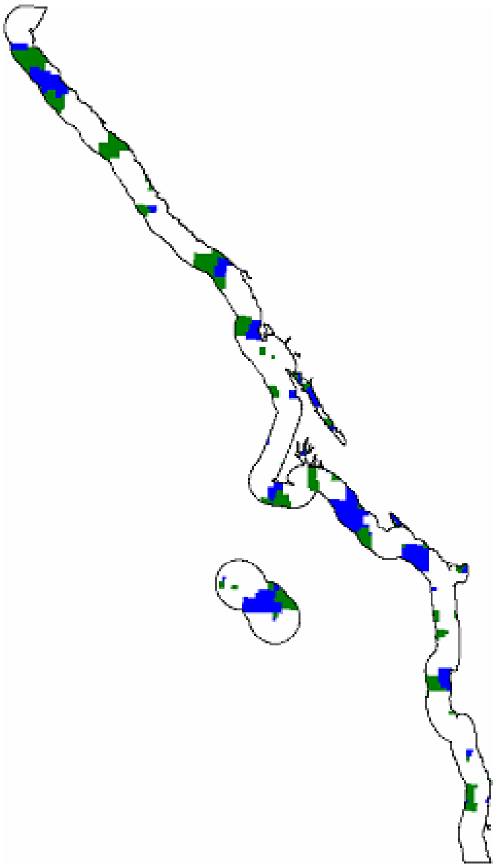
2a Second Step	Available	Reserve	Conservation
Available	0	0.0001	0.0001
Reserve	0.0001	0	0.0001
Conservation	0.0001	0.0001	0

Third Step



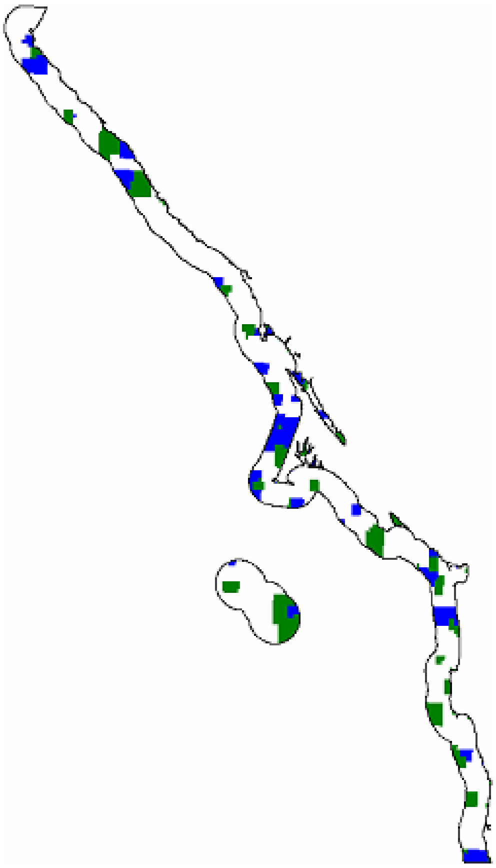
2a Third Step	Available	Reserve	Conservation
Available	0	0.001	0.001
Reserve	0.001	0	0.001
Conservation	0.001	0.001	0

Fourth Step



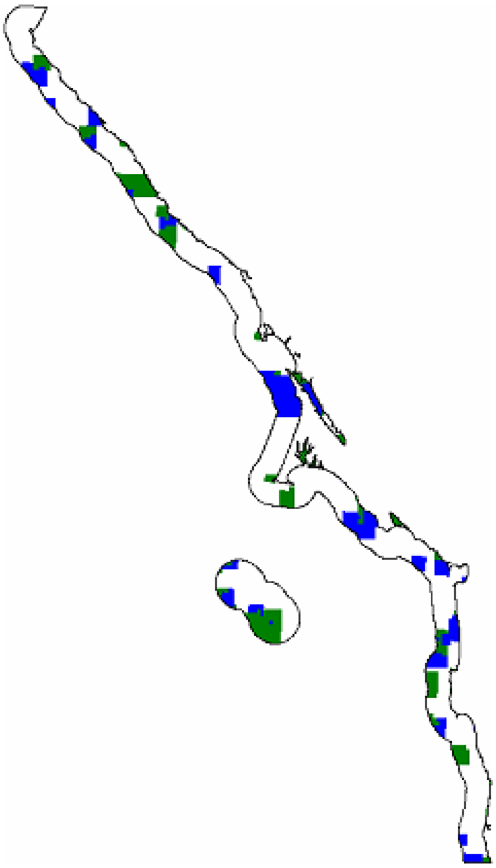
2a Fourth Step	Available	Reserve	Conservation
Available	0	0.01	0.01
Reserve	0.01	0	0.01
Conservation	0.01	0.01	0

Fifth Step



2a Fifth Step	Available	Reserve	Conservation
Available	0	0.1	0.1
Reserve	0.1	0	0.1
Conservation	0.1	0.1	0

Sixth Step

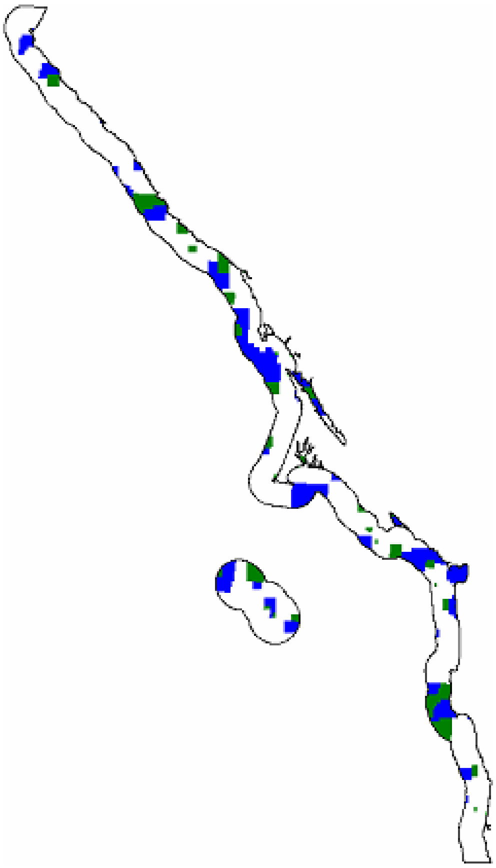


2a Sixth Step	Available	Reserve	Conservation
Available	0	1	1
Reserve	1	0	1
Conservation	1	1	0

We judged that the value for the reserve zone was high enough as this zone has achieved moderate spatial clumping. As a result, we no longer modified elements referencing the zone reserve zone (Reserve vs. Available, and Reserve vs. Conservation).

