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# Evaluation of Site Selection Methodologies For Use In Marine Protected Area Network Design

# Évaluation des méthodes de choix de sites pour la conception du réseau de zones de protection marines

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## *EXECUTIVE SUMMARY*

This report identifies and compares different methodologies used for the selection of (candidate) marine protected areas (mpas[1]), termed areas of interest (AOIs). It is hoped that this will provide DFO with the necessary information to evaluate which selection methodology would be most effective in furthering it's mpa objectives within the IM framework.

Choosing the most appropriate methodology depends on the underlying goal for establishing the set of marine protected areas. Clearly defining the purpose and the overall conservation goal is an important first step that must not be overlooked.

There are two main approaches to selecting AOIs; scoring/weighting (non-systematic) and systematic.

Scoring methods assign a rank of relative importance to all sites based on some user-defined criteria and then add those sites with the highest rank to an existing reserve. The product from this type of reserve site selection is not able to identify how each site relates to the others in the system beyond it's 'score' which is not indicative of what is being captured by the sites. While the objective nature of a scoring selection process is preferred to subjective or opportunistic decision-making, it is not very rigorous, it is not able to efficiently select a set of complementary sites and does not have the spatial capacity to create a network.

Systematic methods of reserve selection make use of algorithm-based decision support tools. Systematic selection of mpas is based on the concept of 'complementarity' in which new sites contain features that are not currently captured in the reserve system and thus augment the overall diversity and representivity of the system. Of the systematic methods there are 4 main types of algorithms used; integer linear programming (ILP), simple iterative algorithms (heuristics), iterative simulated annealing and explicitly spatial population based models.

The advantage of the ILP methodology over other complementarity methods is its ability to find an optimal solution. However, if there are too many constraints or the problem is too complex (non-linear) this method will often fail to produce a solution. Thus it is best applied when there are only a few constraints to be optimised.

Heuristics are much faster than the ILP methods, but may arrive at a solution which is considerably less efficient than the theoretical minimum. These programs can manage conservation problems comprised of large datasets and several constraints. In some cases spatial constraints can be incorporated into the method via additional programming.

The simulated annealing method is considered superior to the other methodologies for selecting priority areas for conservation reviewed here. This algorithm can produce multiple solutions for a given scenario unlike heuristics which only provide one solution. It can produce more efficient solutions compared to heuristics in terms of minimising total area needed to meet the desired conservation objectives. There is a random component of this algorithm that allows for the search of the 'global minima'.

[1] There is a distinction between upper case MPAs and lower case mpas. MPA refers to those protected areas formally designated by DFO while the term 'mpa' is an umbrella term that encompasses all protected areas including the formally designated MPAs, fishery closed areas, National Marine Conservation Areas, Marine Wildlife Areas and Provincial Marine Parks.

The last systematic method reviewed in this paper, explicitly spatial programs, specifically addresses the issue of species persistence through the application of environmental variable models (those which influence the distribution of biodiversity) or metapopulation models that will direct the selection of a 'connected' set of sites. These programs can only select sites for a limited number of species and require detailed data sets regarding either environmental parameters or species population dynamics. Thus, they are often most appropriately applied at smaller scales for which this type of data exists, or as a post-selection tool (see section 3.3) to choose among candidate sites in the development of a network that ensures a particular species persistence.

This report also reviewed two case specific applications of the systematic algorithms to identify priority areas for conservation currently being used in Canada. These projects, by Living Oceans Society and World Wildlife Fund Canada are highlighted with regard to their potential applicability to DFO.

Upon review of the methodologies we recommend that DFO consider the use of a site selection methodology in its IM program. From our analysis we concluded that MARXAN (a software package which employs simulated annealing) would be the most appropriate tool to assist DFO in furthering its mandate and MPA objectives under the Oceans Act.

Other recommendations include;

- multi-scale planning in MPA network design;
- perform analyses with multiple MPA objectives and datasets
- determine if MPA networks created using multiple agency mandates requires less area than performing the analyses separately specific for each agency
- understand the usefulness of the various frameworks and approaches to applying MARXAN, especially those ongoing in Canada;
- current selection analyses in Canada can provide DFO with compiled data and information on lessons learned in applying MARXAN and developing ecological planning frameworks for both coasts
- facilitate further analyses of ecological attributes for cells need to be defined in terms of parameters reflective of criteria used by different agencies to rationalise their mandates to establish mpas;
- a need, and role for DFO to undertake a pilot selection analysis within the Strait of Georgia;

Although spatial optimisation offers a powerful solution to MPA network design and while these programs make a contribution to improving rigour, transparency and efficiency of what is a complex process, they only contribute to part of the process. Other decision support tools (such as GIS and Delphic approaches – see Lewis et al. 2003) may need to be employed when fine-tuning boundaries, developing zoning plans, or when choosing among candidate sites that are of interest to several stakeholder groups.

## SOMMAIRE EXÉCUTIF

Le présent rapport identifie et compare les diverses méthodes utilisées pour choisir des sites candidats à l'appellation de zone de protection marine (ZPM), appelée zone d'intérêt (ZI). L'intention est de fournir au MPO les renseignements nécessaires pour déterminer quelle méthode serait la plus efficace pour ce qui est de faire avancer ses objectifs en matière de ZPM au titre du cadre de gestion intégrée.

Le choix de la méthode la plus appropriée dépend de l'objectif sous-jacent de créer un réseau de ZPM. La définition claire de cet objectif et de l'objectif de conservation général est une importante première étape qui ne doit pas être ignorée.

Il existe deux principales méthodes pour choisir les ZI : la méthode non systématique (notation/pondération) et la méthode systématique.

Les méthodes de notation attribuent un rang d'importance relative à tous les sites reposant sur les critères définis par l'utilisateur, puis ajoutent les sites de rang élevé à une réserve existante. Le produit de ce type de choix de sites de réserve ne permet pas d'établir un lien entre les sites autre que sa « cote », qui n'est pas indicative de ce qu'ils ont à offrir. Bien que la nature objective d'un processus de choix par notation soit préférable à la prise de décision subjective ou opportuniste, ce processus n'est pas très rigoureux, est incapable de choisir efficacement un ensemble de sites complémentaires et n'a pas la capacité spatiale de créer un réseau.

Les méthodes systématiques de choix de sites de réserve font appel à des outils d'aide à la décision reposant sur des algorithmes. Le choix systématique de ZPM repose sur le concept de « complémentarité », selon lequel les nouveaux sites possèdent des caractéristiques qui ne sont pas représentées à ce moment-là dans la réserve et ajoutent donc à la diversité et à la représentativité globales du réseau. Parmi les méthodes systématiques, quatre principaux types d'algorithmes sont utilisés, soit la programmation linéaire en nombres entiers, les algorithmes itératifs simples (heuristique), les algorithmes itératifs du recuit simulé et les modèles spatiaux de population.

L'avantage de la méthode de la programmation linéaire en nombres entiers par rapport aux autres méthodes de complémentarité vient de sa capacité de trouver une solution optimale. Toutefois, s'il existe trop de contraintes ou que le problème est trop complexe (non linéaire), elle ne produira souvent pas de solution. Il est donc mieux de l'appliquer que lorsqu'il n'y a que quelques contraintes à optimiser.

Les algorithmes itératifs simples (heuristique) sont beaucoup plus rapides que la programmation linéaire en nombres entiers, mais peuvent donner une solution qui est considérablement moins efficace que le minimum théorique. Cette méthode permet de tenir compte de problèmes de conservation consistant en de vastes ensembles de données et plusieurs contraintes. Dans certains cas, les contraintes spatiales peuvent y être incluses par le biais d'une programmation additionnelle.

La méthode de l'algorithme itératif du recuit simulé est considérée comme supérieure aux autres pour ce qui est d'identifier les zones prioritaires aux fins de conservation. Cet algorithme peut donner des solutions multiples à un scénario donné, au contraire de l'heuristique, qui ne donne qu'une solution. Il peut donner des solutions plus efficaces en comparaison de l'heuristique pour ce qui est de minimiser la superficie totale requise pour satisfaire aux objectifs de conservation visés. Un élément aléatoire de cet algorithme permet de rechercher le « minimum absolu ».

La dernière méthode systématique évaluée dans ce document, soit les modèles spatiaux de population, abordent nommément la question de la persistance des espèces par l'application de modèles de variables environnementales (celles qui ont une incidence sur la distribution de la biodiversité) ou de modèles de métapopulation qui orienteront le choix d'une série de sites « enchaînés ». Ces programmes ne permettent de choisir des sites que pour un nombre limité d'espèces et requièrent des ensembles de données détaillées sur les paramètres environnementaux ou la dynamique des populations des espèces. Il est donc souvent plus approprié de les appliquer à des échelles plus petites que celles pour lesquelles ce type de données existent ou comme outil pour choisir, parmi les sites identifiés comme candidats (voir la section 3.3), ceux qui permettront de créer un réseau qui assure la persistance d'une espèce particulière.

Ce rapport passe aussi en revue deux applications des méthodes systématiques à des cas particuliers en vue d'identifier des zones prioritaires aux fins de conservation actuellement utilisées au Canada. Ces projets, menés par la Living Oceans Society et le Fonds mondial pour la nature (Canada) sont mis en lumière pour ce qui est de leur applicabilité potentielle au MPO.

Après examen des méthodes, nous recommandons que le MPO considère d'utiliser une méthode de choix de sites dans le cadre de son programme de gestion intégrée. D'après notre analyse, nous concluons que MARXAN (un progiciel reposant sur le recuit simulé) est l'outil le plus approprié qui permettra au MPO de mettre en oeuvre son mandat et ses objectifs en matière de ZPM en vertu de la *Loi sur les océans*.

Parmi les autres recommandations formulées s'inscrivent les suivantes :

- planifier la conception du réseau de ZPM à des échelles multiples;
- faire des analyses reposant sur des objectifs et des ensembles de données multiples en matière de ZPM;
- établir si la superficie des réseaux de ZPM créés en vertu de mandats d'organismes multiples est moindre que lorsque les analyses sont effectuées pour chacun des organismes concernés;
- comprendre l'utilité des divers cadres et approches pour appliquer Marxan, en particulier ceux appliqués à l'heure actuelle au Canada;
- le MPO devrait utiliser les données et les renseignements recueillis sur les leçons tirées dans l'application de MARXAN et l'élaboration de cadres de planification écologique pour les deux côtes.
- faciliter d'autres analyses des attributs écologiques des cellules en terme des paramètres qui reflètent les critères utilisés par différents organismes pour rationaliser leur mandat au titre de la création de ZPM.
- Le Ministère devrait aussi entreprendre une analyse pilote de sites dans le détroit de Georgia.

Bien que l'optimisation spatiale constitue une solution puissante pour la conception d'un réseau de ZPM et que ces programmes contribuent à améliorer la rigueur, la transparence et l'efficience de ce processus complexe, ils n'y contribuent qu'en partie. D'autres outils d'aide à la décision (voir les méthodes SIG et Delphic – Lewis *et al.*, 2003) devront peut-être être utilisés pour établir avec précision les limites des ZPM, élaborer des plans de zonage ou choisir parmi les sites candidats les lieux qui sauront intéresser plusieurs groupes d'intervenants.

