Extension Note

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Marxan analyses and prioritization of conservation areas for the Central Interior Ecoregional Assessment

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Abstract

Terrestrial and freshwater priority areas for conservation were identified using Marxan software as part of the Nature Conservancy of Canada's Central Interior Ecoregional Assessment. Several different scenarios were examined for both the freshwater and terrestrial analyses. Various cost scenarios were tested, along with other Marxan settings such as boundary length modifier and species penalty factor. Climate change scenarios were also developed and compared with a base "NCC" scenario that was used to create the final conservation portfolios. The final output was a set of freshwater and terrestrial priority conservation areas. These areas will be used to guide future conservation activities.

KEYWORDS: *biodiversity; British Columbia; Central Interior Ecoregional Assessment; conservation planning; Marxan analysis; Nature Conservancy of Canada.*

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Objectives

The purpose of the ecoregional assessment analysis is to identify high conservation value areas that minimize threats to conservation and maximize ecological values. The Marxan analysis aims to achieve representation of species occurrences, ecological systems, and physical features, while also factoring in human impacts to the landscape and existing land use scenarios. This extension note describes the use of Marxan software and the post-processing of Marxan outputs to achieve final prioritized portfolios that will be used by the Nature Conservancy of Canada to help identify areas for land conservation action.

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Marxan software

Marxan is a popular conservation planning software (Ball et al. 2009) that has been used by the Nature Conservancy of Canada since 2002 to assist in the prioritization of lands for conservation purposes. Marxan offers efficient and quick solutions to complex spatial problems (Stewart et al. 2003). The software is flexible and once the initial set-up is complete, future analyses are relatively quick to execute.

Marxan selects portfolios of planning units according to targets, goals, and various software settings. Targets can be any type of spatial information, including ecological systems or species occurrences; these are the features we wish to include in our portfolios. The majority of Marxan literature refers to targets as "features." Goals are the amount of each target that is required in the solution. For example, one might set the goal for "endangered grasslands" to 30%, which means Marxan will attempt to find a final solution (portfolio) that includes 30% of the endangered grasslands found within the study area. Goals are called "targets" in Marxan literature.

Additional factors are also incorporated in the Marxan analysis. At the centre of Marxan is an objective function. This equation drives the methods by which the software chooses particular planning units. Marxan attempts to minimize the value of the function (generalized from Ball and Possingham 2000):

$$\textit{Objective function} = \textit{planning unit cost} + \textit{boundary cost} + \textit{penalty},$$

where: *planning unit cost* is a cost assigned to each unit based on area, economic, or social cost, or any combination of these (see "Cost" section below); *boundary cost* is the sum of the boundary length modifier multiplied by the planning units' boundaries—adjacent units have a smaller boundary length, so a higher boundary length modifier will result in less fragmented solutions (see "Boundary files" section below); and *penalties* are added to the objective function if goals are not met (see "Species penalty factor" section below).

Marxan uses a heuristic algorithm called "simulated annealing" that achieves near-optimal results in much less time than would be required by optimization algorithms (Angelis and Stamatellos 2004). Because of the random element in the algorithm, each run (also known as a "restart") results in a slightly different solution (Lieberknecht et al. 2004). For this reason, the algorithm is run repeatedly with a high number of iterations in an effort to best meet goals and minimize the objective function.

A Marxan analysis produces two basic outputs: (1) the summed solution and (2) the best solution. The best solution includes only the planning units selected in the run that had the lowest overall objective function cost. Marxan's random element can result in a different "best" solution with every restart of the software depending on the complexity of the problem.

The summed solution is a count of the number of times planning units are included in the solutions that result from each run of the software. For example, if Marxan were set to complete 500 runs, each planning unit would have a summed solution value between 0 (included in no runs) and 500 (included in all runs). The summed solution takes into account the variations in possible outputs (due to the randomness of the software) and can be used to identify hotspots for conservation and also to evaluate the relative value of planning units.