We noted that the value for the conservation zone was too high as it was being partially buffered by the reserve zone. In the next step, we reduced the value for the conservation zone to its previous amount, and then increased it by a smaller margin (in the Conservation vs. Available cell).

Seventh Step



2a Seventh Step	Available	Reserve	Conservation
Available	0	1	0.15
Reserve	1	0	1
Conservation	0.15	1	0

We judged the values were just right, and stopped the calibration at this point.

Through a similar process, we derived appropriate ZONEBOUNDCOST parameter values for each of our scenarios. These values were appropriate for generating zone configurations with moderate spatial clumping, and are illustrated below;

1a	Available	Reserve	Conservation
Available	0	0.001	0.001
Reserve	0.001	0	0.001
Conservation	0.001	0.001	0

1b	Available	Reserve	Conservation
Available	0	1	0.15
Reserve	1	0	1
Conservation	0.15	1	0

1c	Available	Reserve	Conservation
Available	0	1.5	0.1
Reserve	1.5	0	1.5
Conservation	0.1	1.5	0

1d	Available	Reserve	Conservation
Available	0	1.5	0.1
Reserve	1.5	0	1.5
Conservation	0.1	1.5	0

2a	Available	Reserve	Conservation
Available	0	0.01	0.01
Reserve	0.01	0	0.01
Conservation	0.01	0.01	0

2b	Available	Reserve	Conservation
Available	0	2	0.1
Reserve	2	0	2
Conservation	0.1	2	0

2c	Available	Reserve	Conservation
Available	0	2	0.1
Reserve	2	0	2
Conservation	0.1	2	0

2d	Available	Reserve	Conservation
Available	0	2	0.1
Reserve	2	0	2
Conservation	0.1	2	0

3a	Available	Reserve	Conservation	Fishing
Available	0	0.001	0.001	0.001
Reserve	0.001	0	0.001	0.001
Conservation	0.001	0.001	0	0.001
Fishing	0.001	0.001	0.001	0

3b	Available	Reserve	Conservation	Fishing
Available	0	0.001	0.001	0.001
Reserve	0.001	0	0.001	0.001
Conservation	0.001	0.001	0	0.001
Fishing	0.001	0.001	0.001	0

3c	Available	Reserve	Conservation	Fishing
Available	0	0.001	0.001	0.001
Reserve	0.001	0	0.001	0.001
Conservation	0.001	0.001	0	0.001
Fishing	0.001	0.001	0.001	0

3d	Available	Reserve	Conservation	Fishing
Available	0	0.001	0.001	0.001
Reserve	0.001	0	0.001	0.001
Conservation	0.001	0.001	0	0.001
Fishing	0.001	0.001	0.001	0

Results

For each scenario, we generate results comprising a solution summary table as well as maps of selection frequency and best solution.

Summary table

	Score	Cost	Available	Reserve	Conservation	Fishing	Boundary	Penalty	Shortfall	Missing	MPM
1a	904,050.21	59.83	2,553.07	106.81	950.12		903,990.19	0.18	1,428.99	0.41	1.00
1b	1,014,743.57	226.85	2,531.56	404.74	673.70		1,014,446.86	69.87	4,514.69	0.53	1.00
1c	1,081,672.56	276.78	2,534.61	572.32	503.07		1,081,118.98	276.80	8,121.37	0.68	0.99
1d	1,095,800.10	327.33	2,543.20	748.93	317.87		1,095,383.36	89.41	4,654.24	0.51	1.00
2a	922,955.48	15,189.31	2,520.08	18.59	1,071.33		907,763.45	2.72	417.00	0.17	1.00
2b	1,450,222.83	253,028.73	2,543.87	389.40	676.73		1,197,120.80	73.31	1,441.15	0.39	1.00
2c	1,678,216.21	396,324.63	2,542.59	556.27	511.14		1,281,784.26	107.32	996.94	0.29	1.00
2d	1,869,472.78	552,486.99	2,539.33	723.47	347.20		1,316,904.35	81.44	1,662.26	0.78	1.00
3a	905,897.85	1,501.93	419.93	521.06	581.47	2,087.54	904,351.60	44.31	108,414,339.03	38.69	0.01
3b	905,171.75	970.72	891.20	625.78	874.18	1,218.84	904,178.18	22.84	47,450,434.22	28.73	0.02
3c	905,156.53	954.44	906.94	645.73	870.35	1,186.98	904,180.56	21.53	43,421,734.48	27.21	0.03
3d	905,132.30	927.04	942.53	637.78	878.54	1,151.15	904,183.97	21.30	42,999,041.99	26.32	0.04

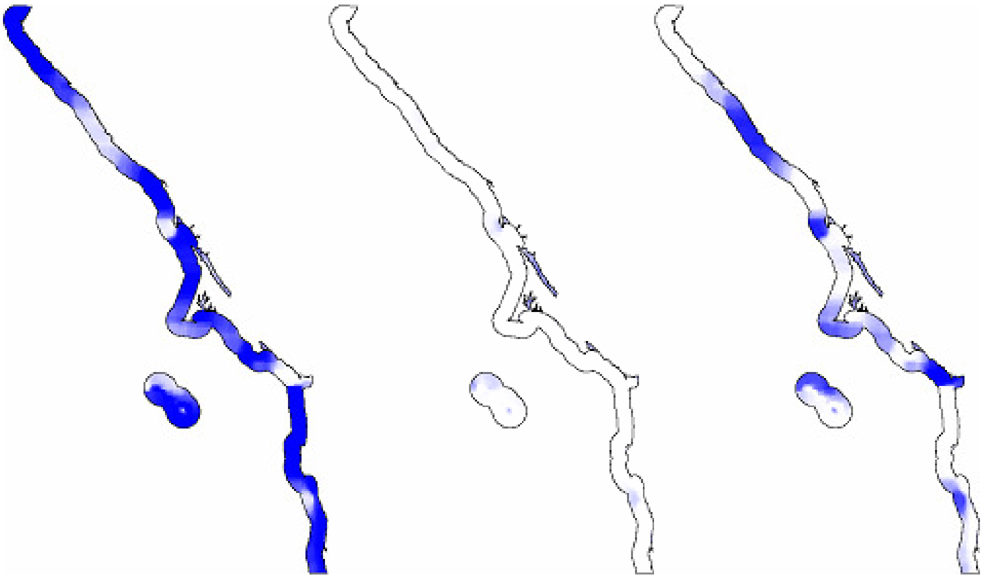
In the summary table, we show the average values for each of our 100 runs across our 12 scenarios. The meaning of the values is shown in the table below

Score	Objective function score.
Cost	Cost term of objective function.
Boundary	Boundary term of objective function.
Penalty	Penalty term of objective function.
Available	Number of planning units in available zone.
Reserve	Number of planning units in reserve zone
Conservation	Number of planning units in conservation zone
Fishing	Number of planning units in fishing zone.
Shortfall	Total amount of unmet targets remaining.
Missing	Number of unmet targets.
MPM	Minimum proportion met for targets.

