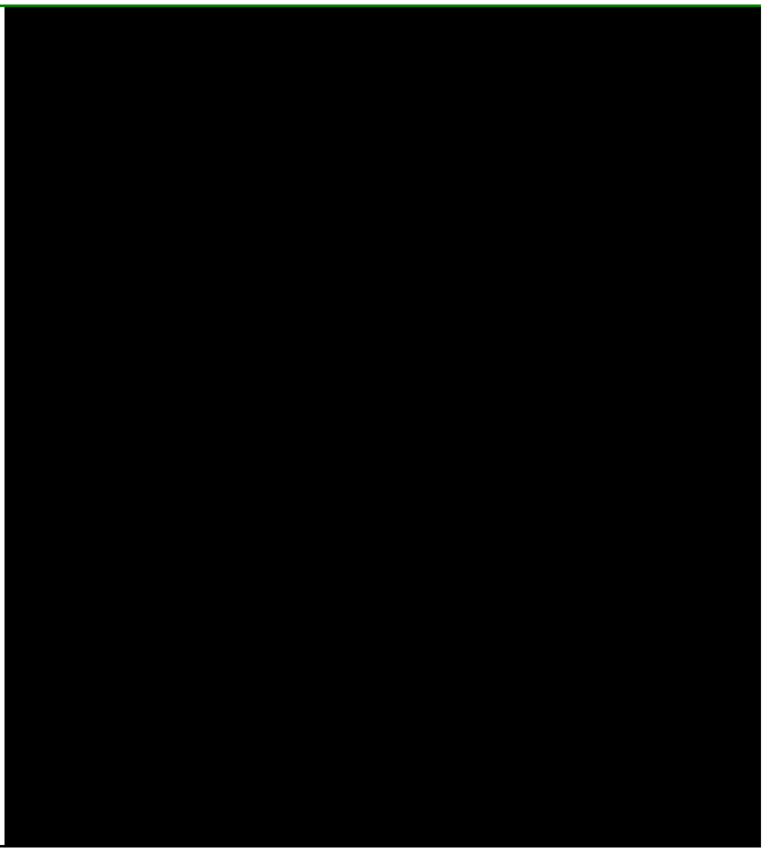
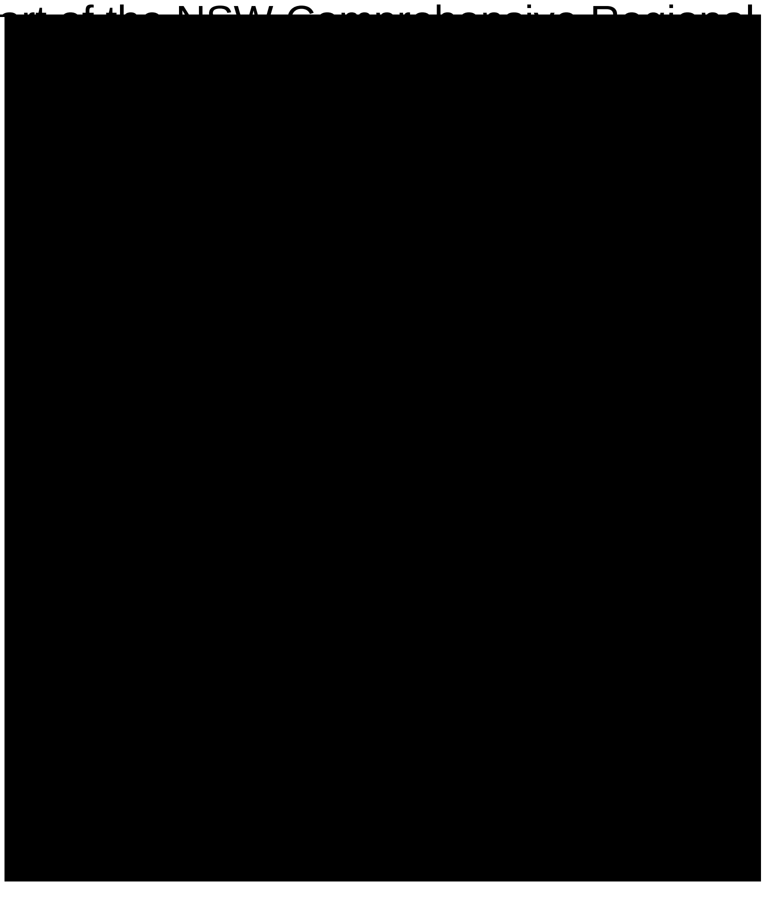


Development of C-Plan functionality to guide achievement of spatial configuration objectives

A project undertaken as part of the NSW Comprehensive Regional



DEVELOPMENT OF C-PLAN FUNCTIONALITY TO GUIDE ACHIEVEMENT OF SPATIAL CONFIGURATION OBJECTIVES

NSW NATIONAL PARKS AND WILDLIFE SERVICE

A project undertaken for
the Joint Commonwealth NSW Regional Forest Agreement Steering Committee
as part of the
NSW Comprehensive Regional Assessments
project number NA 60/EH

July 1999

For more information and for information on access to data contact the:

Resource and Conservation Division, Department of Urban Affairs and Planning

GPO Box 3927
SYDNEY NSW 2001

Phone: (02) 9228 3166
Fax: (02) 9228 4967

Forests Taskforce, Department of the Prime Minister and Cabinet

3-5 National Circuit
BARTON ACT 2600

Phone**:** 1800 650 983
Fax: (02) 6271 5511

ISBN 1 74029 046 1

This project has been jointly funded by the New South Wales and Commonwealth Governments and managed through the the Resource and Conservation Division, Department of Urban Affairs and Planning, and the Forests Taskforce, Department of the Prime Minister and Cabinet

The project has been overseen and the methodology has been developed through the Environment and Heritage Technical Committee which includes representatives from the New South Wales and Commonwealth Governments and stakeholder groups.