Marxan inputs

Planning units

Planning units are the basis for Marxan analyses. These area-based polygons are non-overlapping and cover the entire study area. They can be any shape or size based on natural, administrative, or arbitrary features; however, the size and shape of planning units can have an effect on the Marxan model output (Pressey and Logan 1998).

Considerable debate exists in the literature (and among terrestrial and freshwater specialists) regarding the most appropriate planning unit for Marxan; the decision of which analysis units to use involves trade-offs (Loos 2006). Grids or hexagons have the advantage of consistent size, which helps to avoid area-related bias. Natural planning units (such as watersheds) are more likely to represent ecological systems or landscape patterns; however, larger units may contain more occurrences, which could bias selection if the analysis is not properly calibrated.

For the terrestrial analysis, a hexagonal grid of 500-ha planning units was created. Hexagons were used because their shape approximates a circle, which has a low edge-to-area ratio (Miller et al. 2003). Hexagons provide a relatively smooth output and they have a smaller perimeter-to-area ratio than squares of the same area (Warman et al. 2004). The size of planning units should be related to the scale at which the outputs will be used (Smith et al. 2009). The 500 ha size is small enough for the efficient representation of local-scale targets in small functional sites while allowing for the aggregation of ecological systems into extensive landscape-scale conservation areas (Neely et al. 2001). The terrestrial study area was divided into two subareas, Central Interior and Sub-Boreal Interior, based on British Columbia Ministry of Environment ecoprovinces (Demarchi 1996). The Central Interior subarea contains 22 942 planning units and the Sub-Boreal Interior subarea contains 28 709 planning units. Each subarea was analyzed separately in Marxan to ensure representative selection of targets across the study area.

For the freshwater analysis, third-order (1:50 000) watersheds were used as planning units. This helped ensure that entire freshwater systems and associated ecosystem processes were included in outputs (Klein et al. 2009). The freshwater study area was divided into nine subareas based on ecological drainage units as classified by Ciruna et al. (2007) (see Map 11 from Nature Conservancy of Canada, 2010), which were each analyzed separately in Marxan. Table 1 lists the number of planning units within each ecological drainage unit. The size of the watersheds range from 26 to 255 529 ha.

Cost

The planning unit cost used for the ecoregional assessment is a measure of human impact on the landscape and threat to conservation. It provides a value for the suitability of an area for conservation, and is referred to as the "suitability index." Higher suitability index values result from greater human impacts on the landscape. Inaccessible wilderness areas, for example, would have a very low value.

Many factors could be incorporated into the suitability index including urban growth models, resource extraction activities, and environmental threats; however, Marxan cost inputs should ideally be kept as simple as possible (Ardron et al. [editors] 2010). In an effort to keep the number of different factors to a minimum, only one was used for the terrestrial cost: distance to and density of roads. This is a good overall measure of human presence (Saunders et al. 2002) since most human activities require roads, including urbanization, forestry, and mining. See Map 13 (Terrestrial Suitability Index) from Nature Conservancy of Canada, 2010.

The freshwater suitability index cost was tailored to the human impacts affecting freshwater systems (i.e., the amount of water licensed for extraction, number of barriers to fish passage, and number of stream road crossings). Unlike the road density used for the terrestrial analysis, one overarching layer could not be used to summarize human impacts on freshwater. The three factors were combined into one value, which was

TABLE 1. Planning units per ecological drainage unit

Ecological drainage unit	Number of planning units (watersheds)	Area (km²)
Homathko–Klinaklini	101	11 629
Bella Coola–Dean	182	12 922
Upper Fraser	471	27 694
Upper Nass	614	15 308
Upper Skeena	913	40 437
Thompson	917	55 827
Iskut–Lower Stikine	934	22 885
Upper Peace	1203	72 083
Middle Fraser	1962	128 503