Maps of selection frequency

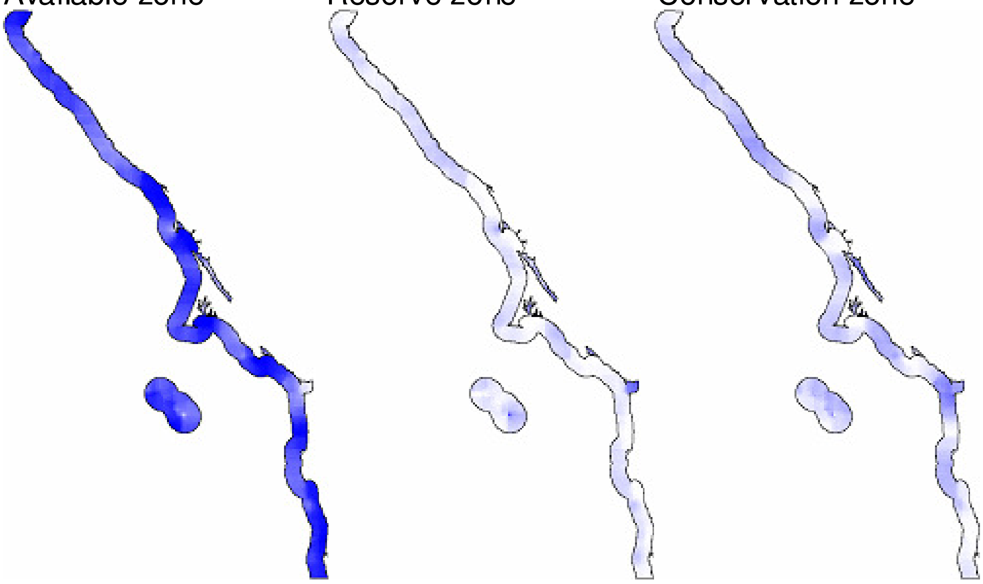
Scenario 1a

Available zone | Reserve zone | Conservation zone



Scenario 1b

Available zone | Reserve zone | Conservation zone

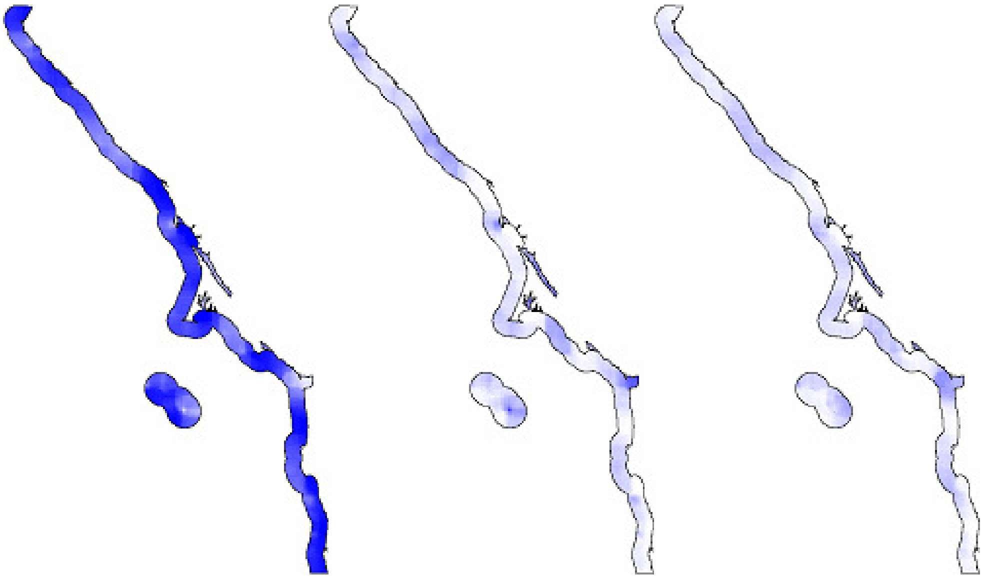


Dark blue indicates highest selection frequency, lighter shades of blue indicate lower selection frequency, and white indicates zero selection frequency.