CONTENTS

PROJECT SUMMARY

This working paper describes a project undertaken as part of the comprehensive regional assessments of forests in New South Wales. The comprehensive regional assessments (CRAs) provide the scientific basis on which the State and Commonwealth Governments will sign regional forest agreements (RFAs) for major forest areas of New South Wales. These agreements will determine the future of these forests, providing a balance between conservation and ecologically sustainable use of forest resources.

Project objective/s

The primary objective of the project was to develop added functionality within the C-Plan decision support software being used to select reserves in the New South Wales CRA process. This new functionality was intended to automate derivation of measures (indices) to guide the achievement of spatial configuration objectives specified by nationally agreed criteria for the establishment of a comprehensive, adequate and representative system of forest reserves.

Methods

Two types of measures were developed and implemented within the C-Plan software :

- *Measures of patch size and connectivity* to facilitate improved consideration of criteria such as "reserves should be large enough to sustain the viability, quality and integrity of populations", "protection of the largest and least fragmented areas of old-growth", "large reserved areas are preferable to small reserved areas" and "reserves should be linked through a variety of mechanisms".
- *Measures of geographical and environmental spread* to facilitate improved consideration of criteria such as "reserved areas should be replicated across the geographic range of the forest ecosystem", "the reserve system should ... sample the full range of biological variation within each forest ecosystem, by sampling the range of environmental variation typical of its geographic range" and "representation of old-growth forest across the geographic range of the forest ecosystem".

Key results and products

The software produced by this project provides a greatly enhanced capability to address spatial configuration objectives when selecting new forest reserves.

1. INTRODUCTION

1.1 BACKGROUND

The *Nationally Agreed Criteria for the Establishment of a CAR Reserve System for Forests in Australia* (JANIS 1997) specify a number of criteria relating to the spatial design or configuration of reserves. Section 7 of the JANIS report specifies general design criteria which should influence selection of reserves. In addition to these general criteria the report also specifies a number of specific criteria relating to the required spatial configuration of reservation for individual biodiversity entities. In relation to species, Biodiversity Criterion 6 states that "reserves should be large enough to sustain the viability, quality and integrity of populations". In relation to forest ecosystems, Biodiversity Criterion 4 states that "reserved areas should be replicated across the geographic range of the forest ecosystem to decrease the likelihood that chance events such as wildfire or disease will cause the forest ecosystem to decline" while Biodiversity Criterion 7 states that "to ensure representativeness, the reserve system should, as far as possible, sample the full range of biological variation within each forest ecosystem, by sampling the range of environmental variation typical of its geographic range". In relation to old growth, Old Growth Criterion 2 includes two specific spatial configuration objectives, namely "representation of old-growth forest across the geographic range of the forest ecosystem" and "protection of the largest and least fragmented areas of old-growth".

Application of the JANIS spatial configuration criteria has proved to be problematic in previous NSW forest assessments (Interim Forest Assessment and Eden CRA). The C-Plan decision support software used in these assessments has not allowed spatial configuration criteria to be addressed in an effective manner. Previous approaches to dealing with spatial configuration have resulted in an overly cumbersome and inefficient reserve selection process. For example, criteria relating to geographical and environmental spread have been addressed by splitting entities into sub-regions and assigning separate reservation targets to each of these sub-regions. This has resulted in a proliferation of reservation targets and has severely limited the flexibility with which geographical and environmental spread of reservation can be achieved. Criteria relating to patch size were addressed in the Eden CRA by visually identifying areas containing large patches of particular entities, which required working with entities one at a time. This resulted in a very slow selection process, and probably promoted inefficiencies in reservation because overlap between the needs of multiple entities could not be readily considered.

1.2 PROJECT OBJECTIVES AND GENERAL APPROACH

The primary objective of this project was to develop functionality within the C-Plan software package to automate derivation of measures (indices) to guide achievement of spatial configuration objectives in building a CAR reserve system. Spatial configuration criteria specified in JANIS (1997) were addressed through implementation of two types of measure:

- ☑ *Patch size and connectivity*, to facilitate improved consideration of Biodiversity Criterion 6 "reserves should be large enough to sustain the viability, quality and integrity of populations", Old Growth Criterion 2 "protection of the largest and least fragmented areas of old-growth" and General Reserve Design Criteria 2 "large reserved areas are preferable to small reserved areas", 3 "boundary-area ratios should be minimised" and 7 "reserves should be linked through a variety of mechanisms".
- ☑ *Geographical and environmental spread*, to facilitate improved consideration of Biodiversity Criteria 4 "reserved areas should be replicated across the geographic range of the forest ecosystem" and 7 "the reserve system should ... sample the full range of biological variation within each forest ecosystem, by sampling the range of environmental variation typical of its geographic range", Old Growth Criterion 2 "representation of old-growth forest across the geographic range of the forest ecosystem" and General Reserve Design Criterion 4 "reserves should be developed across the major environmental gradients".