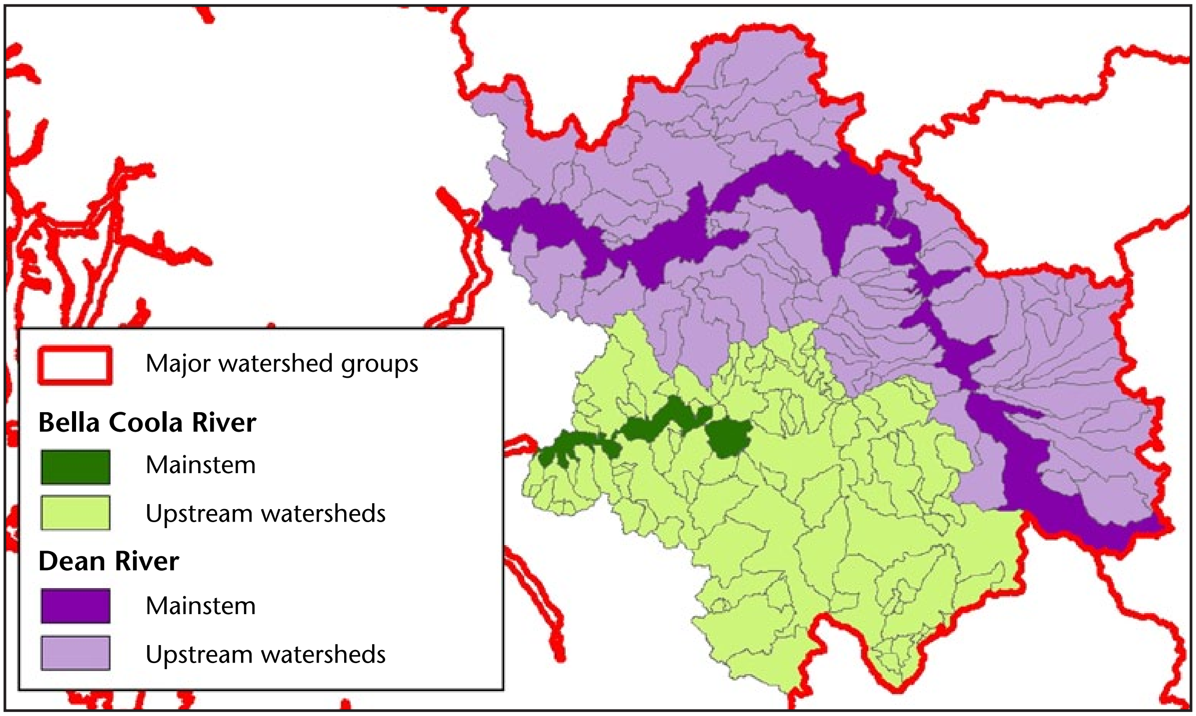

FIGURE 1. Illustration of the vertical stacking method of building the boundary file. Watersheds were grouped according to mainstem river drainages rather than adjacency.

used as the freshwater cost (regardless of the number of factors incorporated in the suitability index, only one cost value is assigned to each planning unit). See Map 14 (Freshwater Suitability Index) from Nature Conservancy of Canada, 2010.

Boundary files

Each planning unit shares a boundary length with every adjacent unit. The default value for the boundary length is the length of the common side. Marxan keeps track of the boundary length of a solution by adding up the length of the shared boundary between all selected planning units. This summed boundary is multiplied by the boundary length modifier, so one of the objectives of Marxan (if a boundary length modifier is used) is to minimize overall boundary length.

For the terrestrial portion of this project, the boundary length was altered based on the land management status of adjacent units. The value of the shared boundary of a unit adjacent to a protected unit was decreased, whereas a boundary adjacent to an urban area was increased. This allows the management status of up to six adjacent planning units to be factored into the overall cost of including a given planning unit in the solution. Because Marxan attempts to minimize boundary length, planning units with lower boundary values (i.e., more conservation-friendly land management) will tend to be selected over higher cost ones.

The freshwater boundary length was also altered but to only include upstream and downstream connections between watersheds. Marxan has no spatial awareness; the only connectivity information is provided through the boundary length value. With a traditional boundary file, all adjacent planning units are considered connected. The freshwater planning units present a unique boundary problem because adjacent watersheds are not necessarily connected. The freshwater boundary file was altered to include boundaries only between watersheds that are hydrologically connected, not simply adjacent. This is based on a method called "vertical stacking" developed by The Nature Conservancy.[1] Figure 1 shows how watersheds were separated and assigned connectivity in the boundary file according to mainstem river groupings.