Maps of selection frequency

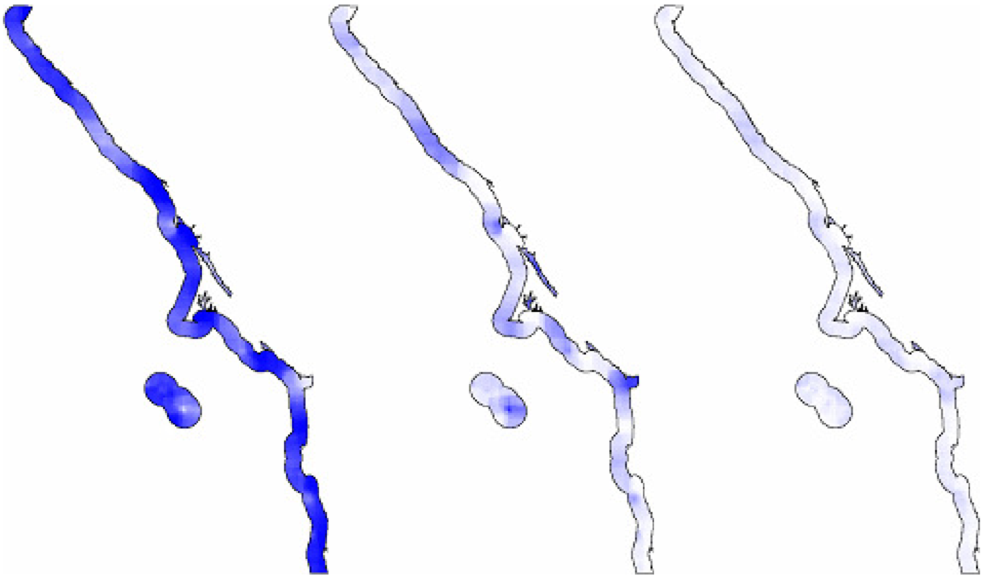
Scenario 1c

Available zone Reserve zone Conservation zone



Scenario 1d

Available zone Reserve zone Conservation zone

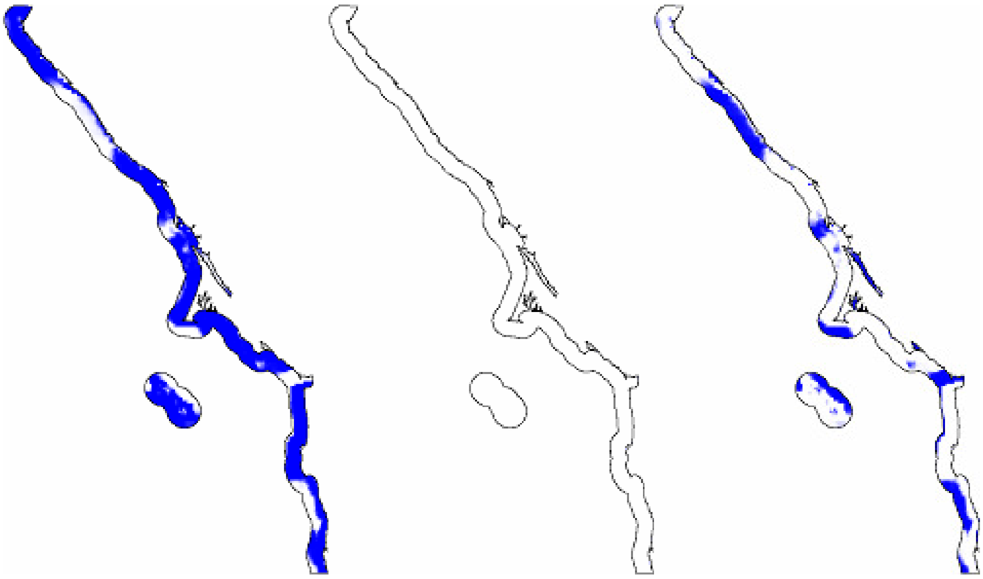


Dark blue indicates highest selection frequency, lighter shades of blue indicate lower selection frequency, and white indicates zero selection frequency.

Maps of selection frequency

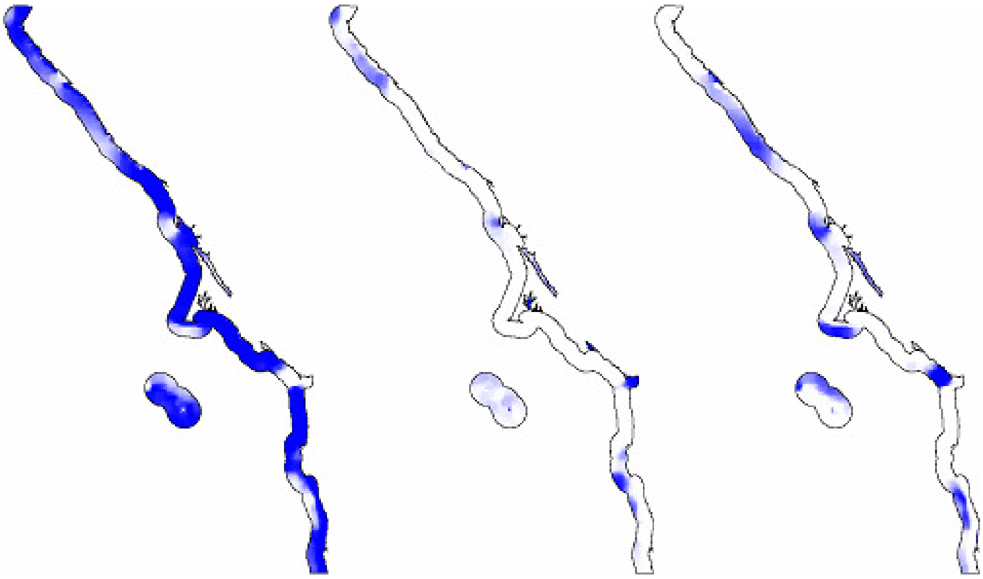
Scenario 2a

Available zone | Reserve zone | Conservation zone



Scenario 2b

Available zone | Reserve zone | Conservation zone

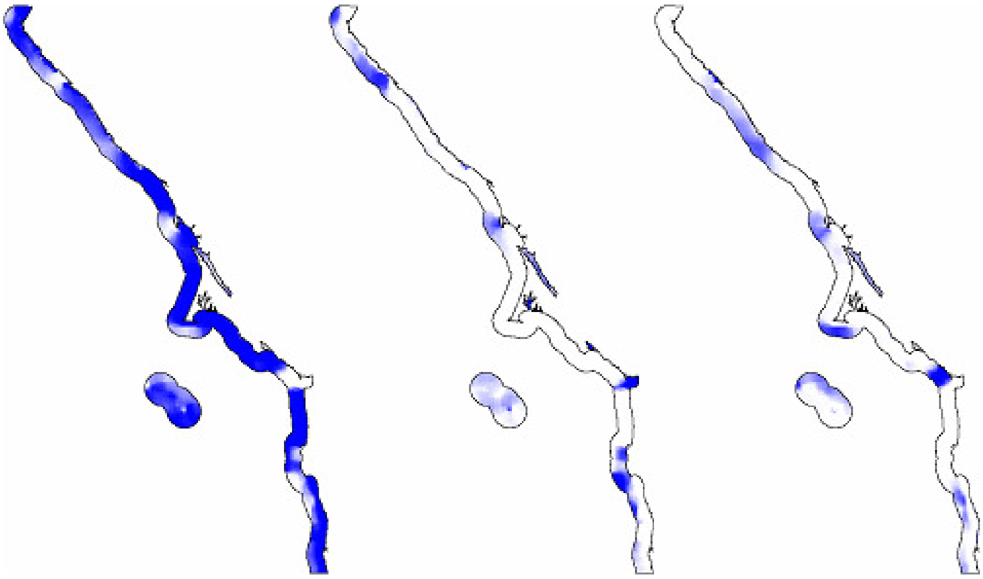


Dark blue indicates highest selection frequency, lighter shades of blue indicate lower selection frequency, and white indicates zero selection frequency.