# *TABLE OF CONTENTS*


**EXECUTIVE SUMMARY ........ I**

**SOMMAIRE EXÉCUTIF ........ III**

**TABLE OF CONTENTS ........ V**

**1 BACKGROUND ........ 1**

1.1 FISHERIES AND OCEANS CANADA'S ROLE IN MARINE CONSERVATION ........ 1
1.2 DEVELOPING A NETWORK OF MARINE PROTECTED AREAS IN CANADA ........ 1
1.3 DEVELOPING A NETWORK IN CANADA ........ 3
1.4 CONCERNS WITH SCALE AND DATA IN NATURAL RESOURCE MANAGEMENT PLANNING ........ 4
*1.4.1 Scale ........ 4*
*1.4.2 Data issues in conservation management planning ........ 5*

**2 PURPOSE OF THIS PAPER ........ 5**

**3 AN OVERVIEW OF RESERVE SELECTION METHODOLOGIES ........ 6**

3.1 SCORING METHODS ........ 6
*3.1.1 Examples of programs ........ 7*
3.2 COMPLEMENTARITY METHODS ........ 8
*3.2.1 Exact Optimisation Methods ........ 9*
*3.2.2 Non-exact Optimisation Methods ........ 10*
3.3 EXPLICITLY SPATIAL METHODS ........ 14
*3.3.1 Examples of Explicitly Spatial Programs ........ 15*
3.4 POST-SITE SELECTION ANALYSIS TOOLS ........ 16
*3.4.1 Ecopath ........ 16*
*3.4.2 FACET ........ 16*

**4 SUGGESTED PROMISING OPTIMISATION METHODS FOR CANADA'S PACIFIC REGION ........ 17**

4.1 EVALUATION OF METHODOLOGIES REVIEWED ........ 17
4.2 EVALUATION OF PROGRAM ATTRIBUTES FOR THE MORE PROMISING OPTIMISATION METHODS ........ 21

**5 CURRENT MARXAN-BASED ANALYSES WITHIN CANADA ........ 22**

5.1 WORLD WILDLIFE FUND CANADA – ATLANTIC COAST ........ 22
*5.1.1 Purpose of analysis ........ 22*
*5.1.2 Methods used to select Priority Areas for Conservation (PACs) ........ 23*
5.2 LIVING OCEANS SOCIETY – PACIFIC COAST ........ 25
*5.2.1 Purpose of analysis ........ 25*
*5.2.2 Methods used to achieve objectives ........ 25*
5.3 CONCLUSION – HOW THESE ANALYSES CAN ASSIST DFO ........ 28

**6 CONCLUSIONS AND RECOMMENDATIONS ........ 28**

6.1 CONCLUSIONS ........ 28
6.2 RECOMMENDATIONS ........ 29

**7 GLOSSARY OF TERMS ........ 31**

**8 REFERENCES ........ 33**

**9 APPENDIX 1 – SELECTION ALGORITHM OVERVIEW SUMMARY TABLE ........ 39**

# 1 BACKGROUND

## *1.1 Fisheries and Oceans Canada's role in marine conservation*

In Canada, the Oceans Act (1997) calls for Fisheries and Oceans Canada (DFO) to lead and facilitate the development of a *National Oceans Strategy.* This strategy is intended to guide the management of Canada's estuarine, coastal and marine ecosystems and calls for DFO to oversee the protection and sustainable development of the marine environment. To implement this conservation and management mandate DFO has proposed the development of an Integrated Management (IM) planning framework. The Integrated Management framework is essentially a two pronged approach which aims to 1) provide conservation and protection of ecosystems and 2) provide opportunities for creating wealth in ocean-related economies and communities. These two aspects of the IM framework should not be viewed as mutually exclusive but as complementary. They need to be dealt with through a framework that is supportive of the diverse needs of a variety of users, yet protective in the long-term (Lovell et al. 2002). However, for DFO to be successful at managing Canada's estuarine, coastal, and marine environment, the IM framework has to be able to protect the ecological processes that support the species and diversity we wish to conserve (Roberts et al. 2003a, Ward and Hegerl, 2003). Currently our knowledge of marine ecological processes is limited and thus we are reliant on the use of surrogates in marine planning which should be in future be validated. It is now generally recognised that the use of an ecosystem-based approach[2] to establish an integrative system of marine protected areas (mpas)[3] can be used effectively to conserve marine biodiversity and contribute to the development of sustainable fisheries (Ward and Hegerl 2003, Roberts et al. 2003b, Pauly et al. 2003, Lewis et al. 2003).

In 2002 at the world summit in Johannesburg, several countries, including Canada, made a commitment to protect marine biodiversity by implementing a *Network* of mpas by 2012, which DFO has been mandated to lead and coordinate. A network differs from a set or system by implying there is some level of connectivity among the designated mpas within a region (see section 1.3 for further explanation on developing a network of mpas).

## *1.2 Developing a network of marine protected areas in Canada*

There are a series of identified steps in establishing a network of mpas which we have summarized in three phases (WWF/CLF 2004; Roberts et al. 2003b; Day and Roff 2000; GBRMPA, 2003a) (Fig. 1). The first phase starts with the compilation of data necessary for mapping habitats and species distributions within a particular region. Completion of this phase results in maps of representative areas, distinctive areas and single species distributions. Such a systematic habitat classification is important to the success of protecting marine biodiversity, as it allows identification of the variety of marine habitats required to be represented (Roff and Taylor, 2000). The second part of phase one is the selection of a set of areas of interest (AOIs), which together could constitute a mpa system. The second and third planning phases are then concerned with moving from a set of AOIs to determining a logical and defensible mpa network. The second phase focuses on identifying connectivity requirements among AOIs, since to conserve marine biodiversity, biota must be both

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[2] Defined by DFO as a strategic approach to managing human activities so that ecosystems, their structure, function, composition are maintained at appropriate temporal and spatial scales (Fisheries and Oceans 2002a).

[3] There is a distinction between upper case MPAs and lower case mpas. MPA refers to those protected areas formally designated by DFO while the term 'mpa' is an umbrella term that encompasses all protected areas including the formally designated MPAs, fishery closed areas, National Marine Conservation Areas, Marine Wildlife Areas and Provincial Marine Parks.

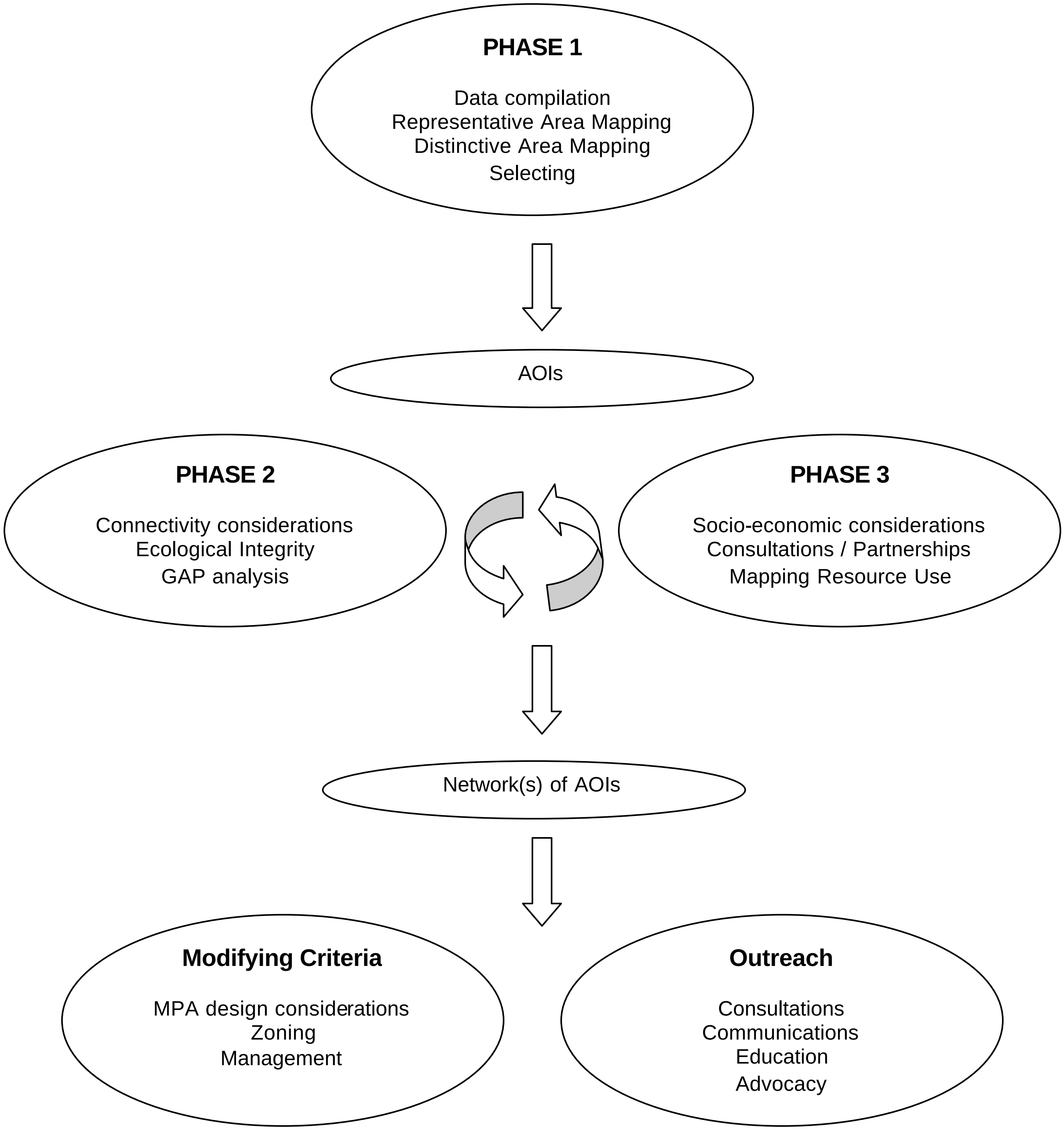


Fig. 1. Steps involved in the development of a network of marine protected areas (based on WWF/CLF 2004).

represented and persist. This involves understanding recruitment of species and the physical processes that govern this. While organisms may inhabit one area, their recruits may replenish populations in other areas. This passive form of dispersal is often in a predictable direction or circular pattern (Jamieson and Levings, 1998). There may thus be some advantages if there was some level of connectivity between mpas within an area. This can be accomplished by the development of a network of mpas that collectively address both the recruitment of selected species and the ecological integrity of marine processes (Roberts, 2000; Roff and Rangely, unpublished). Recently, the idea of connectivity within the marine environment as a necessary tool to link individual reserves to ensure persistence of species has resulted in considerable literature (Largier, 2003; Roberts et al., 2003b; Shanks, 2003; Palumbi, 2003; Sala et al., 2002; Lockwood et al., 2002; Cowen et al., 2000; Allison et al. 2003). The third phase considers the weighting of socio-economic and cultural objectives to choose among AOIs to create a network of mpas that meet identified ecological goals whilst minimising disruption to socio-economic and cultural needs.

Such an approach towards establishing a network of mpas should be systematic, ecologically-based and scientifically defensible using the best available data, (WWF and CLF 2003) and be designed to meet multiple objectives for the diverse set of mpas that can be designated in Canada (i.e. representative and distinctive protection, plus socio-economic development). The advantage of a systematic approach is that it maximises the chance of creating a mpa network that represents the full suite of objectives, it ensures a transparent and defensible process and it makes efficient use of available resources (Leslie et al. 2003, Pressey et al. 1993).

### *1.3 Developing a network in Canada*

DFO has the authority to establish Oceans Act Marine Protected Areas (MPAs) as well as seasonally closed fishery areas. The Oceans Act identifies the following set of reasons for which DFO can designate MPAs :

- *(a)* the conservation and protection of commercial and non-commercial fishery resources, including marine mammals, and their habitats;
- *(b)* the conservation and protection of endangered or threatened marine species, and their habitats;
- *(c)* the conservation and protection of unique habitats;
- *(d)* the conservation and protection of marine areas of high biodiversity or biological productivity; and
- *(e)* the conservation and protection of any other marine resource or habitat as is necessary to fulfil the mandate of the Minister.

However, in Canada, there are several types of mpas that can be designated besides those established by DFO (Jamieson and Lessard 2001). Parks Canada designates National Marine Conservation Areas (NMCAs) which are chosen to represent each of Canada's marine ecoregions. In cooperation with the federal government, the provinces can designate areas within the marine environment as parks or ecological reserves. Finally Environment Canada has recently begun to designate Marine Wildlife Areas (MWAs) within the marine environment for the protection of important wildlife habitats, all of which will contribute to Canada's national network of mpas.

It has been shown in the literature that to effectively conserve marine biodiversity it is necessary to protect both distinctive areas (those areas exhibiting unique physical or biological characteristics of importance to maintaining ecosystem function and species persistence) and representative areas (those areas that capture the full range of habitats and their associated species assemblages that are typical in a prescribed region) (GBRMPA, 2003b; Roberts et al.

2003a; Day and Roff 2000; Roff and Evans 2002). Given these requirements and the diverse set of conservation and socio-economic objectives held by the different government agencies, a collaborative approach would be the ideal strategy for developing Canada's national network of mpas. Recently, a Memorandum of Understanding (MOU) on implementing the Oceans Act was developed by DFO's Pacific region which, indicates the need for DFO to lead and co-ordinate a collaborate mpa planning initiative with other government agencies. If areas to be included in a network can be identified within the context of an comprehensive regional planning framework for a region, then areas which can fulfil several mandates can be recognized and thus eliminate possible redundancies and create a network that is more efficient at capturing the 'most' for the least 'cost' in terms of required area for protection. Creating a reserve system in such a fashion would also decrease the potential loss to socio-economic opportunity while still providing the necessary protection for the maintenance of marine biodiversity. However, it is also important that the identification of mpas be done in such a way that the mandates and jurisdictions of all agencies are respected. No one agency will be able to designate and implement all of the necessary mpas, therefore areas identified for protection should be designated and implemented by the corresponding agency who is mandated to provide protection for that particular feature.

Over time, it is likely that MPAS will be established to address objectives that occur at different spatial scales, and it may thus be advantageous for AOIs (Areas of Interest) to be considered at multiple scales, all of which are nested within a larger decision making framework (e.g., DFO's IM framework) that describes ocean zoning (World Wildlife Fund Canada (WWF)/ Conservation Law Foundation (CLF) 2004). Zoning allows for multi-use planning, and thus tries to minimise tradeoffs between different stakeholder groups while maximising the benefits to the marine environment (Lewis et al. 2003, WWF/CLF 2004).