[1] Schindel, M. 2004. Optimization and integration of conservation targets with SITES. The Nature Conservancy, Portland, Oreg. Unpublished report.

Targets

Targets fall into two classes: (1) fine filter and (2) coarse filter. Fine-filter targets are known species occurrences and habitats, whereas coarse-filter targets are ecosystem- and biogeoclimatic-based and typically cover the full study area. Depending on the size of the study area, fine-filter targets are often incomplete; it is unlikely that every occurrence or population of a particular species has been documented. Coarse-filter data act as a proxy and fill in the fine-filter gaps. By setting coarse-filter goals to include a representative selection of habitats, a cross-section of fine-filter species is also captured, even if individual occurrences have not yet been recorded (Evans 2003; Rumsey et al. 2004). Including a range of habitat types and ecosystems as coarse-filter targets adds robustness to the output.

Fine-filter targets include plant and animal occurrences and range information collected from the British Columbia Conservation Data Centre, the B.C. Ministry of Environment, the Royal British Columbia Museum, and federal Department of Fisheries and Oceans. Over 200 fine-filter targets were included in the analyses. Coarse-filter targets include ecological land units (59 classes), terrestrial systems (30 classes), and freshwater systems (22 classes). Target goals were set through discussions with experts and the freshwater and terrestrial teams. The teams also vetted data based on age, relevance, and quality. The data used for the Central Interior Ecoregional Assessment are discussed in more detail in other articles of this issue: freshwater fine- and coarse-filter targets are discussed in Howard and Carver (2011:72–87); fine-filter terrestrial targets are discussed in Horn (2011:36–53); and coarse-filter terrestrial targets are discussed in Kittel et al. (2011a:54–71).

Marxan settings

Boundary length modifier testing

The ideal boundary length modifier is one that avoids a fragmented solution but also does not overly increase the size of the solution (Possingham et al. 2000). Such measures are subjective and depend largely on the purpose of the analysis (Loos 2006). Visual inspection of outputs is part of the process of determining the boundary length modifier, but a simple graphing exercise can help determine a starting point for refinement (Ardron et al. [editors] 2010).

First Marxan is run through several different boundary length modifier values, then the cost and (or) solution area is plotted against boundary length. The point just before where the solution area or cost increases dramatically is the ideal boundary length modifier (Ardron et al. [editors] 2010). Figure 2