The functionality developed by this project was designed to enable 'patch size/connectivity' and 'geographical/environmental spread' to be considered at two different points within C-Plan:

- ☑ When assessing the 'potential contribution' that individual unreserved planning units would make if they were added to the reserve system. With the new software, potential contribution can now be measured not only in terms of the contribution to achieving areal targets (via existing irreplaceability indices) but also in terms of the contribution to achieving spatial configuration objectives relating to patch size/connectivity and geographical/environmental spread.
- ☑ When evaluating the 'current configuration' of the reserve system. With the new software, current configuration can now be measured (and reported on) not only in terms of the achievement of areal targets but also in terms of the achievement of spatial configuration objectives relating to patch size/connectivity and geographical/environmental spread.

This project was closely linked to the C-Plan Development Project, funded separately by the NSW CRA process. The scope of the current project was the development of software modules for calculating the above spatial configuration measures, using data held in C-Plan databases. These modules were designed to be called by the C-Plan software package. The C-Plan Development Project was primarily responsible for integrating this new functionality into the existing C-Plan system, including the development of a user-interface to control the operation of the spatial configuration functionality and to present results to users.

1.3 PURPOSE AND STRUCTURE OF THIS REPORT

The main purpose of this report is to describe the analytical techniques underlying each of the new spatial configuration measures employed in C-Plan. Techniques relating to measures of patch size and connectivity are described in Section 2, while techniques relating to measures of geographical and environmental spread are described in Section 3. Each of these sections is further divided into two sub-sections, one dealing with measures relating to the potential contribution of individual planning units and the other dealing with measures relating to the current configuration of the reserve system.

Section 4 provides a brief overview of the software modules developed to calculate the new spatial configuration measures. This report does not provide a detailed description of the C-Plan user-interface for invoking and reporting spatial configuration measures (see the C-Plan software package and accompanying user's documentation for this detail), nor does it include technical system or programmer's documentation for the developed software (such documentation has been provided to, and is held by, the C-Plan Development Team within NSW NPWS).

2. PATCH SIZE AND CONNECTIVITY

2.1 POTENTIAL CONTRIBUTION OF INDIVIDUAL PLANNING UNITS

C-Plan already generates a number of indices (irreplaceability etc) that measure the potential contribution of unreserved planning units to achievement of areal feature targets. These indices use information only on the occurrence of features within the unit of interest, without any consideration of the distribution of features in the surrounding area or the proximity of existing reserves. C-Plan now allows spatial context to be automatically factored into the derivation of any of the existing indices. C-Plan can adjust an index to reflect spatial context by first estimating the index for individual planning units in the normal manner and then transforming the value for each unit according to the values of other units in the surrounding area. The extent of the ‘surrounding area’ considered in these calculations is determined by a user-specified radius. The transformed index assigned to each planning unit is calculated as a distance and area weighted average of the values (e.g. summed irreplaceabilities) of units falling within a specified radius of the unit of interest. The contribution of each unit within this radius decreases with increasing distance from the unit of interest and also decreases with decreasing unit area. If only a part of a unit lies within the radius the contribution of that unit to the weighted average is appropriately adjusted (this adjustment accounts for much of the complexity in the calculations given below). Reserved planning units are allocated a user-specified constant value reflecting the weight that existing reserves should carry in the calculations. This allows the user to control the extent to which the spatial index will reflect proximity to existing reserves in addition to proximity to unreserved areas of high potential conservation value.

By transforming an irreplaceability index to reflect spatial context the index is no longer just a measure of the potential contribution of each planning unit to achievement of areal feature targets but is instead a measure of the extent to which the unit is close to other units of high potential value (i.e. part of a large patch of high-value forest) and/or existing reserves. Spatially transformed indices can be derived for any specified subset of features, e.g. a single fauna species, all space-demanding fauna species or all features combined (forest ecosystems, old growth and species). When C-Plan is asked to derive an index (e.g. summed irreplaceability) adjusted for spatial context, both the original index and the transformed index are generated and made available for mapping and use in selection rules.

Spatial data used in deriving the index are extracted from a special-purpose spatial data structure (see Section 4) containing the area of each unit and the distances (edge to edge) between all possible pairs of units in the region. The shape of units is not considered in the approach – all units are assumed to be circular. The index, *Spat_contrib_index*, is calculated for a given planning unit *x* as follows (see Figure 1 for an illustration of some of these parameters):

$$Spat\_contrib\_index = \sum_{i=1}^{n} V_i \left(1 - \left(\frac{D}{d_{\max}}\right)^C\right) \frac{A}{p(d_{\max})^2}$$

where

$d_{\max}$ = the specified radius (m) around the unit of interest, x

n = the number of planning units within the specified radius

V_i = the value of planning unit i (in terms of the specified irreplaceability index)

C = a user specified constant (between 0 and 1) that determines how quickly the weight applied to surrounding units diminishes with increasing distance from the unit of interest

$D = (b + d)/2$

$A = 3a_i(d - b)/(f - b)$

a_i = the area (m^2) of planning unit i

$b = r_x + d_{ix}$

$d = r_x + d_{ix} + 2r_i$

$$f = \begin{cases} d & \text{if } d \le d_{\max} \\ d_{\max} & \text{if } d > d_{\max} \end{cases}$$

r_i = the radius of planning unit i (assuming a circular shape)

d_{ix} = the distance (edge to edge) between planning unit i and the unit of interest, x