## *1.4 Concerns with scale and data in natural resource management planning*

### 1.4.1 Scale

Different disciplines (ecological, social, management, economic) may have differing scales of significance that must be incorporated into an IM framework that establishes an mpa network for the conservation of marine biodiversity and sustainable resources use. This complexity can create conflict between ecological and socio-economic objectives (Perry and Ommer, 2003; Lovel et al. 2002). Scale is a characteristic dimension (or size) in either space or time or both (Lovell et al. 2002). The choice of scale for the selection of AOIs should be associated with the identification of patterns and processes within the marine environment. Planning area boundaries are an important consideration for mpa network design because changing the scale of the planning region affects the relative importance of areas within that region. Focus on a single scale may obscure important processes that only become obvious at either finer or boarder scales (Lovell et al. 2002; Perry and Ommer, 2003). Depending on objectives, it may not be best to force the management of some resources into a specific scale. In other words, one scale does not fit all issues. Thus, it may be advantageous for AOIs to be considered at multiple scales, all of which are nested within a larger decision making framework (e.g., DFO's IM framework). For example, coarser scale analyses may be used to indicate patterns in the marine environment and identify areas of high conservation value within which finer scale analyses may be used to further investigate the significance of those areas. The scale at which the data are analysed should be appropriate for the species and processes being conserved. The scale used also needs to be explicitly stated within the objectives for selecting the AOIs and taken into account when choosing the most appropriate methodology for selecting them.

### 1.4.2 Data issues in conservation management planning

Since the majority of site selection programs are model based, outputs may provide a false sense of security if the model's capabilities or inherent caveats and assumptions are not recognised. Data quality influences output quality: 'garbage in, garbage out'. The spatial coverage of the data used within the area being investigated can also potentially cause problems if there is misrepresentation of actual spatial patterns occurring in that area. Also, in most cases, the models require the setting of quantitative targets that describe conservation objectives; yet if these quantitative targets are ecologically or biologically meaningful has yet to be determined.

Selection models, such as those reviewed here, are just that, models, and they should never be expected to provide the perfect answer as there are numerous influencing variables that may not be known or even measurable that could potentially bias results. Therefore it should be emphasized that the methodologies used to select AOIs are decision support tools that contribute to one part of the process involved in developing a network of mpas. Other phases that occur after the initial selection of AOIs will require the use of other conservation tools, such as GIS to visualize the input data layers, negotiations with other stakeholders, expert Delphic approach to weight or rank importance of areas for conservation, political tools – regulations, bylaws, and so on (Lewis et al. 2003).

## 2 *PURPOSE OF THIS PAPER*

The purpose of this paper is to provide information to evaluate the different site selection methodologies and to determine which methodology is appropriate for the selection of AOIs (part of phase one in the above mentioned network planning process) as specified under the Oceans Act. As indicated in section 1.3, the mpa network planning process involves more than simply selecting candidate sites for protection and thus, this paper only investigates a narrow part of that overall process.

Clearly defining the purpose and the overall conservation goal is an important first step that must not be overlooked. At present, significant efforts have been made in Canada to develop frameworks, compile data and create maps towards completing phase one of establishing an mpa network (Ardron et al. 2002; Ardron 2003; WWF and CLF 2003; WWF 2004; Noji et al. 2002; Levings et al. 1998; Casher et al. 1993). This process should be ongoing and adaptive, with information continually being updated as better data become available. DFO's next step towards completing phase one of the network planning process, is to select a set of AOIs, given a particular set of multiple objectives, ideally established collaboratively with other government agencies and interested stakeholder groups.

To effectively deal with complex site selection problems, optimisation programs have been developed as decision-support tools to identify a set of sites that can efficiently meet a complex set of goals or objectives. The most popular way in which to systematically select and prioritize between sites is to use mathematical siting algorithms (Margules et al., 1988; McDonnell et al., 2002; Ardron et al., 2002; Leslie et al., 2003). Siting algorithms strive to find optimal solutions that meet a set of selection criteria and system design constraints, such as: level of species and/or habitat representation, the number of sites, area, and perimeter of the system. Optimisation methods are designed to work best when they balance a wide variety of criteria and thus can be used to capture the mandates of several agencies including that of DFO. Therefore, the methods reviewed here can not only assist DFO in selecting AOIs as designated under the Oceans Act but also assist in fulfilling their mandate by helping to create a network of mpas that maintain biodiversity. These programs can also assist managers by helping to address management issues such as; connectivity (through the inclusion of spatial parameters within the selection criteria), location of important habitats, zoning, minimising disruption to fishing activity, and negotiation among stakeholders (through providing a range of flexible solutions).

# 3 AN OVERVIEW OF RESERVE SELECTION METHODOLOGIES

Conservation biologists have been developing practice and theory that began from little or no methodology in early park design to our current, more sophisticated, albeit still being perfected, practices. In the past, location of sites for conservation purposes were governed "more by opportunity than design, scenery rather than science" (Hackman, 1993). Much of Canada's current mpa system (Jamieson and Levings 2001) has been established by a number of federal and provincial agencies in an ad-hoc manner with emphasis on near-shore environments (Fisheries and Oceans Canada, 1998) Marine areas designated for protection in the past have often been chosen based on values like; scenic coastal features, human recreational values or local biological characteristics (such as migratory bird habitats),and were rarely established to reflect marine ecological principles (Day and Roff, 2000; Jamieson and Levings 2001). Experience from other jurisdictions have shown that an ad hoc approach to marine protection can lead to decisions which do not necessarily yield efficient[4] or effective mpa design, and may later be regretted (Stewart et al. 2003, Gonzales et al. 2003). A systematic approach to reserve design is typically recommended (Margules and Pressey 2000, Possingham et al 2000).

In the early 1980's, the approach to considering sites for protection began to shift from the earlier 'ad hoc' approach to one where a systematic process using a set of guidelines and/or criteria is used to allocate priorities. Here, we only discuss general purpose algorithms for site selection rather than those that were custom build for specific situations, which tend to be only suitable for the specific cases they were designed for. Regardless of approach choosing an appropriate decision support tool and setting up a selection process (e.g. defining a-priori decisions, if any) is highly dependent on the chosen objectives and the scale of the plan.

There are two general methodological approaches to systematic mpa selection or design; scoring procedures (section 3.1) and those that address the concept of complementarity (section 3.2). The following is a review of the suite of selection methods that have been used to select priority sites for conservation. Appendix 1 provides a summary table comparing the program characteristics for all methods reviewed and a figure illustrating the relationship among them.

## 3.1 Scoring Methods

(Pressey and Nicholls 1989; Cabeza 2003; Killpack et al. unpublished ; Brody 1998; Bryan 2002)

Scoring methods are primarily used to select sites that will be added to an existing reserve system, rather than for creating a new reserve system. Scores are assigned to each site based on a set of criteria. Sites are then ranked in order of their priority according to the cumulative scores from all criteria. The site with the highest score (the 'best') is then added to the existing reserve system (Cabeza 2003; Pressey and Nicholls 1989). The selection process stops when the size of the area deemed desirable for protection or the cost of implementation has been

[4] 'Efficiency' as used in this paper refers to minimizing the area required to meet stated conservation objectives. Naturally, different conservation objectives will demand different minimal solutions; thus, efficiency is directly related to the objectives of the network (see Pressey et al. 1996 for further explanation of optimal reserve design and efficiency)

reached. Selection criteria applied can be defined by the user and is usually dependent on the type of conservation goal being addressed. For example, if the goal was to increase the amount of ‘naturalness’ protected, then an appropriate criterion may be the addition of areas where there is no human activity. However, if the goal was to protect a particular group of species (i.e. fisheries), a more appropriate criterion might be the species’ presence and/or quality of the habitat. When setting up a scoring selection procedure, it is preferable in the ranking of sites to use a combined set of criteria rather than an individual criterion. The more criteria used to rank sites, the less likely it is that an area of importance is overlooked. For example, if the only criteria used to rank sites was level of species richness, then sites that were low in terms of species richness but that contained rare species of value could potentially be overlooked.

The scoring method approach has the flexibility to use any type of data (quantitative, non-quantitative) so long as it can be assigned a relative rank. In some cases data from different disciplines (biological, habitat, economic and social) may be required to assign an appropriate score to each site. The method can be applied at any scale. However, a higher level of detailed data is usually required at finer scales.

There are two assumptions with scoring: that those sites with the highest or next highest score will enhance the system network, and that the range of scoring (high, moderate, little impact) is enough to delineate among criteria and that the indicators used are appropriate to address the criteria.

The limitations to scoring mostly stem from the first assumption, above. The highest ranked site may not contribute the most with respect to the objectives of the existing network. The whole may be different than the sum of its parts – two sites considered independently may be valuable but considered together may be redundant. Also, different sites can have equal scores with no distinction of the actual attributes contained within them, making it difficult to identify a “best combination” of sites. Upon completion of the ranking process, the output is simply a relative combined score for each site, and it does not detail the content of each site. Therefore, it does not allow for changes to the mpa system to be tracked (i.e. it doesn’t take selection efficiency into account) and does not produce readily transparent results.

The scoring method also has only crude capability to incorporate spatial considerations. Finally, the number of sites to be added to a system is usually capped *a priori*, and is difficult to defend scientifically.

In summary, this method is perhaps most appropriately applied in the evaluation of AOIs and existing MPAs, when desiring simple quantitative evaluation of alternative sites.

### 3.1.1 Examples of programs

1) *Compare*

Compare uses a matrix approach in which 17 criteria are numerically scored against a list of 14 objectives in three categories (biotic protection, fishery management, and provision of human use). At the end of the selection process, a matrix of relative scores for each site can be produced. The major limitation to this method is that it requires a lot of detailed data to provide a score for each of the 17 criteria. Therefore this particular example can only be appropriately applied at scales for which data is available (Alaska Department of Fish and Game, 2002; Palsson 2002).

*2) Economic-based Multi-criteria analyses (MCA)*

Any analysis in which there are more than one criteria used can be considered a MCA. For the Buccoo Reef Marine Park in Tobago, West Indies, an economic-based MCA was used as a tool to facilitate deliberations between stakeholders and to integrate ecological, social and economic criteria to investigate possible trade-offs (Brown et al. 2001).

The selection process involved consultation with different stakeholders to develop a set of economic, social and ecological criteria. Stakeholders were asked to weight different criteria, and then the outcomes of different stakeholder weightings in the MCA were used to explore different management options. The criteria were then ranked in a systematic manner. Ecological criteria were used are indicators for ecosystem health. This particular scoring approach was re-iterative, allowing for each stakeholder group to separately reconsider scores, taking into consideration the outcomes from the other groups as well. At the end of this re-iterative process, stakeholders were brought together for a consensus-building workshop to finalize the selection of priority sites.

The advantages of this particular example were: a) although the type of data used in this analysis needed to be fairly detailed, in this case both social and ecological data were incorporated into an economic model, thereby allowing multiple objectives for protected area management to be considered, b) data could be either qualitative or quantitative, c) the process was transparent to understanding the structure and content of the decision problem, allowing for the trade-offs to be apparent, and d) it permitted trade-offs between competing impacts or stakeholders.

There are a few requirements specific to this particular example involving this type of 'delphic' approach (Brown et al. 2001). First, all stakeholders have to work together and be present at consultations. Second, the questions being posed to stakeholders should not be biased so as to produce a particular type of answer. Limitations to this example are: a) it is process-oriented rather than outcome-oriented, b) it does not attempt to develop a comprehensive ecosystem model, c) it can only reflect the values of those who are involved, and d) the criteria used did not provide any information about a desirable design of the protected area network (e.g., size, replicates etc.).

### *3.2 Complementarity Methods*

Complementarity takes into account the extent to which a site, or set of sites, contributes to meeting the desired objectives of the overall network. These programs stand out from the more traditional scoring methods in that they seek to find the most efficient solution to the problem of designing a network of mpas that meets a specified conservation goal while minimising the 'cost' (defined here as social, economic, implementation, management, foregone opportunity, or any other type of quantifiable cost) of the network (Stewart et al. 2003; Pressey et al. 1996; Stewart and Possingham 2002). This has also been referred to as the 'minimum-set problem', and was first proposed by Kirkpatrick in 1983 (Margules et al. 1988; Stewart et al. 2003; Kirkpatrick 1983).

Algorithms used to solve this type of reserve design problem are referred to as optimisation algorithms, and all are iterative; i.e., sequentially selecting or rejecting candidate sites. Optimisation algorithms can be further subdivided into two types of methodologies; a) exact and b) non-exact.