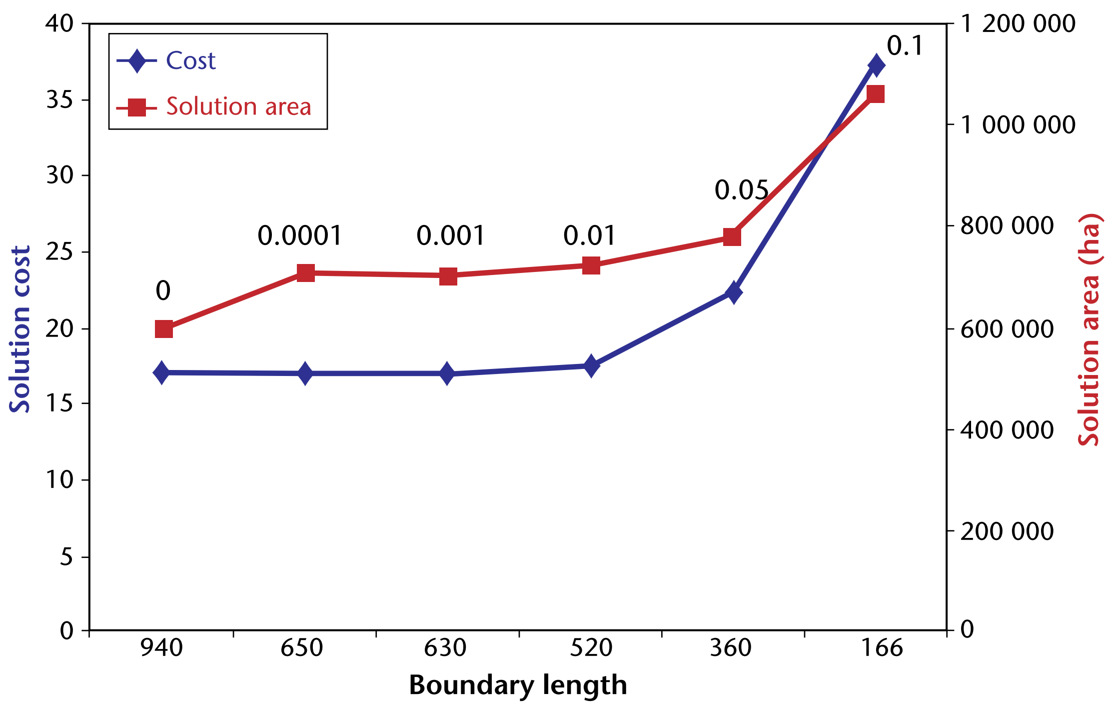

FIGURE 2. Bella Coola–Dean boundary length modifier testing (values range between 0 and 0.1).

shows the boundary length modifier testing graph that was constructed for the Bella Coola–Dean ecological drainage unit. The cost and solution area are relatively stable until the modifier reaches 0.1, at which point a large incremental increase in cost occurs. The modifier that decreases boundary length without a huge increase in cost is 0.05, which was used for the final Marxan runs. Similar testing was done for each of the ecological drainage units and terrestrial sub-areas.

Different boundary length modifier values were used for most of the freshwater analysis areas (ecological drainage units). This is attributed to differences in size and number of planning units between the nine units. The terrestrial boundary length modifiers for the two analysis areas were identical as no variation in planning unit size was detected and the number of planning units is similar.

Some fragmentation is apparent in the final outputs (best solutions) of both the terrestrial and freshwater analyses (see Maps 17 and 20, respectively, from Nature Conservancy of Canada, 2010). Boundary length modifiers were not set to remove all fragmentation from the solutions but rather to minimize it while still allowing the distribution of data and hotspots to appear. Some studies use intentionally lower modifier values to develop solutions that are not overly clustered, thus offering more freedom for planners when decisions are made (Meerman 2005). Another reason for using lower boundary length modifier values is that although solutions are more fragmented, hotspots are more apparent (Rumsey et al. 2004).

Species penalty factor

The species penalty factor controls the magnitude of the penalty that is added to the objective function if a target is not met. Thus, the larger the species penalty factor, the higher is the likelihood that the solution will include a target. Species penalty factors cannot simply be set to a high value for all targets, as this can adversely affect outputs (Ardron et al. [editors] 2010). Values were set according to methods outlined in the Marxan Good Practices Handbook (Ardron et al. [editors] 2010). All species penalty factor values were set to a very low value and Marxan was run. Any targets whose goal was not met had their species penalty factor value increased and then the software was run again. This process continued until all targets' goals were met.

Other settings

Marxan was put through 500 runs with a million iterations for each analysis. Larger numbers of iterations were tested; however, these did not result in more efficient solutions and all goals were met at one million. The software was set to use the simulated annealing algorithm with iterative improvement, which is the setting most commonly used by Marxan users (Ardron et al. [editors] 2010). All other settings were left at default values.

Scenarios

Nature Conservancy of Canada ("NCC" scenario)

Marxan runs were set up using goals determined by the freshwater and terrestrial teams. The NCC scenario runs included all fine- and coarse-filter data and were used to develop the final portfolios. Also included in the terrestrial analysis were ecosystem services targets for sportfishing and carbon storage (Chan et al. 2011). For full details on targets and goals that were used for the NCC runs, see: Kittel et al. (2011b:7–35); Horn (2011:36–53); Kittel et al. (2011a:54–71); Howard and Carver (2011:72–87); and Chan et al. (2011:98–100). One scenario was run for each subregion and all goals were met in all of the runs.