Maps of selection frequency

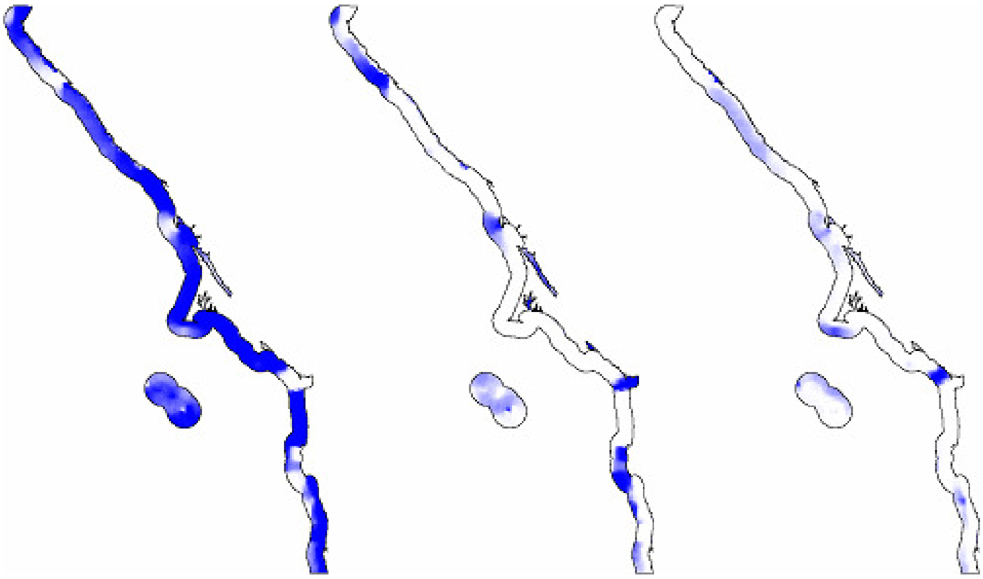
Scenario 2c

Available zone Reserve zone Conservation zone



Scenario 2d

Available zone Reserve zone Conservation zone

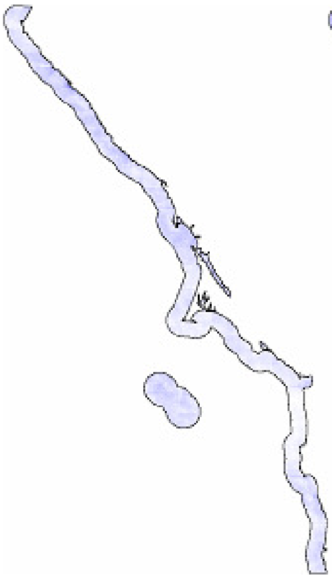


Dark blue indicates highest selection frequency, lighter shades of blue indicate lower selection frequency, and white indicates zero selection frequency.