### 3.2.1 Exact Optimisation Methods

(Pressey et al. 1996; Church et al. 1996; Possingham et al. 2000; Cabeza 2003; McDonnell et al. 2002; Ward unpublished; Polasky et al. 2000)

Exact optimisation algorithms are those in which an optimal answer is expected to be found. The general structure of these methods is to express the design problem in the form of an Integer Linear Program (ILP) and then to use an optimising mathematical technique such as 'branch and bound' to find the optimal solution (Possingham et al. 2000). Integer Linear Programming (ILP) techniques were the first alternative suggested to the scoring method (Kirkpatrick 1983). When using these algorithms, the conservation problem is usually stated as a 'min-set' problem in which it is desired to have every conservation feature represented at least once.

The ILP requires that all data be represented as an integer value, and assumes that each feature can be represented as an integer unit. Thus, presence data are often used in these analyses. This method starts by selecting the site with the highest ranked score and then linearly adds complementary sites thereafter, assuming that the highest ranked site should be part of the reserve system.

At the end of the ILP selection process, an output file containing all sites that together met the desired objective (representation, rarity, richness etc.) is produced. This allows evaluation of sites with respect to their attributes, cost and total area. The majority of these programs do not have spatial capabilities. However, some newer versions have the capacity to incorporate spatial constraints (such as adjacency) in the design of the program. This usually requires the user to re-write parts of the mathematical code that the algorithm is based upon.

Advantages to the ILP method are: 1) it can find solutions to a MPA selection problem that require a smaller number of sites than those found by other approaches. Heuristics is a name given to a group of algorithms that attempt to solve problems by simulating the way in which a person selects among choices. 2) These methods are designed to find an optimal solution if it finds a solution at all.

Limitations to this method are: 1) it does not always find an answer to a reserve design problem. The difficulty of guaranteeing an optimum solution increases exponentially with the number of constraints (features to be represented), which usually results in a large analysis. The program may computationally fail or 'time-out' before a solution is found because often conservation problems are non-linear (Moore et al. 2003). 2) Solutions that are found take a long time to compute 3) Linear programs do not distinguish sites by their specific contents, but rather by their scores, which may not always be desirable. 4) There is only one final solution created, thereby decreasing flexibility in subsequent stages of network design. 5) There are typically no spatial capabilities in a linear program, and so networks produced are usually highly fragmented.

This method tends to be most appropriate at smaller spatial scales where the number of solutions is generally small. If the problem is small enough, then this type of algorithm is attractive since it will find an optimal answer.

#### 3.2.1.1 EXAMPLES OF EXACT OPTIMISATION METHODS (GENERAL ITERATIVE):

*1) CPLEX*

A software program developed by ILOG which uses optimisers for solving linear, quadratic, mixed integer linear and mixed integer quadratic programming problems. CPLEX is set up so that the user can read or write problem files and thus the algorithm can be changed to represent a specified problem. Although CLPEX usually employs a linear 'branch-and-bound' technique to solve the site selection problem, it can also apply heuristic algorithms to determine integer feasible solutions. This means that it can be set up to find either the optimal solution or to find a reasonably good feasible solution in less time. This program can only operate using integer values (Polasky et al. 2000; Moore et al. 2003; www.cplex.com). This software can be difficult to obtain and may require considerable expertise to run (Moore et al. 2003).

*2) LP_SOLVE*

Is a simplex based program, developed by Michael Berkelaar, which solves mixed integer problems using branch-and-bound methods. It can operate with both real and integer values (Pressey et al. 1996).

### 3.2.2 Non-exact Optimisation Methods

Non-exact optimisation programs produce solutions that are near or approaching optimality, defined as maximum efficiency of representation in terms of the number or area of selected sites or maximum complementarity of sites.

These programs are interactive systems where either planners or the program itself can make departures from efficiency if they feel that it will enhance the selection process later on. They allow for the consequences of changing one or a few component sites within the network to be understood quickly and clearly (transparency). There are two general groups of non-exact optimisation algorithms: 1) simple iterative heuristics and 2) global search techniques.

#### 3.2.2.1 SIMPLE ITERATIVE HEURISTICS

(Church et al. 1996; Pressey et al. 1996; Margules et al. 1988; Kirkpatrick 1983; Ward et al. 1999; Brunckhorst and Bridgewater 1996; Possingham et al. 2000; McDonnell et al. 2002; Palsson 2002; Ward unpublished)

There are few common types of heuristics, the greedy heuristics (also referred to as richness heuristics) and rarity heuristic. The Iterative Heuristic selection process is a stepwise analysis that selects sites based on their complementarity. Each site is given a score based on a specific set of criteria (e.g. richness, rarity, and/or cost).

Richness heuristics seek the highest increment of new features at each step (seek to find the site with the highest number of unrepresented features and the lowest cost). Rarity heuristics differs by beginning with sites that have unique features and progressively adding those that contain the next rarest under-represented feature. In both types of heuristics, this process continues until all conservation features (e.g. species, communities or habitats) are theoretically preserved or until further selection of sites is no longer 'cost-effective'. The output files produced by a heuristic can provide a listing of the selected set of sites as well as the relative ordering of these sites. If for some reason all of the selected sites can not be utilised (i.e. too costly), the relative ordering of the sites provides the user with the ability to 'wind back' the solution and to discard those sites that contribute the least to the network. Heuristic outputs can usually be interfaced with a visualisation tool, such as any Geographical Information System, to provide maps of priority areas selected.

The advantages to using heuristics are; 1) the computational time for these types of selection algorithms to find solutions is extremely short. 2) they are more efficient at meeting the desired conservation objectives whilst minimising area than scoring methods. 3) they have the capacity to consider a variety of constraints such as; level of representation, cost and adjacency (if additional coding is incorporated). Also, any form of presence data can be used by these programs.

Requirements with this method are that: 1) appropriate weightings be assigned and 2) an appropriate level or target for each selection criteria (determined from the conservation objective) be agreed upon. The model also assumes that the first priority area identified by the program is the best and that it should always and will always be part of the reserve system. These considerations lead to the limitations of these algorithms.

Limitations are: 1) The order in which sites are selected by a heuristic may not necessarily be a reliable guide to their priority for protection. Due to a step-wise process, it is ineffective in comparing with sites that give the same complementarity value to the reserve. They don't have the means to determine the level of sub-optimality, which may make evaluation of some options difficult. 2) The selection process makes 'locally' optimal decisions that do not necessarily add up to a 'globally' optimal solution for representing all the features in a region. 3) Since heuristics only produce near-optimal solutions, some desirable conservation targets may not be met. However, Moore et al. (2003) found that simple heuristic methods often provided solutions as good as those produced by exact optimisation programs (such as C-Plex). 4) they generate only one solution 5) 'bad' heuristics can produce solutions quite far from optimal; using the same data, the two reserve systems produced by the richness and rarity methods can vary greatly. 6) Scoring by rarity leads to a more efficient network than scoring by richness alone (Moore et al. 2003). 7) Heuristics do not have spatial capabilities unless they are specifically programmed with an additional adjacency constraint to deal with clustering of sites (for example, BIOSELECT by Ward et al. 1999). 8) When comparing heuristics to simulated annealing (see next section) heuristics produce fewer different solutions and less compact networks when an adjacency rule is applied. Heuristics are designed primarily to identify a relatively small set of complementary sites which contain samples of all known attributes.

###### *3.2.2.1.1 <u>Examples of Simple Heuristic Programs</u>*

*1) CPlan*

This was developed by Bob Pressey, Simon Ferrier (NSW National Parks and Wildlife Service) and programmer Mathew Watts (University of New England, NSW), for the systematic conservation of forests in New South Wales, Australia. C-Plan uses a heuristic algorithm to provide real-time or near real-time solutions to inform the land-use decision making process. This program is interfaced with GIS to facilitate mapping and visualization of selected sites. Constraints such as cost can also be incorporated as an input data layer. This method has been used to add sites to existing protected area systems, and can be used to identify the 'utility' of an additional site (in terms of species composition) to the reserve system. In this case, 'utility' is an objective measure that indicates how necessary a site is to achieving desired conservation goals. The program documents all decisions made throughout the site selection process in a log file that enables the user to 'wind back' the earlier stages and resume the selection process from there, thus enhancing the programs flexibility to achieve multiple solutions (Bedward et al. 1992; Johnson and Lachman, 2001).

*2) TRADER (Tree-based Representative Area Determination, Evaluation and Representation)*

This was developed by Glenn De'Ath at James Cook University, Townsville. Trader is an adaptable three-stage heuristic based method that employs multivariate regression trees and simple pruning techniques. This selection process starts by first creating an initial reserve system. Secondly it randomly adds to or takes from these areas using a process called "Grow, Pick and Peel". Multivariate regression trees are used to classify sites based on specific attribute data, making sites within a cluster very similar with respect to these attributes. This program maximises the number of choices the user is able to define (Ward unpublished).

*3) BioRap*

This is a set of tools developed for the rapid assessment of biodiversity in the terrestrial system to systematically select priority areas for conservation through the use of an iterative heuristic algorithm. Costs and constraints, such as management effectiveness and persistence, have been incorporated into this set of tools to allow for a more realistic selection process (Faith et al. 2001)

BioRap attempts to achieve a balance between biodiversity conservation and other land use opportunities. Foregone opportunity costs and biodiversity constraints are considered together in a trade-off analysis so that solutions will provide high 'net-benefits'. The output from this program can indicate the level of complementarity or the utility of a site to achieving the desired objectives. This program can optimise several feature data layers together.

*4) WORLDMAP*

This software program was developed by Paul Williams at the Natural History Museum's Biogeography and Conservation Lab based in London, England. The program iteratively explores a study area for geographical patterns in quantitative measures of diversity, rarity and conservation priorities (set by the user and dependent on goals). It can be applied at any spatial scale and can handle large biological datasets. The outputs from this program can indicate the level of complementarity or the utility of a site to achieving the desired objectives. It also provides a detailed list of each iterative decision step indicating which site was chosen and what attributes it contributed. A unique attribute of this selection program is that it can incorporate phylogenetic diversity. A disadvantage to this program is that a maximum number of sites that can be selected is set a priori (Williams et al. 2002; Moore et al. 2003; ww.nhm.ac.uk/science/projects/worldmap).

*5) Portfolio*

Portfolio was developed in the Landscape Ecology Lab at Duke University run by Dean Urban. It is a multi-criteria decision support tool for assembling reserve networks with the richness heuristic algorithm. This program allows for the user rather than the program to make the heuristic decisions (i.e. the user can select when the program will depart from efficiency, or make poor decisions). If when the program prompts the user to choose among a set of sites there is a tie, the user has the ability to apply other quantitative or non-quantitative selection criteria not used by the program. The selection process terminates when indicated by the user, which is usually when all features are represented or when a maximum cost has been reached. This particular heuristic based program also has the capacity to incorporate spatial constraints into the selection process. Portfolio uses the following types of data to base its selection on: a) total habitat area, b) core (high quality) habitat area, c) species richness, and d) species rarity (Urban 2002; Wiersma 2002; www.env.duke.edu/landscape/export/products.html).

#### 3.2.2.2 SIMULATED ANNEALING

(Lewis et al. 2003; Possingham et al. 2000; Leslie et al. 2003; Stewart et al. 2003; Stewart and Possingham 2002; Airame et al. 2003; Ardron 2003; WWF and CLF 2003; WWF 2004; Ward unpublished)

Simulated annealing is another non-exact optimisation method. This is an iterative stochastic (i.e., involving a random variable) complementarity model. This method strives to solve the network design problem of representing every feature at least once (or to capture maximum representation) in the most efficient way possible (i.e. in a minimum area).

The simulated annealing selection process begins by generating an initial reserve system that consists of a completely random set of sites. Next, it iteratively explores trial solutions by making sequential random changes to the system. Either a randomly selected site, not yet included in the reserve system, is selected, or a site already in the reserve system is deleted (determined by which choice has the least cost). At each step, the new solution is compared wit the previous solution (i.e. it searches for the least costly site in each iteration). At the beginning of the iterative process, the program allows for suboptimal decisions to be made. As time progresses, the algorithm is more likely to only accept optimal decisions. The longer it runs the better the solution will be. This selection process uses penalties rather than constraints to assign costs.

Assumptions inherent in Simulated Annealing algorithm method are: 1) by allowing bad changes as well as good, it is assumed that local minima can be avoided; 2) in order for the program to run, quantitative values must be assigned regarding criteria levels (degree of representation or clustering etc.) and assigning of penalties. If these values cannot be scientifically deduced or have not yet been determined, then arbitrary values for these criteria must be assigned. Although assigning arbitrary values should be avoided when possible, this type of selection allows the user to explore a range of different values for representation, cost, boundary length (adjacency), number of replications, and the minimum distance between potential reserves within the system. This can allow the tradeoffs between criteria to be estimated.