Climate change

Climate change scenario runs were set up to examine how Marxan solutions would change if species' goals were altered to account for potential changes in climate. Only a handful of species' goals were changed for the freshwater and terrestrial runs. In most cases, the goals were increased to account for climate uncertainty. For more information on the climate change scenario maps, see the Central Interior Ecoregional Assessment map volume (Nature Conservancy of Canada 2010).

Irreplaceability

Irreplaceability is a measure of how important a planning unit is for achieving goals. It is one of the inputs for prioritizing the Nature Conservancy of Canada portfolio. Alternative methods for calculating irreplaceability exist, and the version calculated for the Central Interior Ecoregional Assessment should not be confused with other methods, such as the one available through C-Plan software (Pressey et al. 2005).

Marxan was run without the suitability index as the cost. Instead, a flat cost was applied to each planning unit, and thus only the presence or absence of species influenced planning unit selection. Target goals were set to incremental values and Marxan was run for each (5%, 10%, 20%, 30%, 40%, and 50%). The summed solutions for the six runs were averaged for a final irreplaceability score.

The ability to quantify the relative relationship of conservation value and vulnerability provides a basis for strategic planning and fosters debate on conservation needs.

Portfolio prioritization

The Marxan best solution output was used to create final conservation portfolios for the freshwater and terrestrial analyses. This is the NCC scenario run that best minimized the objective function.

The best solution was first examined by experts to determine whether additional areas were required in the solution. These are areas that are known anecdotally to have special value or that add connectivity between selected planning units. These areas were manually added to the best solution, and then the best solution and newly added planning units were grouped together into priority conservation areas. Adding additional planning units reduces the efficiency of the Marxan solutions; however, it addresses data deficiencies and adds connectivity. The priority areas were assigned names and unique identifiers, and were then ranked on the basis of conservation value and vulnerability. A description of conservation value and vulnerability are provided below; the methods used are based on the Canadian Rockies Ecoregional Assessment (see Wood et al. 2004).

Conservation value

Conservation value is a measure of target abundance, uniqueness, and value. The equation for calculating conservation value includes four factors:

$$\textit{Conservation value} = \textit{diversity} + \textit{rarity} + \textit{richness} + \textit{irreplaceability}$$

where: *diversity* is the number of different fine-filter target types per planning unit divided by the total number of different types in the Marxan analysis area (types include fish, birds, insects, etc.); *rarity* is the average of Global Rank (GRANK) values for fine-filter targets within a planning unit (targets were assigned a value of 1 for a GRANK of 1, 0.75 for a GRANK of 2, and 0.5 for GRANKs of 3 and lower); *richness* is the number of different fine-filter targets per planning unit divided by the total number of different targets in the Marxan analysis area; and *irreplaceability* is the average of the summed solution output that did not include suitability index for the incremental runs between 5–50%.

The four factors were each scaled between 0 and 1 and summed together. To get the conservation value for the priority conservation areas, the values of individual planning units were averaged.

Vulnerability

Vulnerability is the suitability index (cost) of planning units. It is essentially a measure of threats to conservation. To get the vulnerability value for the priority conservation areas, the cost values of individual planning units were averaged.

Prioritization of conservation areas

The conservation value and vulnerability values were each divided into quartiles based on area. These were plotted against each other to give a final prioritization value for each priority conservation area (Figure 3). For the final priority conservation areas map, see the Central Interior Ecoregional Assessment map volume (Nature Conservancy of Canada 2010).

Conclusion

All of the outputs from the different analyses outlined above have value for conservation planning. To make the ecoregional assessment results easier to use (which is especially important when faced with such a large study area), a set of priority conservation areas was developed and ranked. For planners working at an ecoregional scale, the prioritization process allows potential conservation sites to be clearly sorted according to factors that are important for biodiversity value as well as those that pose threats. The measures of value and vulnerability are composed of the relative importance and confidence weightings applied to the various factors. The ability