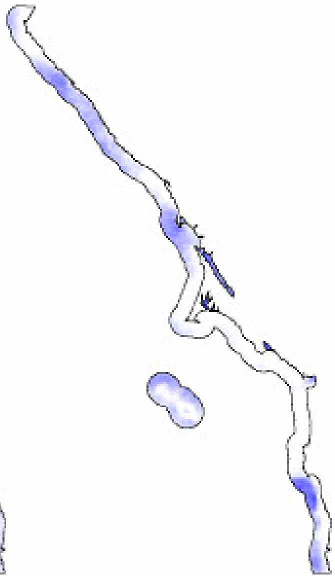
Maps of selection frequency

Scenario 3a

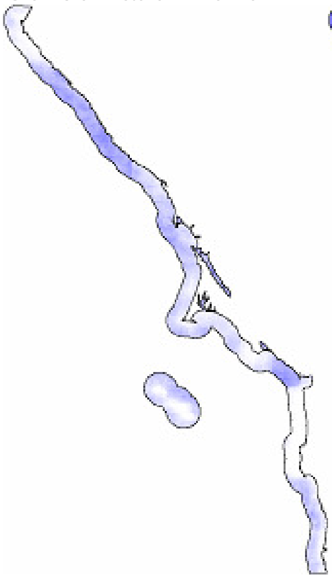
Available zone



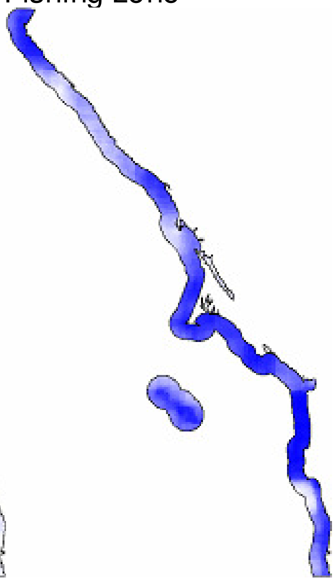
Reserve zone



Conservation zone



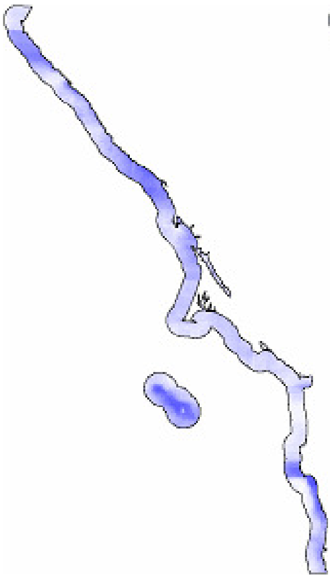
Fishing zone



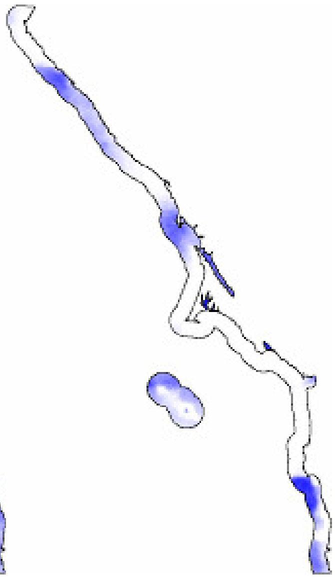
Maps of selection frequency

Scenario 3b

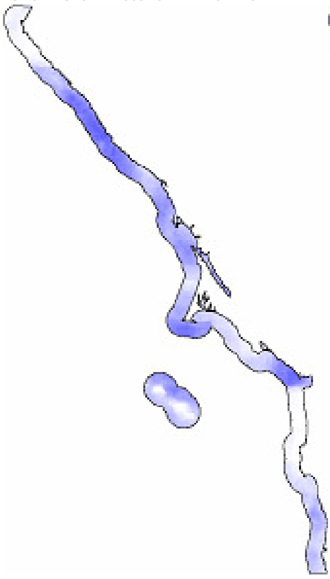
Available zone



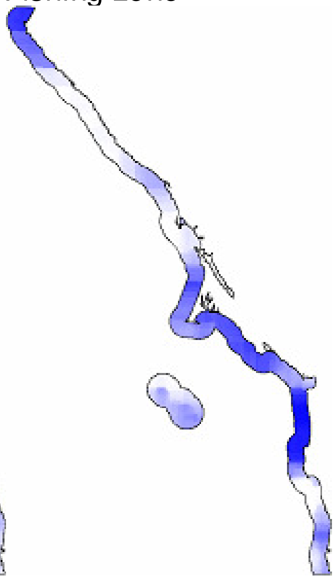
Reserve zone



Conservation zone



Fishing zone

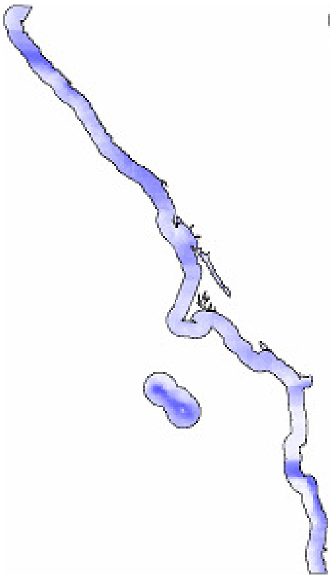


Dark blue indicates highest selection frequency, lighter shades of blue indicate lower selection frequency, and white indicates zero selection frequency.