There are several advantages to the Simulated Annealing method. First, it starts with a randomly determined network rather than one which is ranked the highest. This allows the system to move temporarily through sub-optimal space increasing the number of alternatives that can be explored and the range of near-optimal solutions that are possible. It can potentially avoid getting caught in a local minimum and continue to search to find the desired global minimum. It can also produce networks of similar or identical size as exact-optimisation programs in a fraction of the time. This method may be a practical compromise between exact optimisation methods and stepwise heuristics as it allows for a range of possible solutions, i.e. more flexibility. Several studies have shown that Simulated Annealing generally performs better than simple heuristics (Pressey et al., 1997; Leslie et al., 2003; McDonnell et al., 2002; Pressey and Nichols, 1989) producing more efficient reserve systems that meet design criteria with a fewer number of planning units.

The simulated annealing algorithm has the capability for spatial constraints to be used in the reserve system design while heuristic methods generally do not (unless code for spatial constraint is incorporated into the program by the user). Also, while the heuristic method provides only one solution whereas simulated annealing provides a range of possible solutions - thereby allowing flexibility for decision making later on when choosing among potential priority sites. However, simulated annealing is not as fast as a simple heuristic at finding solutions with respect to computational time, but is relatively fast compared to all other methods.

Like all other mathematical selection methods, simulated annealing 1) is still relatively static and thus does not deal explicitly with temporal dynamics; 2) in order to effectively apply spatial design constraints, detailed data are needed to identify ecologically meaningful areas; and 3) this method can require more computational time than a simple heuristic approach.

This selection algorithm can use presence data, abundance data and has the ability to perform with limited data. However, if data are too limiting, as with any approach, outputs may not be ecologically meaningful. This method can be appropriately used at any scale. Again, the appropriate scale for use is more dependent on the scale at which data has been collected (see Section 2). The output created from this method is a network of sites that constitute a near-optimal solution to meeting desired targets in the least amount of area (i.e., most efficiently). The sum of solutions for each run (iteration) is another output option from some systems (e.g., MARXAN) that allows identification of sites that are repeatedly chosen to be part of the reserve system.

*3.2.2.2.1 Examples of Simulated Annealing Programs*

1) *MARXAN/SPEXAN/SITES*

This family of decision support tools has been employed by the Great Barrier Reef Marine Park Authority, Living Oceans Society (LOS), WWF-Canada, Channel Islands, and The Nature Conservancy. All three programs are a basic extension of the Fortran model SIMAN, with SPEXAN preceding SITES which preceded MARXAN. The most recent in the lineage of this software family, MARXAN (Ball and Possingham 2000), is geared towards finding spatially explicit solutions to the reserve design problem in the marine environment. These programs are able to incorporate numerous parameters in the selection process including: level of representation desired, measures of cost for each site and the entire system, level of clustering, number of replicates, and minimum distance between sites (in MARXAN only). MARXAN is the most advanced in terms of spatial capabilities. A unique feature of this program is its capacity to calculate the frequency at which a site is chosen to be included in a solution. Those sites that are repeatedly chosen are likely to represent areas that are more useful to developing the effective and efficient mpa network design. Thus this output can act as a measure of conservation utility. A unique feature to MARXAN is its ability to calculate the frequency at which a site is chosen to be included in a solution out of a number of runs for a given scenario. Those sites that are chosen more often can be considered of higher 'utility' to finding the most efficient reserve system design.

## 3.3 Explicitly Spatial Methods

Explicitly spatial models are those that are able to specifically address the issue of species persistence through the application of environmental variable models (those which influence the distribution of biodiversity) or metapopulation models that will direct the selection of a 'connected' set of sites. Although some of these methods usually have a conservation goal to protect a particular species of conservation value (endangered, commercially valuable etc.), some try to select a set of sites that will allow for the persistence of a suite of species (Conroy and Noon 1996) or even biodiversity (Gerner and Bryan unpublished).

All of these methods require detailed data sets regarding either environmental parameters or species population dynamics and thus are often most appropriately applied at smaller scales for which this type of data exists.

Explicitly spatial methods may be more useful at identifying areas of regional significance to direct more intensive studies or as a post-selection tool (see section 3.3) to choose among candidate sites in the development of a network that ensures a particular species persistence.

### 3.3.1 Examples of Explicitly Spatial Programs

1) Environmental Distance Model

This method has been used in South Australia (Gerner and Bryan unpublished). The purpose of the environmental distance (ED) model was to identify under-represented areas through the identification of those sites that were most complementary to an existing reserve system for enhancing representation. This method is similar to the iterative heuristic algorithm except that it selects solely based on spatial relationships.

The ED model compares all potential candidate sites in the study area based on their environmental parameters and how much they added to increasing biodiversity representation. This program requires detailed datasets for environmental parameters that influence the distribution of biodiversity. These environmental parameters are usually of a geophysical nature and do not involve any species data. This program relies on a region-wide spread of data for each variable. Since the premise of this method is to evaluate how much a new site adds to an existing reserve system, there is a need for good input data on currently protected areas.

The model starts with an existing reserve system and then the distances between sites in environmental space is compared against new potential sites. The greater the distance, the more complementary the site is to the existing reserve system, i.e., it would contribute more to increasing the representativeness of the existing reserve system. At the end of each iteration, the cell with the greatest environmental distance is given the next highest priority value and is added to the existing reserve system. The ‘new’ reserve system created from the previous iteration is then used as the ‘existing reserve’ system for the next iteration. This process repeats until all of the ‘unreserved’ sites have been assigned a priority value. The model provides the user with a priority value for each site, calculated as the environmental distance, which can be mapped to indicate areas of high priority. However, this method does not explicitly delineate boundaries.

This model assumes that the greater distance between sites in environmental space reflects greater differences across a range of different environmental characters. It also assumes that a representative system is one that has a broad spread, not necessarily only in spatial terms, but in multidimensional environmental space. Lastly it assumes that the CAR (Comprehensiveness, Adequacy and Representativeness) approach is valid and that ‘complementarity’ contributes additional biodiversity to a reserve system.

2) Other Population Models

Conroy and Noon (1996) developed an approach to site selection in which they used population demographic models that related habitat to predicted species persistence. This method focuses on mapping the dispersal of a single species between source and sink habitat types. The scale of dispersal mapping is unique for each species type and therefore different species need to be mapped at differing scales. While this method does give important information regarding the issue of connectance, it requires extremely detailed data that does not exist everywhere and is rather intensive to gather. Therefore this particular method is probably more appropriately applied as a post-selection tool.

### *3.4 Post-site selection analysis tools*

Other decision support tools exist that do not directly select candidate sites but which may prove useful during the later stages involved in developing a network of mpas. Such support tools are usually geared towards finer-scaled analyses in which very species specific questions are answered, and thus detailed data are required. The following are two such post-site selection decision support tools that could potentially be useful in the further refinement of the mpa system design.

#### 3.4.1 Ecopath

This software package (Walters 2000; www.data.fisheries.ubc.ca/ecopath/index.php) was developed at the UBC Fisheries Centre and is essentially a predictive population model that consists of three parts: Ecopath, Ecosim and Ecospace. Ecopath is a mass balance (trophic structure) model that can be used for the particular system being investigated, and must be developed before the other two components, Ecosim and Ecospace, can be run. Ecosim has a temporal component in it and allows you to simulate and predict probable changes in the population model over time. Ecospace is an explicitly spatial component that can test different spatial scenarios on the Ecopath model.

The purpose of this suite of programs is to help in the design of MPA activity restriction alternatives (i.e. degree of fishing effort allowed – intensity and location), to estimate trophic mass-balance relationships, to provide broad assessment of fishing impact on trophic structure and to measure the effect that MPAs might have on fish populations/dynamics. Output from Ecospace predicts spatial variation in steady-state biomass (for a particular species or group of species) along a transect through an area. These programs may help with identifying appropriate sizes of zones of varying activity restriction within MPAs. They can help to demonstrate ecological consequences of alternative design strategies (i.e. placing MPAs close to or far from intensive fishing areas and can illustrate the effectiveness of an MPA for conserving fish abundance. However, this program is extremely fisheries oriented and requires detailed species-specific data about predator-prey dynamics, age structure, and dispersal rates in order for the model to produce meaningful results, and thus could most likely not be applied at large regional scales. This model may be most appropriately used to monitor and assess the usefulness of an mpa network in achieving fisheries specific goals. It can also link individual species assessments and decisions, towards achieving a better understanding of overall ecosystem effects.

#### 3.4.2 FACET

FACET is a consulting company which creates decision support software systems. The programs offered by this company can either be purchased or consultants from the company can be contracted to perform desired analyses. FACET consultants can create functions that work with the original code so that the program can model a specific area, which then allows the user to manipulate desired parameters. FACET has been used by DFO in the past to assist with whale habitat classification (www.facet.com) and to develop a complex time-step model for managing fisheries in British Columbia's Fraser River (Ian Williams pers. comm.; www.facet.com) **.** For these latter analyses, this "cause and effect" software program was used, allowing calculation or prediction of what effect different situations would have on fish populations. It is an extremely powerful program that can incorporate a variety of point, spatial or temporal databases (e.g. environmental, management, population dynamics) and allow the user to filter and manipulate data at a very high resolution (at approximately one meter squared). This program can be set up to investigate different scenarios and compare their outcomes.  A limitation of this program is that it requires detailed population dynamic and environmental data sets for the study area, and thus is most appropriately applied at scales where such data are available.

While there are undoubtedly numerous other post-selection techniques that can assist in the development of networks of protected areas.  For example, the applications of graph theory to conservation planning by Urban and Keitt (2001) and Bunn et al. (2000) provides an overview and an example of how it can be applied to terrestrial conservation.  However, their review is not the focus of this document and thus have are only briefly mentioned.

# 4 SUGGESTED PROMISING OPTIMISATION METHODS FOR CANADA'S PACIFIC REGION

## 4.1 Evaluation of methodologies reviewed

For designing mpa networks, the complementarity approach is generally better than the scoring because; 1) they are more systematic, 2) they take efficiency into account, 3) they allow tracking of site contents and 4) some can incorporate spatial constraints (i.e. connectivity).

Among complementarity approach, non-exact optimisation methods are often superior to exact optimisation methods for regional conservation planning because; 1) a solution is always found, 2) a near-optimal solution can be found for complicated problems with several constraints, 3) exact optimisation methods usually are not capable of incorporating spatial constraints, and 4) computational time to produce a solution is less.

However, if the reserve selection problem is not very complex (few constraints, data layers, and potential sites), then using a non-exact optimisation method may be recommended.  However, for marine conservation planning, the site selection problem is usually quite complex and requires the optimisation of several constraints.

Among Non-exact methodologies, simulated annealing is considered to be a superior algorithm compared to heuristics because; 1) it can produce multiple solutions that meet the conservation objectives, 2) it is stochastic and therefore does not assume that the site with the most features should be part of the final reserve system, 3) it assigns costs as a penalty rather than a constraint, thereby allowing flexibility and 4) it is more efficient at finding solutions in terms of minimising total area selected.

Although it may be that simulated annealing is the most promising algorithm for selecting priority areas for conservation, a further review of other  design considerations beyond the basic algorithm capabilities is necessary to recommend the most appropriate methodology specifically for assisting DFO in selecting AOIs.  Thus, we have chosen to review three available software packages; two heuristic based programs (WORLDMAP and Portfolio) and one simulated annealing program (MARXAN) in greater detail to determine which package is most appropriate for DFO.  Table 1 below provides a summary of a more detailed review of these program's capabilities.  For this review  DFO's site selection needs were not specifically identified, as it is more appropriate that these be determined by the managers rather than science.  Instead a list of program attributes were used within Table 1 as an attempt to address those considerations for marine network planning that we felt stemmed from DFO's mandate.