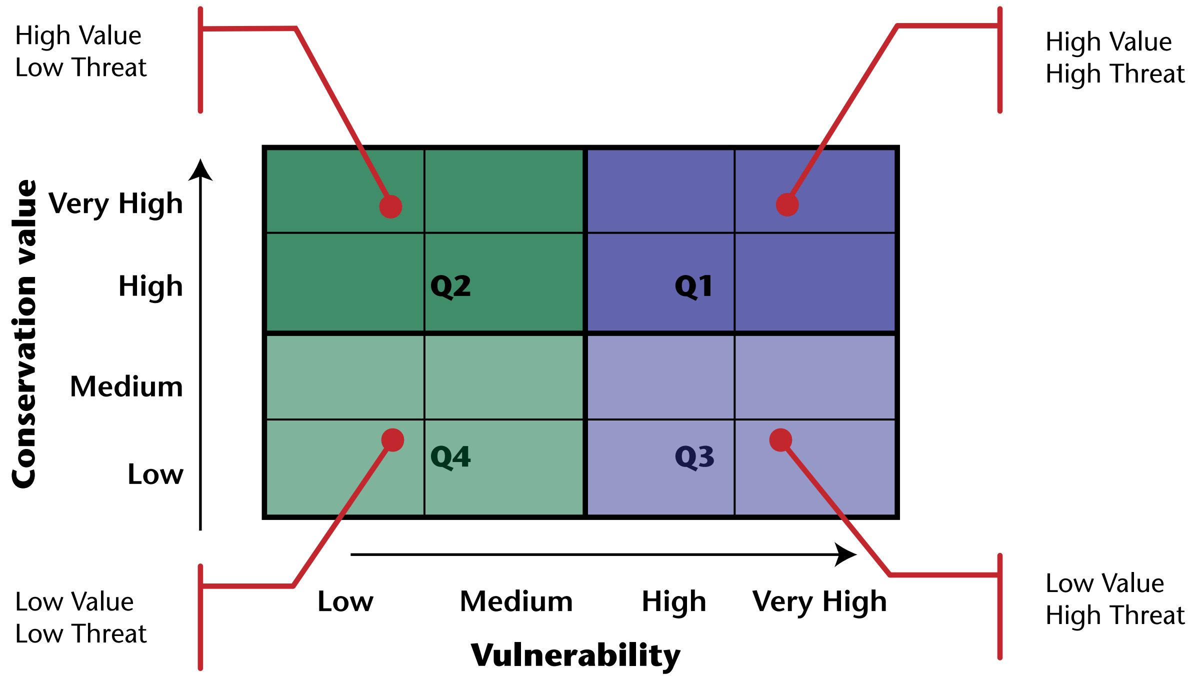

FIGURE 3. Relative conservation value and vulnerability scores (modified from Iachetti et al. 2006).

to quantify the relative relationship of conservation value and vulnerability provides a basis for strategic planning and fosters debate on conservation needs.

The analyses presented here were done at a coarse scale and are meant as a starting point for conservation actions. Closer examination and ground-truthing will be needed for actual site-specific decision making. The Nature Conservancy of Canada will use the priority conservation areas in the preliminary evaluation of potential land conservation projects and as a starting point for finer-scaled conservation planning.

The results are freely available to other organizations and outside use is encouraged. Spatial results are available through the online decision support tool Hectares BC (*http://www.hectaresbc.org*), which provides quantitative analysis and display of a wide range of data across British Columbia.

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Test Your Knowledge . . .

Marxan analyses and prioritization of conservation areas for the Central Interior Ecoregional Assessment

How well can you recall some of the main messages in the preceding Extension Note? Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. The suitability index is a measure of:
   A) The range of conservation values across the landscape
   B) How well a Marxan solution meets conservation goals
   C) Human impacts and threats to conservation on the landscape

2. Marxan software was used for this analysis because:
   A) It is the only option available
   B) It provides near-optimal solutions to complex problems while meeting multiple decision criteria
   C) It allows one to achieve optimal solutions and there is no randomness in the outputs

3. The final conservation portfolio is a combination of:
   A) The Marxan summed solution and expert input
   B) The Marxan best solution and expert input
   C) The Marxan best and summed solutions

ANSWERS

1. C 2. B 3. B