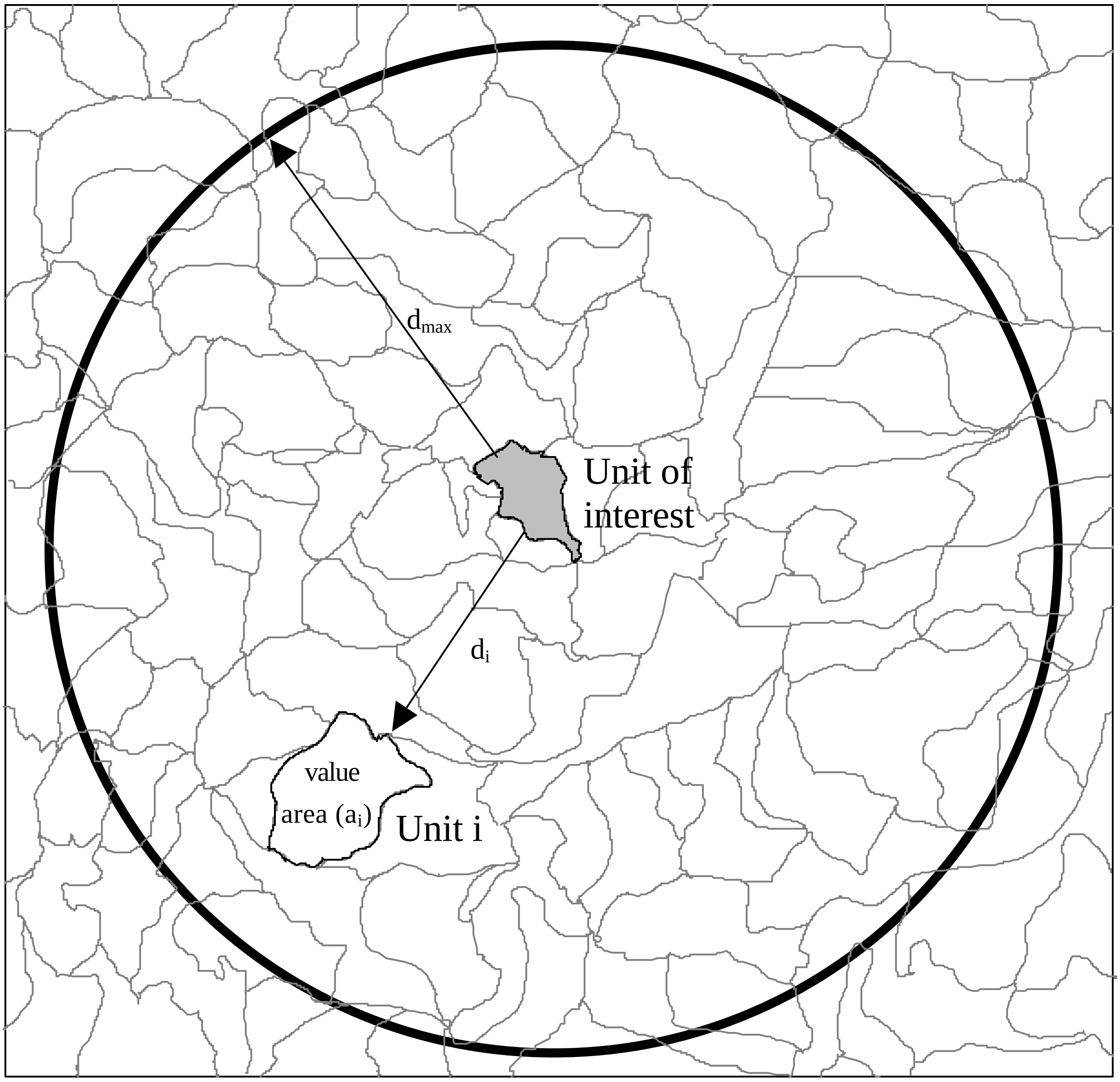


Figure 1. Parameters used in transformation of irreplaceability indices to reflect spatial context.

2.2 CURRENT CONFIGURATION OF RESERVE SYSTEM

C-Plan can now calculate a patch size/connectivity configuration index for the reserve system at any point in negotiations. The index measures the extent to which a reserve system consists of large, well connected blocks of forest as opposed to small, isolated fragments. The analytical approach employed is largely new, but incorporates ideas from incidence function modelling of metapopulations (Hanski 1994, 1997) and gravity modelling of spatial interaction processes (Sen and Smith 1995). An overall index can be calculated for the reserve system as a whole as well as separate indices for any individual features nominated by the user. For example, if six fauna species are nominated then a separate index will be calculated for each of the six species, with each index measuring the configuration of the reserve system in terms of patch size/connectivity of reserved habitat for the species concerned.

Two basic sets of data are used to calculate the index for a given feature:

- The area of the feature of interest contained within each reserved planning unit. The total area of each unit (and therefore the proportion of the unit occupied by the feature) is also known. For the overall index, the area of the ‘feature of interest’ is set equal to the total area of the unit.

- The straight line distance (or separation) between each pair of reserved planning units. For example, if there are three reserved units A, B and C then the data consist of distances A to B, A to C and B to C. Each distance is initially measured as the minimum straight line distance between the edges of the two units involved. If two planning units are immediate neighbours (i.e. they abut) the distance between them is zero.