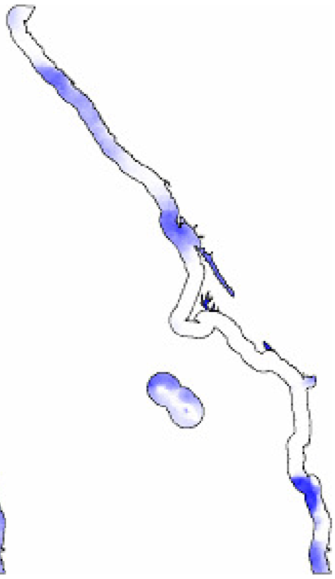
Maps of selection frequency

Scenario 3c

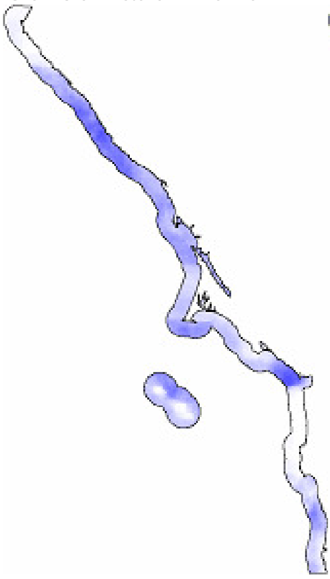
Available zone



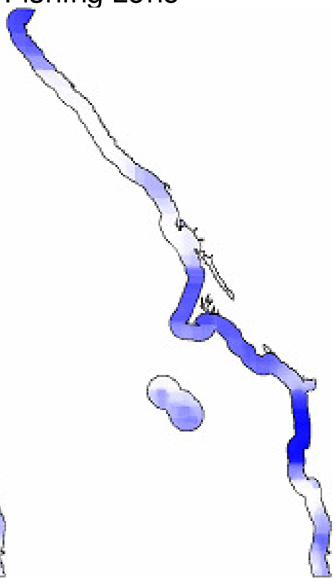
Reserve zone



Conservation zone



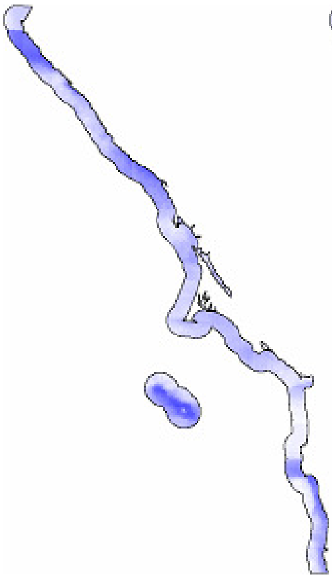
Fishing zone



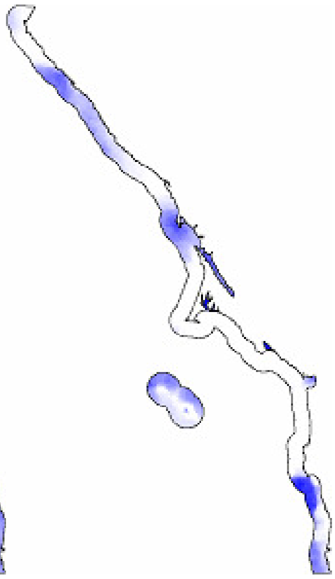
Maps of selection frequency

Scenario 3d

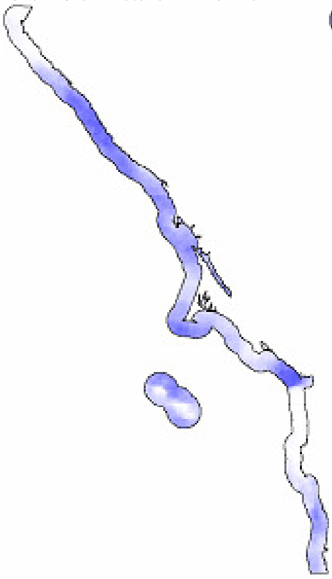
Available zone



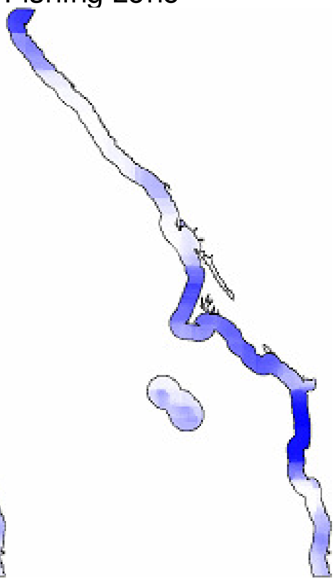
Reserve zone



Conservation zone



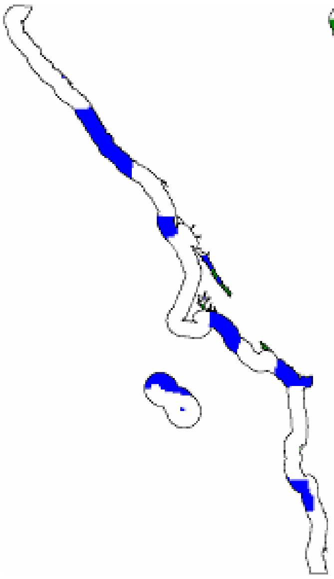
Fishing zone



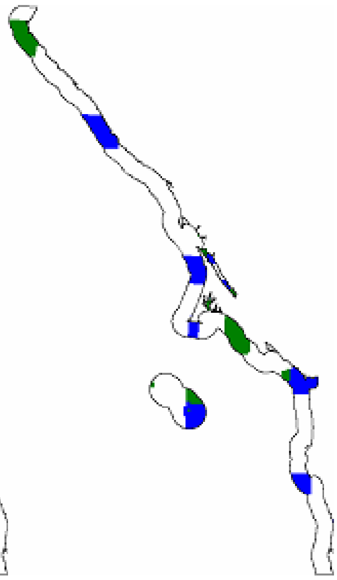
Dark blue indicates highest selection frequency, lighter shades of blue indicate lower selection frequency, and white indicates zero selection frequency.

Maps of best solutions

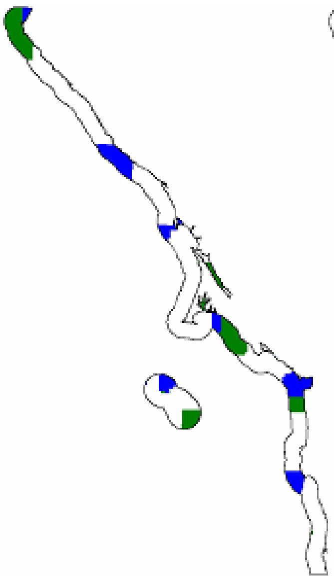
Scenario 1a



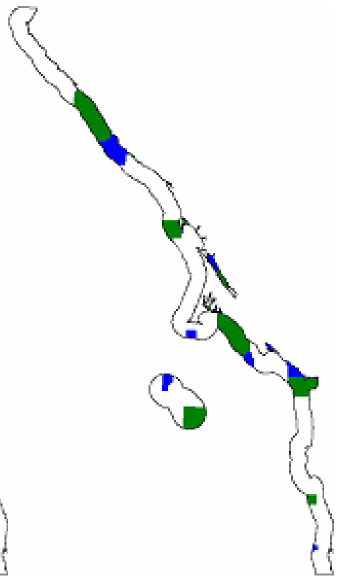
Scenario 1b



Scenario 1c



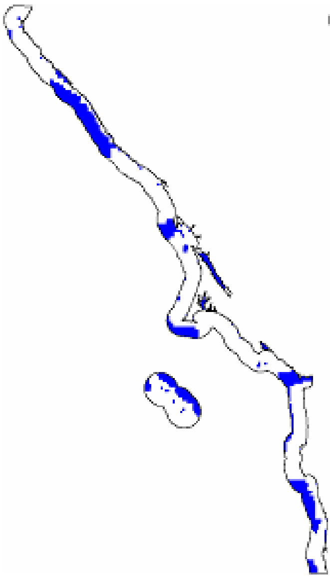
Scenario 1d



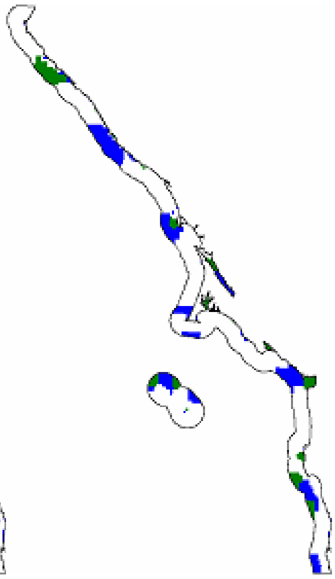
Green areas are reserve zone, blue areas are conservation zone, and white areas are available zone.

Maps of best solutions

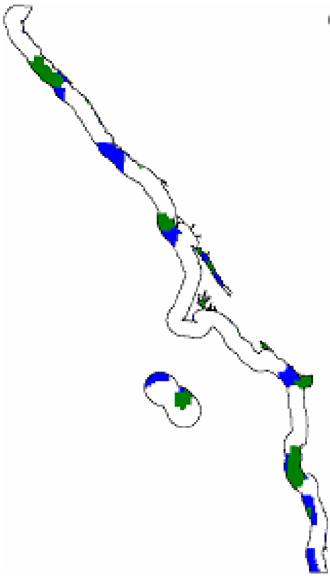
Scenario 2a



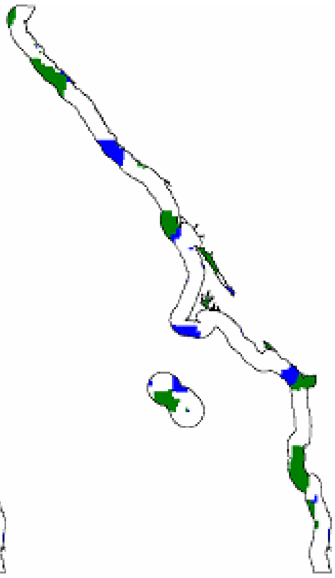
Scenario 2b



Scenario 2c



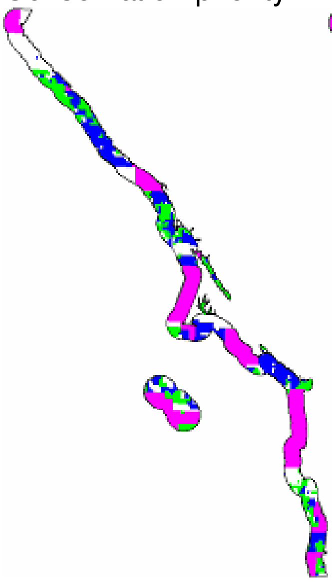
Scenario 2d



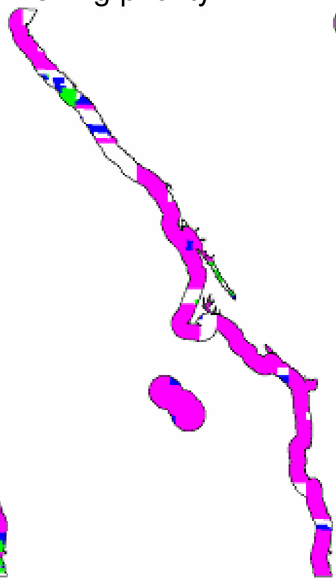
Green areas are reserve zone, blue areas are conservation zone, and white areas are available zone.