Table 1: Further review of program capabilities for two heuristic-based (WORLDMAP and Portfolio) and one simulated annealing- based (MARXAN) site selection software programs.

| **Program Attributes** | **WORLDMAP** | **Portfolio** | **MARXAN** |
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| **Most appropriate application** | ▪ Helpful for identifying a set of sites that give you the most 'bang for your buck' for a maximum area set a priori. | ▪ Good for choosing among candidate AOIs of variable size and quality (essentially used as a refining tool)<br>▪ Can only deal with small datasets | ▪ Best for selection of (or among) candidate AOIs for small or large regions<br>▪ Best for selection using several datasets<br>▪ Best for selection using large datasets<br>▪ Best for selecting a network of mpas |
| **Flexibility** | ▪ Only one solution provided per analysis<br>▪ Each site is assigned a 'flexibility' class (most, more, less, or least flexible) which indicates if a site is unique or if there are other similar sites that could be substituted | ▪ Only one solution provided per analysis<br>▪ Backward analysis – where the selection process runs backwards sot that the removal or 'swapping' of sites can be assessed. | ▪ Multiple solutions produced (set by the user) for each analysis which allows for more flexibility<br>▪ Sum of solutions output file indicates the relative conservation utility of each selected sites and therefore can help identify those sites where flexibility (tradeoffs with socio-economic activity) can occur. Thus facilitating stakeholder negotiations. |
| **Communication abilities** | ▪ Visualisation – incorporated into the selection program<br>▪ Transparency – extremely transparent as this program has a visualisation aspect built into it.<br>▪ Each step in the selection process is logged in an output table<br>▪ The user can drag their mouse over any site and double click to bring up a list of the attributes contained in that sight | ▪ Visualisation – can be interfaced with GIS<br>▪ Transparency - the selection process is extremely transparent as the decisions made by the user are logged at each step.<br>▪ Solutions can be visually represented using a GIS<br>▪ Can run the selection process backwards. Thus able to identify the relative utility of each site selected<br>▪ Contents (scores for a criterion) of each site are given in the log output file | ▪ Visualisation – can be interfaced with GIS<br>▪ Transparency – the selection process is transparent although it may take some understanding and analysing of output files to obtain all the necessary information<br>▪ Solutions can be visually represented using a GIS<br>▪ The sum of solutions output file indicates the relative conservation utility of the selected sites<br>▪ Contents of each selected site is not given in an output but it can be obtained manually or through a simple database query. |

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| **Possible Selection Criteria** | ▪ species richness<br>▪ species rarity<br>▪ opportunity cost | ▪ species richness (complementary)<br>▪ species rarity (simple – total site rarity)<br>▪ species rarity (Complementary)<br>▪ species presence absence<br>▪ total habitat area,<br>▪ core (high quality) habitat area<br>▪ connected area<br>▪ connected core area | ▪ species richness<br>▪ species rarity<br>▪ species presence/absence<br>▪ species abundance<br>▪ unique habitats<br>▪ representative habitats<br>▪ biologically distinct areas (e.g. spawning and high productivity areas)<br>▪ physically distinct areas (e.g. upwelling and frontal areas)<br>▪ economic foregone opportunity cost data<br>▪ The possibilities are endless |
| **Spatial Capacity** | ▪ Can request that a particular species is captured in more than one site (replication) | ▪ Connectivity – based on area weighted dispersal probabilities and dispersal flux for each site.<br><br>▪ Sites are given a score based on their relative connectivi ty to the reserve portfolio that is being created and then the user can use this as a criterion to base their site selection on. | ▪ Connectivity - Minimum separation distance between planning units containing a given conservation feature<br>▪ Level of aggregation among selected sites within the entire network<br>▪ Minimum clump size for a given conservation feature<br>▪ Number of replicates of mutually separated planning units in valid clumps for a given conservation feature<br>▪ Number of occurrences for a given conservation feature desired within the entire network<br>▪ |
| **Outputs** | ▪ Tables of accountability – indicating why each site was chosen and which species are represented<br>▪ Provides a relative flexibility score (low, medium, high) for each site. The delineating of the score classes is user defined and can be arbitrary | ▪ Log – provides a log of the information provided to the user and the decisions made at each step in the selection process<br>▪ Summary – At each step the program indicates the site selected for addition or removal from the portfolio, # of sites in the reserve system, and the cumulative statistics for each criteria (e.g. # of species, total rarity, connectivity and son on) | ▪ Log 1 – solutions for each run<br>▪ Log 2 – indicates how well each run did at meeting the desired conservation criteria<br>▪ Best solution – run with the best score<br>▪ Summary – lists stats for each run (run #, score, cost, # of planning units, boundary length, penalty value, shortfall, and # of features with unmet targets.)<br>▪ Scenario details |

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| | | | ▪ Summed Solution<br>▪ Screen log file<br>▪ Snapshot file |
| **Algorithms used** | ▪ Greedy Heuristic<br>▪ Rarity Heuristic | ▪ Greedy Heuristic | ▪ Greedy Heuristic<br>▪ Richness Heuristic<br>▪ Rarity Algorithms (5)<br>▪ Irreplaceability Algorithms (3)<br>▪ Simulated Annealing |
| **Iterative process** | ▪ Program defined -<br>▪ Finite number of sites to be selected set a priori | ▪ User defined – the user decides if a site is to be added or removed from the reserve system | ▪ Program defined – the program decides if a site is to be added or removed from the reserve system. |
| **Computational Details** | ▪ No maximum number of data layers or sites<br>▪ Sites must be on a grid system | ▪ Maximum number of species data layers (24), and sites (32) that can be selected among<br>▪ Sites can be of variable size | ▪ No maximum number of data layers or sites<br>▪ Sites must be on a grid system |
| **Data** | ▪ Quantitative<br>▪ Species data<br>▪ Socio-economic data can be incorporated through assigning a cost value to each site | ▪ Quantitative<br>▪ Habitat and Species data<br>▪ Dispersal probability data needed<br>▪ Socio-economic data can be incorporated through assigning a cost value to each site | ▪ Quantitative<br>▪ Any ecological data that can be quantified<br>▪ Socio-economic data can be incorporated through assigning a cost value to each site or by 'locking' a site out of the reserve system thus disallowing its selection for the mpa network.<br>▪ |
| **Ease of Use** | ▪ User friendly, has a built in visualisation tool thus allowing for immediate interpretation of results<br>▪ Creating input data files can be quite intensive | ▪ User friendly, outputs are easy to interpret<br>▪ Creating input data files can be slightly intensive<br>▪ Setting up input files for use within Portfolio can be rather complicated | ▪ User friendly<br>▪ Most complicated part of this program is setting up the input data files<br>▪ Setting up selection scenarios has an easy to navigate windows interface and allows for settings to be changed easily and quickly<br>▪ Output files are fairly straightforward and easy to interpret |
| **Other Design Features** | ▪ sites can be locked in or out of the selection analysis<br>▪ can incorporate phylogenetic diversity | ▪ Ancillary data for each site indicating its habitat heterogeneity, cost, and level of threat can also be used as selection criteria if the user so | ▪ Weightings – penalties for not meeting the targets for a conservation feature can be applied, thus regulating search effort |

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| | | desires. | ▪ Proportion of a given conservation feature can be set as the target<br>▪ sites can be locked in or out of the selection analysis<br>▪ cost threshold |

### *4.2 Evaluation of program attributes for the more promising optimisation methods*

Due to the superior capabilities of MARXAN, we suggest it is the most promising software program available for DFO to use at this time for the following reasons:

- Outputs allow for the identification of areas of high conservation utility, i.e. a 'Sum of Solutions' output file, where results from all runs for a given scenario may be added together to discern general trends in the selection process. Sites that are consistently selected can be considered to have higher utility relative to sites that are not (Ardron et al. 2003; Pressey et al. 1996, Stewart et al. 2003; Leslie et al. 2003;).
- Outputs such as that described above can help facilitate stakeholder negotiations by identifying which sites are flexible with respect to possible inclusion.
- It uses penalties rather than constraints to assign cost. Penalties direct the relative search effort for a feature, whereas targets (constraints) set the end-point of that search (Ardron et al. 2002).
- It can assist in drawing mpa boundaries – if the planning units used to define the study region mimic meaningful ecological boundaries or are at a high enough resolution, they can help in determining where appropriate boundaries should be placed. However, there will be administrative and socio-economic concerns that will also be involved in drawing boundaries that MARXAN may not be able to incorporate into the selection process.
- It can apply the simulated annealing algorithm.
- If so desired, it allows one to run several different algorithms and compare the solutions produced.
- It can use integer and non-integer data and it can incorporate ecological as well as socio-economic data. Socio-economic concerns can be incorporated through a cost function which directs the algorithm away from more expensive areas. Cost can be defined as economic value, commercial resource and so on.
- It can be used at any scale and there is no ceiling to the number of data layers (selection criteria) or constraints that can be incorporated into analyses.
- It has the ability to identify MPAs for the five reasons given in the Oceans Act, as well as for other reasons that fulfil other agency mandates (such as representation).
- It is highly spatially capable and therefore can incorporate the necessary requirements for connectivity. Thus it can indirectly help to ensure species persistence. However, the appropriate level of connectivity (i.e. separation distance) must be determined outside of the program.
- It has the added feature of allowing sites to be locked in or out of the selection process. This is a useful function as it can ensure that existing areas are included in the network design and/or that areas of high socio-economic use are left out.

- Relative weightings can be assigned to different conservation features, thus promoting that the search effort of the selection process is either driven towards or away from particular areas.
- It is currently being applied in Canada (see 4.0 below).

Although there are numerous advantages to using the MARXAN software over others reviewed here, it is important to be aware of and understand the limitations as well.

- The designation of weightings that can be applied to the selection process in MARXAN is inherently value-ladened and subjective. Although most model-based programs have this limitation it is of value to understand how the different weightings or other program parameters set by the user will effect the outputs produced. An easy way in which to address this issue is to perform a sensitivity or power analysis. MARXAN does provide a type of power analysis itself through generating the "missing values" output file. This file gives a 'score sheet' for each analysis run that indicates the amount or percentage of a target met for each conservation feature. This allows for managers to identify if features are under or over-represented and adjust the weightings accordingly. This also identifies the importance of critically evaluating the outputs from selection algorithms.
- There is a lack of transparency as to why or when (during the selection process) a given site is selected because this technique is attempting to evaluate the 'set of sites' rather than individual sites;
- Uncertainty and variability in results associated with the removal or locking in of any given site. This method is the most likely to show variability in the set of sites selected if any given site is removed from consideration. Other selection processes are more deterministic and therefore predictable in this aspect;
- MARXAN and its predecessors are very flexible with numerous user inputs that can create markedly different selection results. This flexibility and the lack of fixed methods of using this tool create variation in outputs.
- Software packages that incorporate Selection Algorithms of any sort are only as good as the input data used to run them. Therefore it is important to be cautious of the quality of the data going into these programs as much as the solutions coming out.

# *5 CURRENT MARXAN-BASED ANALYSES WITHIN CANADA*

In Canada, Living Oceans Society (LOS) and World Wildlife Fund Canada (WWF) have already been exploring the use of selection algorithms in marine network design. Therefore it is important that we recognise and review these analyses to determine if they can be used by DFO to help further their mandate. The near shore analysis conducted by The Nature Conservancy (TNC) within the Georgia Strait region and for the Coast Information Team was not reviewed because we are only examining marine rather than coastal analyses at this time.

## *5.1 World Wildlife Fund Canada – Atlantic Coast*

### 5.1.1 Purpose of analysis

WWF, in collaboration with the US-based Conservation Law Foundation, have been developing a mpa planning framework for the greater Gulf of Maine and Scotian Shelf region along Canada's Atlantic coast (Fig. 1). The objective of the framework is to identify and assess Priority Areas for Conservation (PACs) as an initial step towards the establishment of a network of mpas that incorporates both ecological and socio-economic considerations.

Like DFO, WWF advocates a two pronged approach to marine conservation that strives to 1) protect and conserve marine life and habitats and 2) allow for sustainable resource utilisation.

Their process for establishing such a network of mpas is set out in 3 phases. Phase 1 involves the mapping of representative and distinctive areas and the subsequent identification of a set of PACs, phase 2 seeks to determine connectivity requirements among PACs and phase 3 considers socio-economic and cultural factors (WWF 2004).

WWF/CLF are currently in the process of completing phase one and are expecting to release a formal report describing their identification of an initial set of PACs later this year (2004). It is anticipated that the initial set of PACs identified will provide the starting point for a broad public discussion about what a regional conservation plan and network of protected areas should look like.