Calculating the index for a given feature involves the following steps:

1. The distance between each pair of planning units is adjusted upwards to account for the distribution of the feature of interest within the two units involved. It is assumed that the units are circular in shape and that the known area of the feature in each unit is distributed randomly across the total extent of that unit. The adjusted distance is an estimate of the mean distance across unreserved and/or unsuitable land traversed in travelling along a straight line between any two randomly selected occurrences of the feature (one in each unit). This adjusted distance therefore reflects both the separation of the two units and gaps in the distribution of the feature of interest within each unit. An adjusted distance is also calculated between each unit and itself, which is an estimate of the mean distance across gaps in distribution encountered along a straight line connecting any two randomly selected occurrences of the feature (both in the unit of interest).

2. The adjusted distances from Step 1 are used to derive a ‘minimum spanning tree’ connecting all reserved planning units containing the feature of interest. A minimum spanning tree is a special type of linked graph consisting of nodes (planning units in this case) and connections (or branches) such that 1) all nodes have at least one connection, 2) there are no loops in the tree and 3) the summed length of branches is minimal (see Gower and Ross 1969 for details).

A simple example of a minimum spanning tree connecting eight planning units is given in Figure 2. The circles depict planning units, with A_i denoting the area of the feature of interest within planning unit *i*. The values on the branches of the tree are the adjusted distances between each pair of connected units (i.e. the units at either end of a given branch).

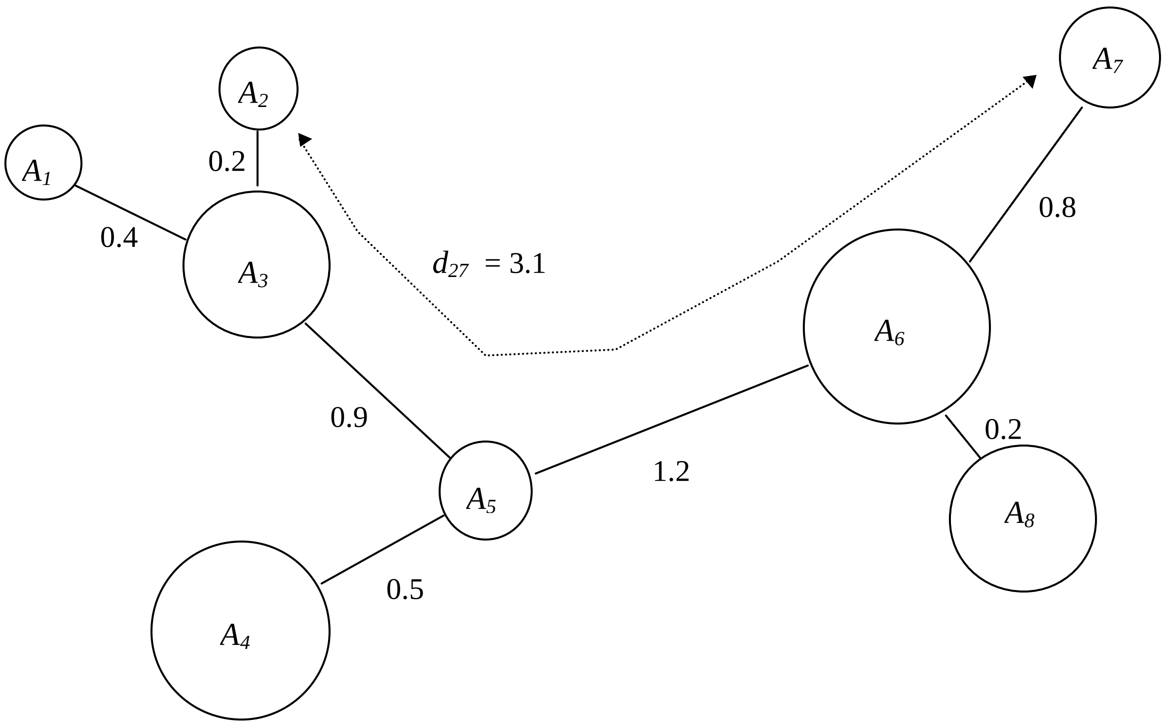


Figure 2. Simple example of a minimum spanning tree connecting eight reserved planning units.

3. The minimum spanning tree derived in Step 2 is used to estimate the 'effective distance' between all possible pairs of planning units in the reserve system. The effective distance d_{ij} between units *i* and *j* is calculated as the sum of the lengths of all branches connecting these two units. For example, in Figure 2 the effective distance between Units 2 and 7 is 3.1 (0.2+0.9+1.2+0.8).

4. An index of reserve configuration in terms of patch size/connectivity is then calculated as:

$$Spat\_config\_index = \frac{\sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n} A_i A_j e^{-\left(\frac{d_{ij}}{c}\right)}}}{\sum_{i=1}^{n} A_i}$$

where n = the number of reserved planning units
d_{ij} = the effective distance between planning units *i* and *j*
A_i = the area of the feature of interest in planning unit *i*

c = a constant parameter specified by the user

The parameter c determines how quickly the spatial interaction of units declines with increasing separation. When dealing with individual species this parameter should be an estimate of the mean dispersal distance of the species of interest (see Hanski 1994). C-Plan allows the user to specify a c value to be used in calculating the overall configuration index, as well as separate c values for individual features.

