Title:

Isolate Connectivity Index: an advancement in modelling patch to patch influence across landscapes.

Authors:

Stuart Kininmonth[1], Nick Rollings[2] and Chris Stokes[1]

[1] Present Address and corresponding address:
Stuart Kininmonth
CSIRO Sustainable Ecosystems,
Davies Laboratory,
PMB PO Aitkenvale,
Queensland 4814,
email: stuart.kininmonth@TAg.CSIRO.au
Tel:+61 (0) 7 47528622
Fax:+61 (0) 7 47538650

[2]Department of Ecosystem Management
University of New England
Armidale
NSW 2351

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Abstract

Landscape ecology deals with the strong interactions between ecological processes and the patterning of landscape elements. However existing tools do not always adequately model the complexity of interactions between landscape elements. This paper describes the development of a new landscape configuration metric, the Isolate Connectivity Index. This index describes the neighbourhood configuration of landscape elements relative to a selected isolate based on the proximity, shape, size and position of patches. Using the measurements between randomly placed points in neighbouring and selected polygons, a GIS macro computes summary data that reflects the complex interaction between polygons.

1. Introduction

Establishing a measure of the relationship between each patch in a landscape is fundamental to landscape ecology studies (Forman and Godron 1986) yet the overwhelming complexity of the ecological interactions continues to defy empirical analysis (Krummel, Gardner et al. 1987; Gustafson 1998). Intricate webs of abiotic and biotic linkages operate with both random and directional forces to create an ecosystem that is dynamic, evolving and difficult to describe (Ver Hoef 1991). Each linkage is reshaped through forces as subtle as hunger in a beetle (McIntyre and Wiens 1999) to devastation of the landscape by wildfire (Trabaud and Galtie 1996). Structural influences operate at all scales and provide a physical conduit to channel a multitude of resource transfers (Forman and Godron 1986). Describing the structural configuration of a patch is difficult even when considering simple metrics such as shape. For example, the intricate extrusions of a rainforest nestled into an eroded sandstone ravine create structures that defy reduction to empirical figures. When considering the structural juxtaposition between multiple patches, empirical descriptions that reflect the ecological complexity appear to be unobtainable (Cale, Henebry et al. 1989; Scheiner 1992; Li and Reynolds 1995). Consequently, descriptions of landscape pattern tend to be highly simplified, imprecise, uncertain or ambiguous in their approach (Kampichler, Barthel et al. 2000).

The fragmentation of natural systems adds another level of complexity that obscures the processes required to maintain biodiversity (Haila, Saunders et al. 1993; Turner and Corlett 1996; Luiselli and Capizzi 1997; Bowers and Dooley 1999) yet comparative measurements are required for planning and management. In particular, a metric is required that indicates which fine scale structural changes (e.g. fence line alterations) most strongly affect change in the biota of a region. In this paper, the term metric is used to describe any measure of spatial configuration or composition. The term index is used to denote a single metric that constructs a relative value, which can be compared to other similarly derived values.

The tools used to measure the complex spatial *interactions* between landscape elements are currently too simplistic (Hargis, Bissonette et al. 1998; Wiegand, Moloney et al. 1999) despite the use of a wide range of techniques. An exception to this is the metapopulation modelling by Hanski (1999, 2000). Two main procedures of simplification tend to be utilised:

- reduction of the neighbour or target polygons to a single point (Hanski 1999), and;
- isolating single measurements as indicators of a structural phenomenon.

Metrics, such as the nearest neighbour indices, will select a point (e.g. closest point on edge) and measure the distance to another point on a target patch as an indicator of patch separation. The failure to incorporate the shape of the patch obscures the ecological interactions that occur (Collinge 1998). For instance, the neighbouring patch might be teardrop in shape with the thin end closest to a patch in question or the neighbour patch may be shaped as a ring around the target patch. Both neighbours may exhibit the same nearest neighbour metric value but have different ecological functionality (Gutzwiller and Anderson 1992). The combination of a suite of independent metrics as a means of providing a comprehensive description tend to be difficult to interpret (Ritters, O'Neill et al. 1995). Indeed the array of metrics available is considerable and potentially confusing (Gustafson 1998).

A proposed metric, which accommodates the size, shape, position and proximity of multiple polygons, is described in this paper and is called the Isolate Connectivity Index (ICI). This metric utilises the measurement of random point allocations similar to the influence or 'gravity' models used to describe patterns of human interaction over distance (Smith 1975).