### 5.1.2 Methods used to select Priority Areas for Conservation (PACs)

MARXAN was chosen as the decision support tool and simulated annealing as the algorithm to carry out the selection of an initial set of spatially optimal PACs. The study area was divided into three Biogeographic regions (Scotian Shelf, Bay of Fundy/Gulf of Maine, and Georges Bank) (Fig. 1) The following groups of conservation features (totalling 80 individual data layers) were used as selection criteria (a combination of species distribution data, physical anomalies and habitat data) in their preliminary selection analyses:

1) Pelagic and benthic seascapes (surrogates for habitat types) – (representation)
2) Adult fish species abundance – (surrogate for important habitat)
3) Juvenile demersal fish species abundance – (surrogate for nursery areas)
4) Demersal fish species richness – (biologically distinct areas)
5) Cetacean species abundance – (surrogate for important habitat)
6) Areas of anomalous Chlorophyll a concentration – (surrogate for areas for high primary productivity)

The fundamental goal of their analysis is the representation of conservation features from each biogeographic region. In MARXAN the level of representation desired is stated in the form of a target. Targets were defined as simple percentages of values already expressed in the conservation feature. However, since an appropriate level of representation for each of the conservation features needed in order to conserve biodiversity is not known at this time,

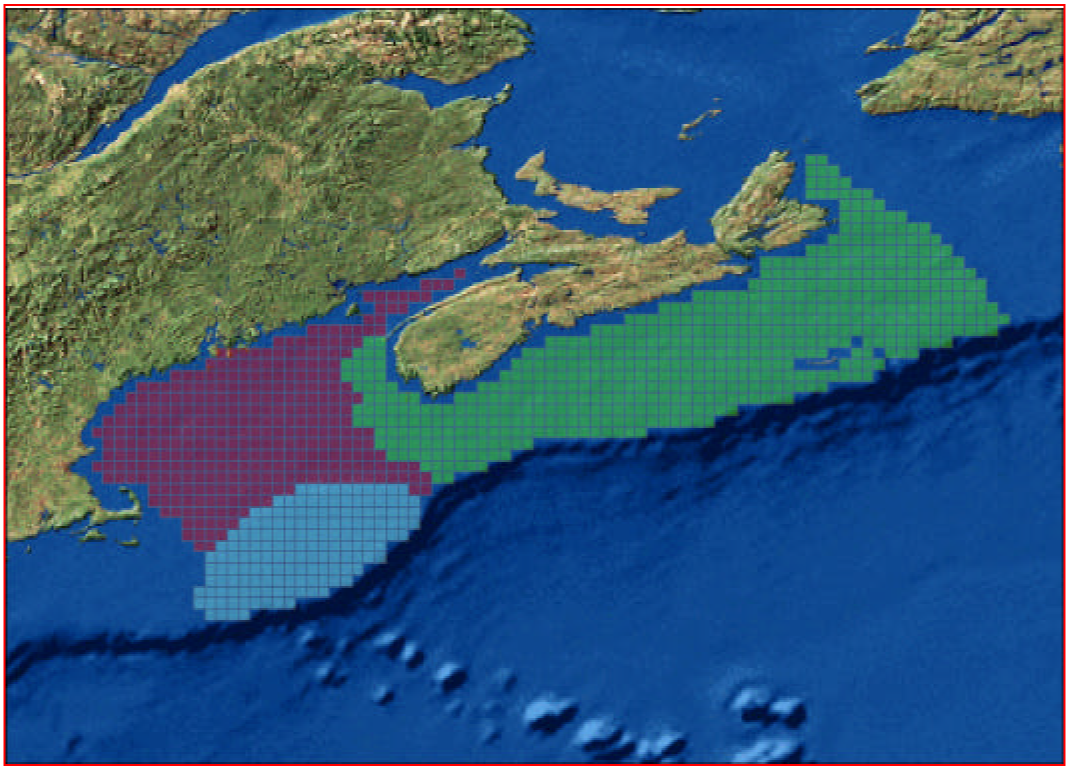

Figure 1. Planning units included in Marxan analysis, symbolised by Biogeographic Region. Green represents the Scotian Shelf Biogeographic region, red the Gulf of Maine/Bay of Fundy region, and light blue the Georges Bank region.

WWF/CLF applied a range of targets (10%, 20%, 30%). All conservation features were given the same representation target for a given scenario.

To assure that the desired level of representation was being achieved for all conservation features and not just some, WWF/CLF iteratively increased the CFPF for individual conservation features whose targets were not met until representation of those features in the best scenario of 100 runs reached at least 90% of the representation target (WWF unpublished).

Investigating the concept of spatially efficient reserve compactness is quite important since perimeter length can be seen as having an effect on ecological viability and also as a measure of implementation cost and management complexity. WWF/CLF set out to explore this through varying the level of aggregation among selected sites by small increments (0.1, 0.25, 0.5, 0.75, 1.0) within the scenarios they ran. They applied a general 'rule of thumb' that an appropriate level of aggregation would be when the reserve system appeared cohesive and it contained no more than about 30 distinct clumps. However they did not set out to directly address spatial concepts in phase 1 of their analysis (WWF unpublished).

WWF/CLF have plans to continue to refine their analysis by adding other ecological data layers into new Marxan analysis for the selection of an initial set of PACs such as; pelagic seabird distributions, important areas for deep sea corals, gravid female demersal fish species abundance, bathymetric anomalies, sea surface temperature anomalies, sea surface height anomalies.

Results / Outputs
When reviewing and interpreting results from their analysis, the initial set of PACs in phase 1 have been determined mainly through identifying areas of high conservation utility from MARXAN's 'sum of solutions' output file. This is due to the fact that the present selection analysis created by WWF/CLF, the 'best run' does not constitute a network and does not reflect data on socio-economic preferences, existing protected areas, ecological integrity or connectivity. The utility of a site is expressed as the percentage of times, over several MARXAN runs (in this case 100), that a site is selected. The more consistently a planning unit is selected, the more useful it is to a portfolio of protected areas. Again this type of output allows for areas of flexibility to be identified and can facilitate discussions with other stakeholders (WWF unpublished). It is important to point out that while these areas of high utility on their own may not capture 100% of the representation targets for all conservation features, it does highlight areas of substantial overlap and indicate where initial conservation efforts should be focussed.

## *5.2 Living Oceans Society – Pacific Coast*

### 5.2.1 Purpose of analysis

Living Oceans Society has carried out several marine ecosystem spatial analyses along Canada's Pacific coast, with the majority of their work within the Central Coast region. The most recent analysis has been conducted as part of an ecosystem spatial analysis project headed up by the Coast Information Team (CIT; see www.citbc.org and Ardron. 2003). The study area for this includes Haida Gwaii, Central Coast, and the North Coast regions of British Columbia.

The purpose of the CIT analysis, including the marine ecosystem spatial analyses performed by LOS, is to identify priority areas for biodiversity conservation. More specifically, there are four goals of this project:

1) represent ecosystems across their natural range of variation
2) maintain viable populations of native species
3) sustain ecological and evolutionary processes within an acceptable range of variability
4) build a conservation network that is resilient to environmental change

The focus of the marine analysis conducted by the LOS has been on applying mathematical algorithms to choose an efficient collection of marine reserves amongst numerous combinations of many differing features with the eventual goal of creating a network of mpas within the region (Ardron 2003).

### 5.2.2 Methods used to achieve objectives

LOS also used the simulated annealing algorithm in MARXAN to identify the priority areas for conservation within the CIT study region. This analysis completed by LOS is of a more complex nature than that initiated by WWF and CLF. Data layers for 93 conservation features were used in their selection of priority areas which comprised of species, biologically distinct areas, and habitats (for a full listing of these layers please refer to Ardron 2003). The following list summarizes the data layers used by type.

1) Regional data regions – (regional representation)
2) Ecosections – (ecosystem representation)
3) Enduring features and processes – (ecosystem representation)
4) Benthic complexity (distinctive feature)
5) High current areas (distinctive feature)

6) Focal species (flora, seabirds, fish and mammals)
7) Rare and threatened species (sponges, corals, sea otter, estuaries, seabirds)

Beyond the difference in data layers incorporated into the analysis, there are also differences in the way LOS and WWF/CLF set up their MARXAN selection scenarios. LOS chose to assign relative rankings (low, moderate-low, moderate, moderate-high, high and very high) to each of the 93 conservation features. Lower rankings were assigned to features that were common (i.e. plentiful) and higher rankings were assigned to features that were more unusual or rare. This allowed for each feature to be assigned a level of importance (class) relative to the other features.

When designing the selection scenarios each class was assigned a numerical representation target (i.e. all features within the same class would have the same representation target but those within different classes had different representation targets). The range of representation targets assigned corresponded to the overall reserve system size desired. LOS explored a variety of scenarios that produced overall areas ranging 5%, 10%, 20%, 30%, 40%, and 50% of the study area. Relatively ranking the features in such a way allowed LOS to incorporate dimensionless criteria such as distinctiveness or naturalness.

LOS also ranked areas within an individual data layer to apply an indication of relative importance of individual sites within a data layer. For example areas of higher quality habitat or known areas of importance for a particular species were given a weighting to indicate their relative value when choosing among sites within a data layer.

The following MARXAN parameters were used in their analysis: 1)conservation feature representation targets 2) penalty values assigned to each conservation feature to indicate the relative cost accrued for not attaining that features representation target, 3) varying levels of clumping among selected sites, and 4) boundary cost - also used to influence degree of clumping and allow for more fragmented solutions in areas constrained by geography (such as inlets) but encourage clumped solutions in open water areas such as the continental shelf or slope regions.

<u>Results / Outputs</u>
LOS examined the results from several scenarios with varying conservation feature representation targets and reserve degrees of fragmentation among selected sites, for emergent trends (similar to WWF/CLF's analysis). Not only did they look at the trends within the runs of an individual scenario but also across scenarios, thus identifying those areas that are repeatedly selected under a variety of conditions (Fig. 3). Again those sites that are repeatedly selected can be interpreted as having a high 'utility' to meeting the desired design requirements of the reserve system.

Again while the areas identified as having high utility alone may not constitute a network which fully meets all representation targets, they can indicate where initial conservation efforts should be focused. Additional sites can then be added to these areas to build a network of mpas that fully meet the desired reserve network design requirements. This can be done through subsequent MARXAN analysis in which the areas of high utility chosen to be part of the network are locked into the analysis and then MARXAN is asked to select additional sites until those features with under-represented targets are fully met.

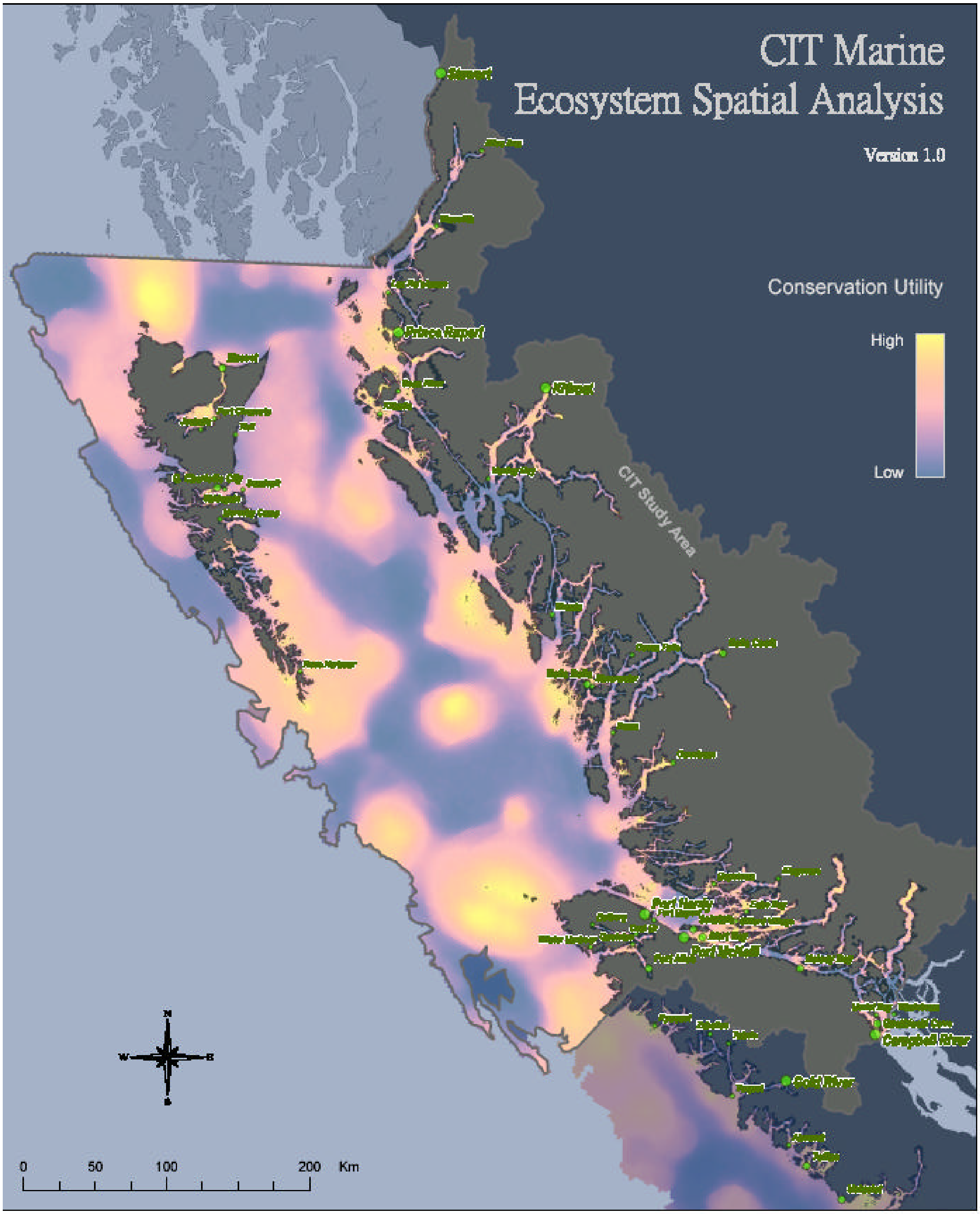


Figure 3. Example of the trends resulting from the selection analysis along Canada's BC coast performed by Jeff Ardron, Living Oceans Society, for the Coast Information Team marine

### 5.3 *Conclusion – how these analyses can assist DFO*

Both the WWF/CLF and LOS analyses hold promise and can provide DFO with critical information on the lessons learned from the development of their ecological framework (WWF) and their application of numerous MARXAN explorations along both Canadian coasts (LOS and WWF). Both groups have gathered and compiled enormous amounts of data, from multiple sources, into useable input data layers for selection algorithms. The information gained from the different MARXAN explorations performed by both WWF and LOS provides insight into 1) meaningful ways in which to integrate different types of data; 2) various ways in which to deal with assigning conservation targets and weightings; and 3) the various outputs available and their possible interpretation. These lessons learned and the compiled data can be of great value to DFO when performing its own selection analysis.