The configuration index described above ranges between zero and one. A value of one indicates a reserve system configured as one contiguous area, with no internal gaps. The value of the index decreases with increasing fragmentation of reserves. As can be seen in the above equation, the index is expressed (or scaled) as a proportion of the total current area of the reserve system. The index is therefore a measure of reserve shape, not area. C-Plan also uses this index to derive an indicative measure of configuration that combines both the shape and the total area of a reserve system (or the reserved area of a specific feature). This is achieved by simply multiplying the initial index by the total reserved area of a feature, i.e. cancelling out the denominator in the above equation.

The indices described above can be used to compare different reservation scenarios/options in terms of spatial configuration of reservation. This can be done in real-time during negotiations, allowing the impact of reservation decisions on spatial configuration to be progressively tracked throughout the process. Unless some target is set for the index (in relation to a feature) such comparisons, while extremely useful, will be relative only. In other words we can say something about whether reserve system A is better than reserve system B in terms of spatial configuration for a feature, but not anything about how good scenario A or B is in relation to a desired or optimum configuration, i.e. a target or objective.

Setting realistic targets for the patch size/connectivity index is not easy. It is theoretically possible to derive a target value from parameters indicating optimum patch size, minimum and maximum spacing between patches and average proportional occupancy of the feature within patches. However, such a target may not be achievable if sufficient patches satisfying these parameters do not exist within the region of interest. An alternative approach involves using C-Plan to manually configure a hypothetical reserve system for each feature (e.g. fauna species), containing the exact area of habitat targeted for the feature and exhibiting a spatial configuration which experts feel is ‘optimum’ for the feature in terms of patch size/connectivity. The configuration index calculated for this optimum reserve system can then serve as a target or objective for the feature concerned.

3. GEOGRAPHICAL AND ENVIRONMENTAL SPREAD

3.1 POTENTIAL CONTRIBUTION OF INDIVIDUAL PLANNING UNITS

When calculating summed irreplaceability, C-Plan can already weight features according to the proportion of target met for each feature (Ferrier et al. in press). This weighting can now be further adjusted to account for geographical/environmental spread. The analytical approach employed is largely new, but was inspired by recent work by Faith and Walker (1996) on the measurement of environmental diversity. The adjustment is applied only to those features for which a configuration goal has been specified, in terms of the level of spread required. Such a goal is specified in C-Plan by assigning a ‘spread radius’ to the feature concerned. For this feature, the proportion of target met for a given planning unit is then estimated for that part of the region falling within the specified radius of the unit rather than for the region as a whole. The proportion of target met for a given feature therefore varies between planning units, reflecting the extent to which reservation has been evenly spread across the range of the feature. This effectively adjusts feature weights to give emphasis to planning units in those parts of the region with poorest reservation of the feature.

For a given feature, the adjusted proportion of target met p_x in planning unit x is calculated as follows (see Figure 3 for an illustration of some of these parameters):

$$p_x = \frac{\sum_{i=1}^{n_r} A_i \left(1 - \left(\frac{d_i}{d_{\max}}\right)^C\right)}{\sum_{j=1}^{n_a} A_j \left(1 - \left(\frac{d_j}{d_{\max}}\right)^C\right)} \times \frac{A_{total}}{A_{target}}$$

where d_{max} = the specified radius around the unit of interest
n_r = the number of reserved planning units within the specified radius
n_a = the total number of planning units within the specified radius
A_i = the area of the feature in planning unit i
d_i = the distance between planning unit i and the unit of interest

C = a user-specified constant (between 0 and 1) that determines how quickly the weight applied to surrounding planning units diminishes with increasing distance from the unit of interest
A_{target} = the reservation target for the feature, for the entire negotiation region
A_{total} = the total area of the feature, across the entire region

In the current implementation of the above approach all distances are simple geographical distances. The weighting therefore considers geographical spread but not environmental spread (although the former is likely to function reasonably well as a surrogate for the latter). The approach could be readily extended to incorporate consideration of environmental spread by replacing the underlying inter-unit distance matrix based on geographical distance (see Section 4) with one based on some amalgam of geographical and environmental distance, e.g. predicted biological dissimilarities derived from modelling of biological survey data in relation to geographical and environmental separation of sites (see report on separate CRA project: *Evaluation of effectiveness of derived forest ecosystems as biodiversity surrogates and analysis of biological variation within forest ecosystems*).