2. Methods

2.1 The basis for vector analysis

The derivation of the ICI utilises vector-based GIS data structures (point, line, area) although raster-based structures (grid cell) could equally be employed, perhaps allowing additional functionality such as cost-distance analysis to be built into the metric (see later section on future research). Vector coverages provide a clear demarcation of the boundary position for a patch. The concerns with this method are the artificial delineation of boundaries across environmental gradients and the implied homogeneity of the internal environment within the patch boundaries. Raster or grid coverages can provide a stepped boundary for ecological gradients and can indicate heterogeneous resource distributions within a patch boundary. However, the use of vector data to describe habitat patches is widespread in the environmental management field due to the popularity of desktop GIS packages, such as ArcView (ESRI, USA).

2.2 Calculating the Isolate Connectivity Index

To calculate the ICI, random points are allocated in both the target and neighbourhood patches and the distances between each point are calculated with adjustments for the deviation from a central line and to a prevailing force. The sum of the inverse square of each distance provides an indication of the relationship that each part of the target patch has with all sections of the neighbourhood. The sum of all the neighbour contributions is the ICI value for the target polygon.

Eight processing stages form the core of the ICI calculation:

1. Random points are created at a user-specified density located in both the selected target and neighbouring polygons. If an ecologically "sterile" matrix exists (i.e., cleared land, water) then random points are not assigned to this zone. At low user-specified random point densities small neighbour polygons may fail to have a point allocated. In this case the centroid is used as a substitute point so that all neighbour polygons are accounted for.

2. The distance and angle, relative to an east-west axis, is calculated between a random point on the target polygon and a point on the neighbouring polygon.

3. The shape penalty is imposed for points deviating from a connecting central line. This method of shape measurement is based on the principle that migrating species will favour a patch configuration that optimises the travel distance to the central region of a neighbour patch (Fleury and Brown 1997; Keitt, Urban et al. 1997; Hinsley 2000). The optimum configuration is to cluster the patch around the connecting central line.

The deviation from this line is added to the distance between the two random points (figure 1). The shape penalty option can be switched off by the user.