The planning framework developed by WWF/CLF mimics other frameworks that have been successfully used in other countries (e.g. GBRMPA in Australia). Consulting this framework for guidance may be advantageous for DFO while they continue to refine their own framework for implementing a network of MPAs.

The intended purpose of the initial set of sites selected through both analyses is to provide a broad-brush report of the distribution of conservation values and a methods of prioritising those places in most urgent need of research, mapping and action. However the selection analysis performed by WWF/CLF is still in its infancy and thus can't be evaluated with respect to meeting its objectives in the same way the completed project performed by LOS can. With regard to the four goals of the CIT project noted above, only the first one was fully addressed and met in our opinion within this analysis. However, this is likely a result of insufficient data than a poor analysis per se. This analysis did not have the spatial data necessary to fully meet goals 2 and 3 which deal with species persistence (pers. comm. J. Ardron, Mar. 2004). However, the incorporation of many differing datasets indirectly tries to address ecosystem function issues.

# 6 *CONCLUSIONS AND RECOMMENDATIONS*

## 6.1 *Conclusions*

Choosing the most appropriate methodology depends on the underlying goal for establishing the set of mpas. Clearly defining the purpose and the overall conservation goal is an important first step that must not be overlooked.

Spatial optimisation offers a powerful solution to MPA network design and while these programs make a contribution to improving rigour, transparency and efficiency of what is a rather complicated process, they only contribute to part of the marine conservation planning process. Thus, other decision support tools (such as GIS and Delphic approaches – see Lewis et al. 2003) may need to be employed in conjunction with these selection programs when fine-tuning boundaries, considering zoning, or when choosing among candidate sights that are of interest to several stakeholder groups. Selection programs such as those reviewed here are most successful when they are embedded within a larger decision making framework such as that used in the re-zoning of the Great Barrier Reef in Australia (Lewis et al. 2003).

It is important to recognise that while the approach to establishing a network of MPAs must have a scientifically sound design, It must also have stakeholder buy-in for the implementation to be a success (Ward et al. 2001). Public Consultations with other stakeholder groups will be necessary to identify additional selection criteria encompassing social, economic and cultural concerns that will need to be incorporated into subsequent MARXAN analyses to refine the initial set of site selected. Communities and Industry should also be highly involved in determining the objectives for the MPA network. It is important to engage and bring other interest groups to the table and encourage their participation in reviewing and selecting among the candidate sites. This will undoubtedly require discussion and flexibility among all stakeholders.

Site selection algorithms also perform best when they are optimising more versus fewer constraints. When combined with distinctive area conservation features, MARXAN capitalises on the flexibility inherent in the representation habitat criteria to build sites that protect both types of ecological values while minimising cost and area selected (excerpt from WWF 2004).

DFO Managers require information that will help them make decisions while allowing them the flexibility to evaluate possible trade-offs between multiple stakeholder activities. The outputs of selection algorithms can assist in managers drawing boundaries given that the model's planning units (sites) are of appropriate for the desired scale of planning.

There are limitations to the selection methods reviewed here that should be recognised so that they can be used appropriately. Results should not be considered a final evaluation as not all requirements of an MPA network can be addressed using optimisation algorithms (Oeting and Knight, 2003). For these considerations (e.g., species-persistence), a post or pre-selection analysis would be necessary. The programs reviewed here also cannot answer questions such as what size an mpa should be, or directly indicate where the exact boundaries of an mpa should be drawn. Nevertheless, these programs provide a powerful contribution by objectively synthesizing large amounts of data and "allowing decision-makers to focus on the most critical points of evaluation" (Oeting and Knight 2003).

### *6.2 Recommendations*

1) DFO should consider the use of site selection methodologies in its IM program
2) MARXAN is the most appropriate method for DFO to use at this time in identifying AOIs in mpa network design since it is the most sophisticated program of its kind.
3) We recommend that planning a network of mpas be done at multiple scales to account for the diverse set of objectives involved in developing a network. For example it may be necessary to run separate analyses for the coastal management area (CMA; fine scale) and Large Ocean Management Area (LOMA; coarser scale) scales within the marine environment. This is in part due to the fact that significant ecological processes and available data will occur at different scales within these regions. Finer scale data tends to be available for coastal regions as they are easier and more frequently surveyed. There is also usually more activity within this region, so we tend to know more about it and need to protect it to a greater extent.
4) Ideally, analyses should be performed using a multiplicity of datasets and MPA objectives across government departments as optimisation programs are most powerful when balancing a wide variety of objectives. Such an approach would produce more efficient solutions for an optimal mpa network design than addressing each department's objectives individually.
5) Whether there is a difference in the efficiency (amount of area required) to meet each agency's mandate separately or in a combined network design should be evaluated. This would involve determining how much overlap there is among analyses considering each agency's mandate.
6) The analyses performed by WWF-Canada and Living Oceans Society can help DFO develop their own MPA network by providing information on the lessons learned from

applying MARXAN on both coasts such as the need for clearly defined ecosystem objectives, data requirements and program limitations.

7) Mpa analyses are currently ongoing, at least by engos, in the Central/North coast and West coast of Vancouver Island, but a noticeable gap in areas being analysed is the Strait of Georgia (there has been a limited analysis in the “Orca Pass” area (northern San Juan islands and southern Gulf Islands) by some American engos). Given that a Parks Canada National Marine Conservation Area is being proposed for part of this area, and many rockfish protection areas have recently been established by DFO, there would seem to be an immediate need to undertake a more comprehensive analysis here. Since DFO supposedly has the lead in coordinating mpa planning among at least federal agencies, there is opportunity to show leadership here by initiating mpa network analyses in the near future.
8) It is recommended that the outcomes produced by these selection methods be compared and evaluated within the context of DFO’s management needs.
9) To facilitate future analyses, ecological attributes for potential priority sites need to be defined in terms of parameters reflective of criteria used by different agencies to rationalise their mandates to establish mpas.
10) The work done by Living Oceans Society on the pacific coast to date has not been specifically designed with any particular agency’s mandate in mind. In fact in a sense it is a ‘melting-pot’ addressing several agency mandates. Therefore it might be advantageous to run the analysis again and separate out the data layers used in the selection process by which mandate they speak to. For example, Environment Canada would be concerned with areas important for birds, but not for fish and DFO would be concerned with those areas important to fish but not to birds. Separating the analysis out in such a fashion can help to identify those sites chosen in a network analysis that can help the individual agencies meet their mandate (i.e. which sites out of those identified as candidates should be designated by which agency).

# 7 GLOSSARY OF TERMS

**Algorithm -** A step-by-step problem-solving procedure, especially an established, recursive computational procedure for solving a problem in a finite number of steps.

**AOI -** Area of Interest. These are candidate MPAs announced by Fisheries and Oceans Canada that are being considered under the Oceans Act.

**Bioregion -** An area of land and /or water whose limits are defined by a geographical distribution of biophysical attributes and ecological systems.

**Complementarity -** The state or quality of being complementary.

**Connectivity -** Refers to the necessary spatial connection among selected marine protected areas to ensure species persistence and the conservation of ecological processes.

**Conservation feature –** Any feature for that can be used as a selection criteria from which to select areas for conservation priority.

**Cost -** Quantifiable measure of social or economic cost such as foregone opportunity, implementation, management, acquisition, or nearly anything else.

**Distinctive areas -** Those areas exhibiting unique physical or biological characteristics of importance to maintaining ecosystem function and species persistence.

**Ecoregion -** A part of a larger marine area (ecoprovince) characterized by continental shelf-scale regions that reflect regional variations in salinity, marine flora and fauna, and productivity (Harper et al. 1993).

**Ecosystem -** A definable part of the biosphere consisting of several interacting communities which receives inputs from the surrounding land, water and atmosphere.

**Efficient -** The ability of the site selection program to choose a set of sites that will achieve comprehensive representation of biodiversity whilst also minimizing the total cost.

**Gap Analysis -** A technique designed to evaluate existing protected areas with regard to their representativeness (of marine ecosystems), to determine what further representation is required and to identify where those additional protected areas are located.

**Greedy Heuristic -** Also known as the richness heuristic, these heuristic algorithms attempts to improve a reserve system as quickly as possible by choosing the sites which have the most unrepresented features.

**Habitat -** A space with definable physical characteristics and limits within which organisms live.

**Heuristic -** Relating to or using a problem-solving technique in which the most appropriate solution of several found by alternative methods is selected at successive stages of a program for use in the next step of the program.

**Iterative -** Characterized by or involving repetition, recurrence, reiteration, or repetitiousness.

**MPA -** Federal Oceans Act Marine Protected Areas.

**mpa -** A term that encompasses all the legislated designations of protected areas established by any government agency. This includes MPAs, National Marine Conservation Areas, provincial and federal parks, etc., as summarised for BC by Jamieson and Lessard (2001).

**Network -** A network of marine protected areas differs from a set or system by implying there is some level of connectivity among the designated mpas within a region.

**Optimality -** Maximum efficiency of representation in terms of the number or area of selected sites or maximum complementarity of sites.

**Planning unit -** An individual grid site (of some particular size) within the planning region.

**Representativeness -** The extent to which sites identified for , or already declared as, protected areas reflect known biological diversity, environmental and ecological patterns and processes, and physical features at various scales.

**Representative areas -** Those areas that capture the full range of habitats and their associated species assemblages that are typical in a prescribed region.

**Stochastic -** Involving or containing a random variable or variables; Involving chance or Probability.

**Utility -** The utility of a site is expressed as the percentage of times, over several MARXAN runs (in this case 100), that a site is selected. The more consistently a planning unit is selected, the more useful it is to a portfolio of protected areas.

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# 9 APPENDIX 1 – SELECTION ALGORITHM OVERVIEW SUMMARY TABLE

Table 1. Comparison of the program attributes for the selection algorithms reviewed.

| | Program type | | | | | | | Scale | | Run Time | | Data type | | | Spatial Constraints | | | Output | | | | Other Aspects | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Site Selection Methods** | **Scoring** | **iterative** | **Complementarity** | **Exact optimisation** | **Non-exact optimisation** | **Stochastic** | **Pre/post-selection** | **Fine Scale** | **Large Scale** | **Slow Computation** | **Fast Computation** | **Quantitative data** | **Qualitative data** | **Requires detailed data** | **Clumping / adjacency** | **Site separation distance** | **Population Demographics** | **Deterministic solution** | **Multiple solutions possible** | **Tracking of selection process** | **Visually displayed** | **Transparent process** | **Excessive uncertainty** | **Incorporates many objectives** | **Value ladened decisions** |
| **Scoring** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Compare | v | | | | | | | v | | | v | v | v | v | | | | v | | | | | v | v | v |
| MCA | v | | | | | | | v | v | | v | v | v | v | | | | v | | v | | v | v | v | v |
| **General Iterative** | | | | | | | | | | | | | | | | | | | | | | | | | |
| CPLEX | | v | v | v | | | | v | v | v | | v | | | | | | v | | v | v | v | | v | v |
| LP_SOLVE | | v | v | v | | | | v | v | v | | v | | | | | | v | | v | v | v | | v | v |
| **Simple Heuristics** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Cplan | | v | v | | v | | | v | v | | v | | | | | | | v | | v | v | v | | | v |
| TRADER | | v | v | | v | | | v | v | | v | v | | v | | | | v | | v | | v | | v | v |
| BioRap | | v | v | | v | | | v | v | | v | v | | v | | | | v | | v | | v | | v | v |
| WORLDMAP | | v | v | | v | | | v | v | | v | v | | | | | | v | | v | | v | | | v |
| Portfolio | | v | v | | v | | | v | v | | v | v | | v | | | | v | | v | v | v | | | v |
| **Simulated Annealing** | | | | | | | | | | | | | | | | | | | | | | | | | |
| MARXAN | | v | v | | v | v | | v | v | | v | v | | | v | v | | | v | v | v | v | | v | v |
| **Explicitly Spatial** | | | | | | | | | | | | | | | | | | | | | | | | | |
| Environmental Distance Model | | | v | | | | v | v | | | v | v | | v | | v | v | | | v | v | v | v | | v |
| Population Model | | | v | | | | v | v | | | v | v | | v | | v | v | | | v | v | v | v | | v |

Figure 1. The relationship of the various site selection methodologies reviewed within this paper.