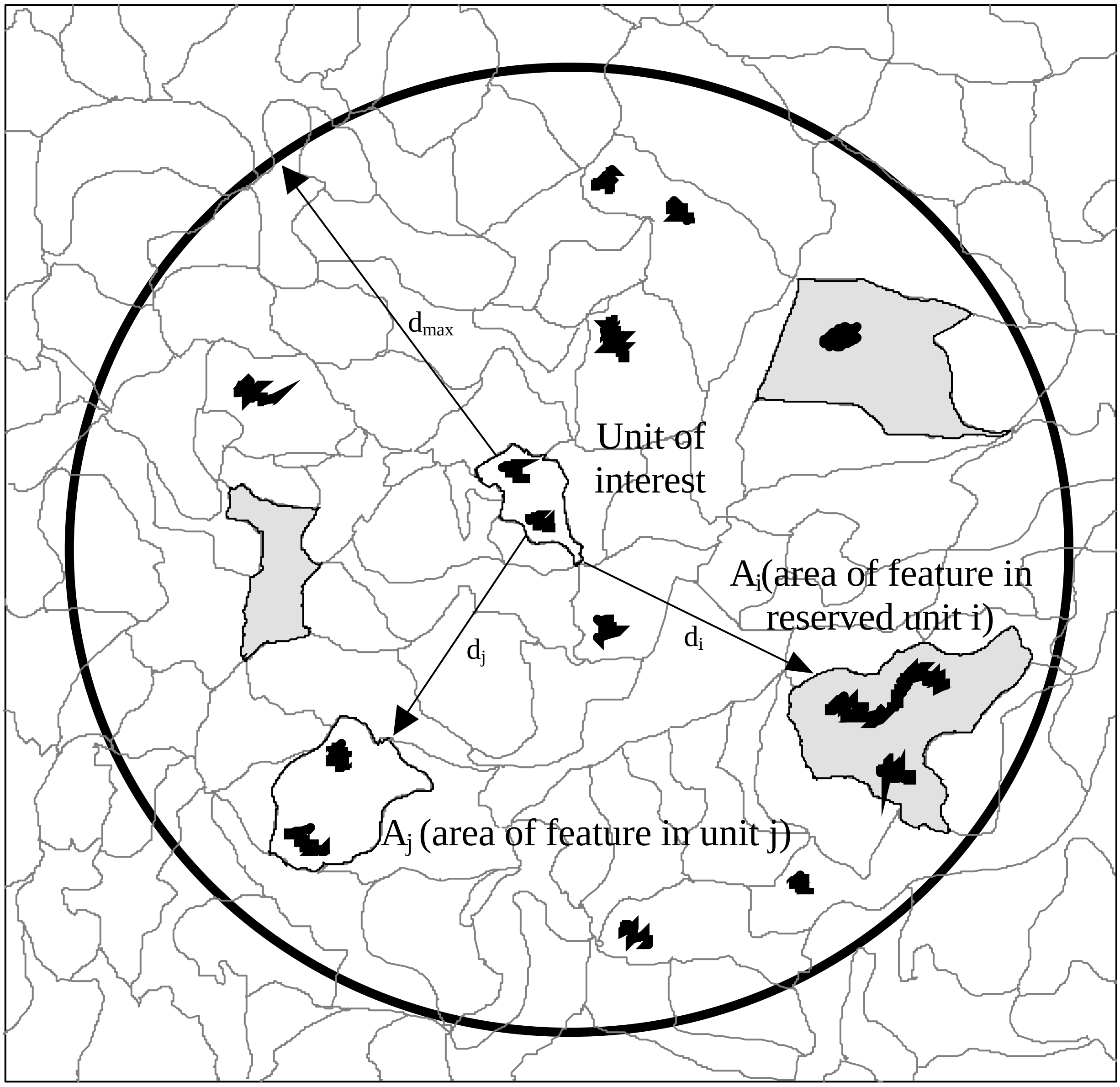


Figure 3. Parameters used to calculate the proportion of target achieved for a given feature, adjusted to reflect the geographical spread of reservation. Light shading indicates areas currently selected for reservation. Dark shading indicates the distribution of the feature of interest.

3.2 CURRENT CONFIGURATION OF RESERVE SYSTEM

For any given feature assigned a spread radius, C-Plan can also calculate (and report on) an overall measure of the spread of reservation across the feature's range. This index is derived using the 'adjusted proportion of target met' values calculated for individual planning units (see Section 3.1). The index is essentially a measure of the evenness of these values, and ranges from 0 (very uneven, biased spread of reservation) to 1 (very even, unbiased spread of reservation):

$$Spread\_index = \frac{\sum_{i=1}^{n} \left(p_i / p_{mean} \right) A_i}{\sum_{i=1}^{n} A_i}$$

(if p_i / p_{mean} > 1 then set equal to 1)

where $$p_{mean} = \frac{\sum_{i=1}^{n} p_i A_i}{\sum_{i=1}^{n} A_i}$$

n = total number of planning units in the region (including reserved units)
p_i = proportion of target met within specified radius of planning unit i
A_i = area of feature in planning unit i

As for the patch size/connectivity index described in Section 2.2 this spread index must always be interpreted in conjunction with information on the total area of the feature reserved.

4. SOFTWARE

The major components of the software developed to derive the measures of spatial configuration (described in Sections 2 and 3) are illustrated in Figure 4 (pre-existing components are shaded).