Maps of best solutions

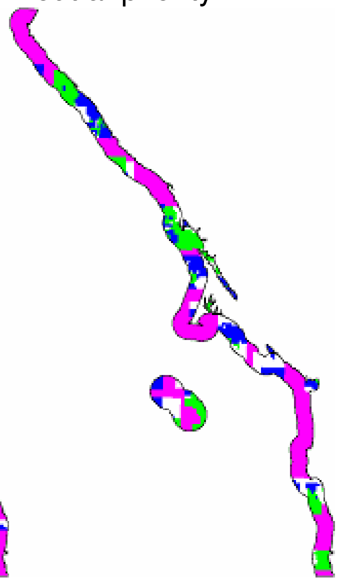
Scenario 3a
Conservation priority



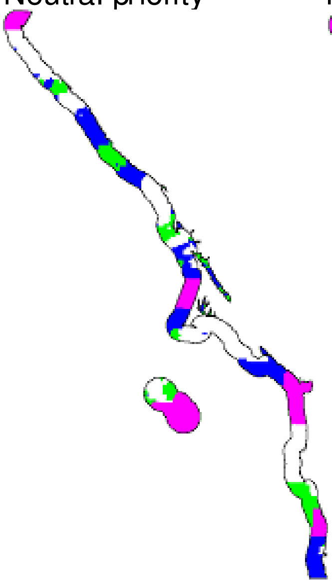
Scenario 3a
Fishing priority



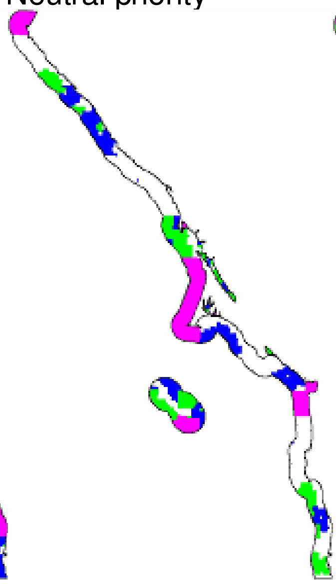
Scenario 3a
Neutral priority



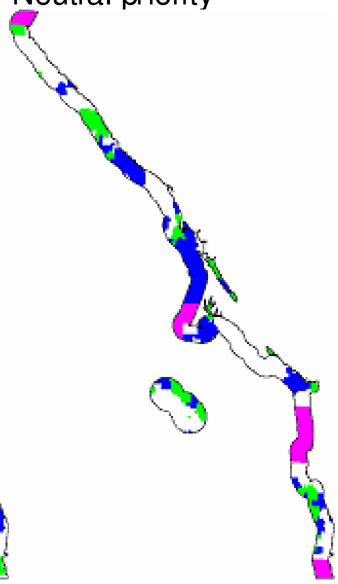
Scenario 3b
Neutral priority



Scenario 3c
Neutral priority



Scenario 3d
Neutral priority



Green areas are reserve zone, blue areas are conservation zone, pink areas are fishing zone, and white areas are available zone.

Discussion

For scenarios 1a and 2a, few planning units were placed in the reserve zone as;

- Costs for the conservation zone were lower than the reserve zone.
- Both zones had the same contribution value for conservation targets.

Efficiency dictated that the zoning was spatially allocated to planning units with the lowest cost, so only planning units with a cost equivalent to the conservation zone were allocated to the reserve zone in these scenarios.

We progressively introduced explicit targets for conservation features in the reserve zone in scenarios 1b, 2b, 1c, 2c, 1d and 2d. In these scenarios, progressively more planning units were selected in the reserve zone and progressively fewer planning units were selected in the conservation zone.

For scenario 3, target levels for conservation and fisheries features were too high for them all to be met. A higher relative penalty for fisheries features allowed their targets to be met at the expense of conservation features. A higher relative penalty for conservation features allowed their targets to be met at the expense of fisheries features. We varied the penalty values for features and examined the tradeoff relationship between conservation and fisheries.

We progressively reduced explicit targets for fishery features in the fishery zone over scenarios 3a, 3b, 3c and 3d. In these scenarios, progressively fewer planning units were selected in the fishery zone, and progressively more planning units were selected in the available, reserve, and conservation zones.

Scenario 3 illustrates the utility of Marxan with Zones for finding efficient tradeoffs for mutually exclusive goals that translate the value system of decision makers.

References

Ames, D.P. (2007). MapWinGIS Reference Manual: A function guide for the free MapWindow GIS ActiveX map component. 194 pages. Idaho State Univ., Idaho Falls, ID.

Ball, I. R. and H. P. Possingham (2000) MARXAN (V1.8.2). Marine Reserve Design Using Spatially Explicit Annealing, a Manual

Klein, C. K., M. E. Watts, R. R. Stewart, I. R. Ball, and H. P. Possingham. 2008. Marxan with Zones (V1.0.1): Conservation Zoning using Spatially Explicit Annealing, a Manual.

Klein, C.K, C. Steinback, M. Watts, A.J. Scholz, H.P. Possingham. 2009. Spatial marine zoning for fisheries and conservation: a case study from California. In Review.

Possingham, H. P., I. R. Ball and S. Andelman (2000) Mathematical methods for identifying representative reserve networks. In: S. Ferson and M. Burgman (eds) Quantitative methods for conservation biology. Springer-Verlag, New York, pp. 291-305.

Segan, D., M. Watts, L. Kircher (2009) Using the Zonae Cogito Decision Support System, a manual. University of Queensland.

Watts, M. E., H. P. Possingham, I. R. Ball, R. S. Stewart, C. J. Klein, K. Wilson, C. Steinback, R. Lourival, L. Kircher (2009) Marxan with Zones – software for optimal conservation-based land- and sea-use zoning. In Review.