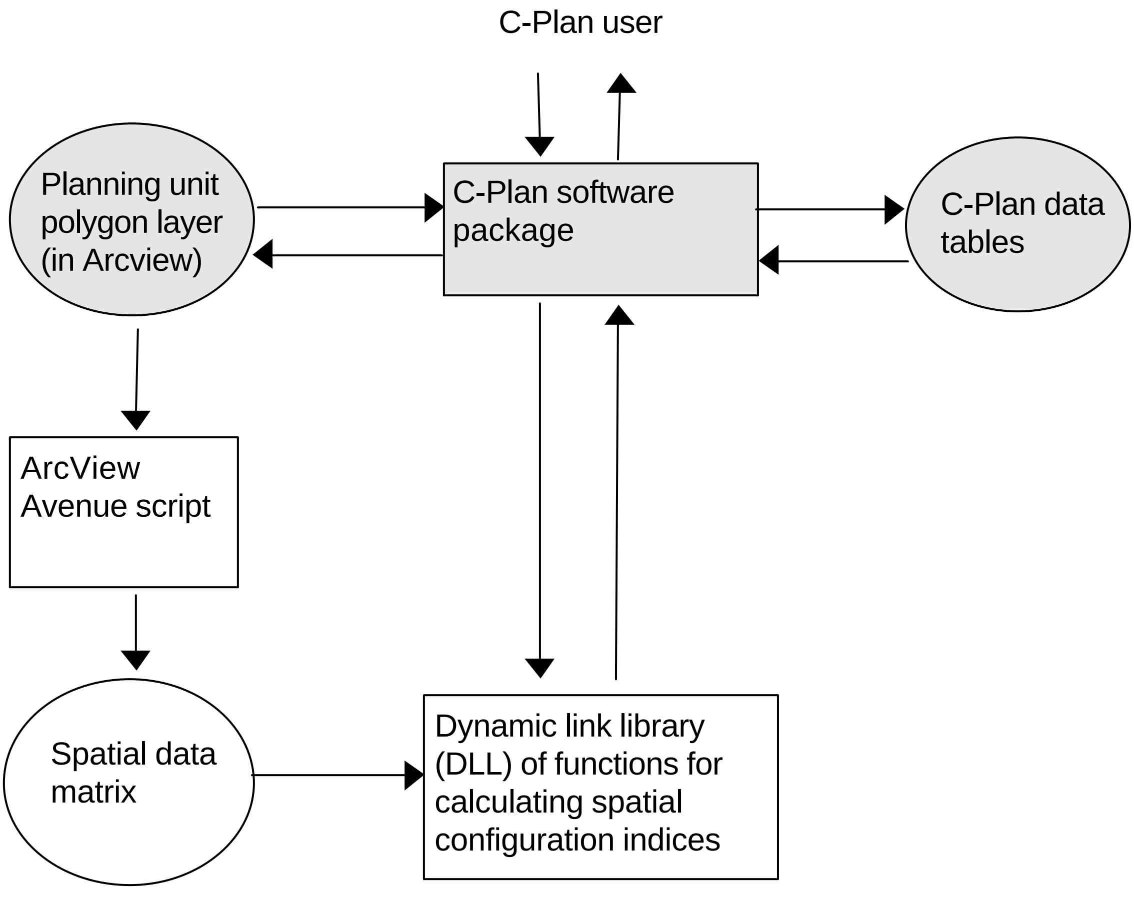


Figure 4. Major components of the software developed to derive measures of spatial configuration

The main challenge in developing this software was to achieve a computational efficiency that enabled 'real-time' calculation of the configuration measures during CRA/RFA negotiations. In other words, the indices need to be calculated in seconds rather than minutes or hours. This efficiency is achieved by performing much of the required spatial computation in a data pre-processing phase prior to negotiations. In this pre-processing phase an ArcView Avenue script is used to derive a ‘spatial data matrix’ from the planning unit polygons. The spatial data matrix contains information on the distances (edge-to edge) between all possible pairs of planning units in the region of interest, and the areas of those units. This information is stored in a very compact binary form and is indexed and linked in a way that optimises the speed with which software can query the distance between any two planning units, or query which other planning units are closest to a given unit, or fall within a specified radius of a given unit. For a large region, the computation time required to derive the spatial data matrix can be several hours or even days. However, the operation need only be performed once for a given region.

Functions for calculating the various spatial configuration indices are contained within a Dynamic Link Library (DLL) coded using the C++ programming language. These functions are called directly by C-Plan, which passes the data (e.g. feature areas, reservation status of planning units) required for calculating a specific index or set of indices. The DLL functions extract all required spatial information directly from the spatial data matrix. Computational efficiency is further optimised through use of a number of innovative data structures and algorithms within the DLL functions. For example the building, storage and traversal of the minimum spanning trees used to calculate configuration indices of patch size/connectivity is performed using a sophisticated algorithm based on fibonacci heaps.

User-control of the spatial configuration functionality is provided through modifications and extensions to the existing C-Plan user interface (i.e. coded in C-Plan rather than in the spatial configuration DLL). All coding relating to the user interface was performed as part of a separate CRA C-Plan Development Project. Further information on this component of the software can be obtained from the C-Plan Development Team in NSW NPWS.

5. REFERENCES

Faith, D.P. and Walker, P.A. (1996) Environmental diversity: on the best-possible use of surrogate data for assessing the relative biodiversity of sets of areas. *Biodiversity and Conservation* 5: 399-415.

Ferrier, S., Pressey, R.L. and Barrett, T.W. (in press) A new predictor of the irreplaceability of areas for achieving a conservation goal, its application to real-world planning, and a research agenda for further refinement. *Biological Conservation*.

Gower, J.C. and Ross, G.J.S. (1969) Minimum spanning trees and single linkage cluster analysis. *Applied Statistics* 18: 54-64.

Hanski, I. (1994) A practical model of metapopulation dynamics. *Journal of Animal Ecology* 63: 151-162.

Hanski, I. (1997) Predictive and practical metapopulation models: the incidence function approach. In D. Tilman and P. Kareiva (eds.) *Spatial Ecology*. pp. 21-45. Princeton University Press.

JANIS (1997) *Nationally Agreed Criteria for the Establishment of a Comprehensive, Adequate and Representative Reserve System for Forest in Australia*. A report by the Joint ANZECC/MCFFA National Forest Policy Statement Implementation Sub-committee. Commonwealth of Australia: Canberra.

Sen, A. and Smith, T.E. (1995) *Gravity Models of Spatial Interaction Behavior*. Springer-Verlag, Berlin.