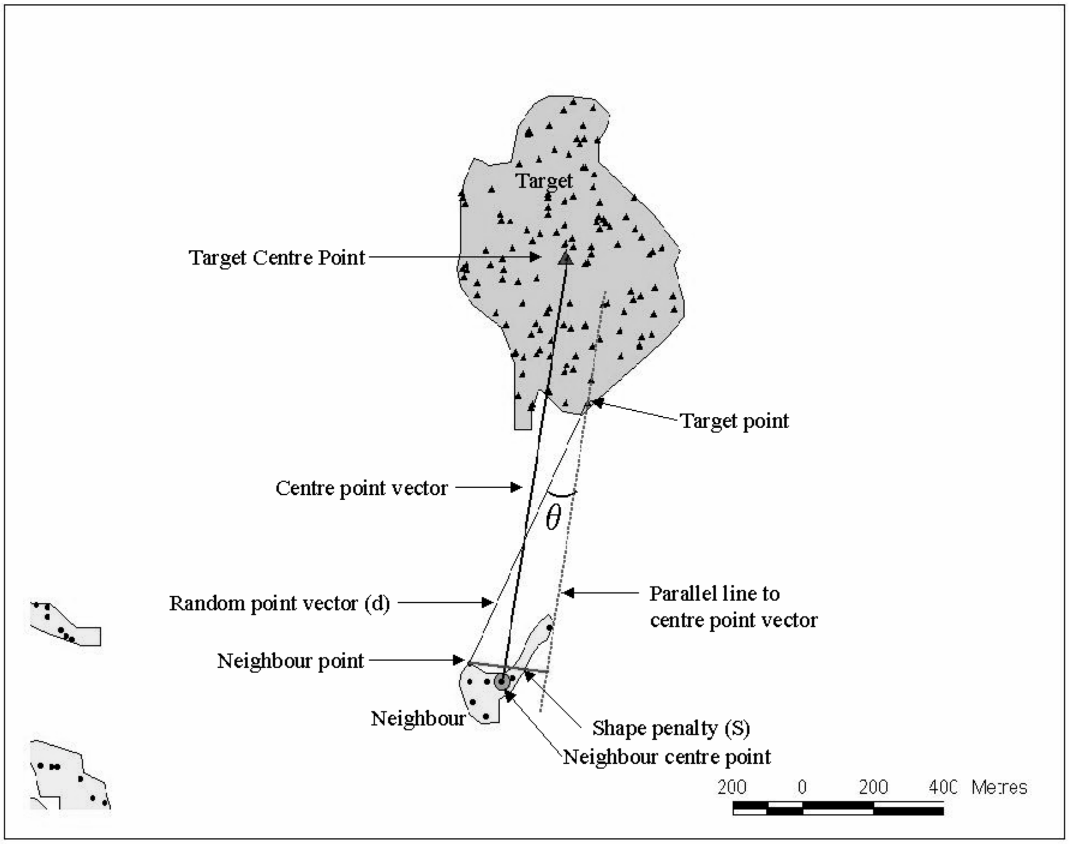

Figure 1. Random points are placed in the target (▲) and neighbour polygons (●). One target point is selected and the distance (d) measured to a neighbour point. The angle (θ), of the point-to-point vector, relative to the angle of the centre point vector determines the shape deviation (S). The deviation is added to the distance between the random points. Notice that shape, position, proximity and size of ***both*** the neighbour and target determine the extracted values.

4. An adjustment is made for angular influences. The user specifies a polar angle direction and intensity that might represent a force such as predominant wind

(equation 1). As the point-to-point angle deviates from 0 to 90 degrees from the force, the modification factor increases from the inverse of the intensity value to one. This effectively lengthens the 'shadow' from the neighbour polygon by reducing the distance between the points. From 90 to 180 degrees, the intensity factor increases from one to the intensity value. As the neighbour points are positioned 'down wind' of the target points, the effect is to reduce the influence from the neighbour. The change in intensity is calculated as a cosine function of the deviation from the force direction.

$$F = I^{(-\text{Cos}\ (\lambda))} \qquad (1)$$

The Angle Weighting factor (F) is a function of the intensity (I), the difference in angle (λ) between the force and the point-to-point angle.

5. The inverse square of the accumulated distance (distance plus shape penalty) is calculated. The inverse square function used here was based on the light intensity formulae used in other indices such as Mean Proximity Index (McGarigal and Marks 1995).

6. Steps two to five are repeated with the remaining points present in the neighbour polygon for the same target point.

7. To complete the comparison for the selected neighbour the steps two to six are repeated with each of the remaining points in the target polygon. This means that every point in the target polygon is compared to every point in the selected neighbour

polygon. The sum of the point-to-point calculations then provides a subtotal of the ICI for the selected neighbour polygon. The ICI values for each neighbour polygon are normalised with the area of the neighbour and target polygons. Each neighbour polygon is attributed with the subtotal ICI in order to view the regional influences.

8. For the remaining neighbourhood polygons steps two to seven are repeated. The summation of the subtotal for each neighbour-target comparison provides the ICI for the target polygon. This looping process is seen in the equation 2.

$$ICI = \frac{A_T}{P_T} \sum_{i=1}^{N} \frac{A_{Ni}}{P_{Ni}} \sum_{j=1}^{t} \sum_{k=1}^{n} \left\{ \frac{1}{(d_{jk} + S_{jk})^2 . F_{jk}} \right\}$$

Equation 2. The ICI formulae where each neighbour polygon (i=1..N) is measured by the distance (d_{jk}), shape penalty (S_{jk}) and angular force (F_{jk}) from the neighbour points (k=1..n) to the target points (j= 1..t). The measurement is normalised by the area of the neighbour (A_{Ni}) and the target (A_T) divided by the number of points in the Neighbour (P_{Ni}) and the Target (P_T) polygons.

2.2 Performance of the ICI under simulated conditions

The behaviour of ICI (using the Avenue script version) in response to changes in polygon configuration is demonstrated with four examples. The first involves applying ICI to a circle moving closer to a rectangular neighbour. **In the second example, the circle is distorted to a star shape and the ICI is compared to the shape index;**

Shape Index = Perimeter/(2√(π * Area) (McGarigal & Marks, 1995). (3)

The third polygon manipulation increases the size of a circular target while maintaining the circle's separation distance.

The calculation of ICI requires the user to specify values for certain parameters such as point density, force angle and intensity. A sensitivity analysis was undertaken to investigate the impact of varying these parameters on a standard dataset. A dataset from the Atherton Tablelands (northern Queensland, Australia) representing a modified landscape of rainforest remnants within an agricultural matrix was selected as it represented a realistic configuration for a range of simulations. To examine the variability of ICI, as a function of point density, a 6 hectare isolated patch was measured ten times with densities of 0.1, 0.5, 1, 2 and 5 points per hectare. To observe the force effects the angle was increased from 0 to 360 degrees by 45 degree steps while the intensity was calculated for a force of magnitude 1, 2 and 3 for a small patch.

3. Results

3.1 ICI performance simulation

The ICI measurements for a circle approaching a rectangular neighbour showed an increase as a function of the inverse square equation (figure 2). *A relationship was observed for the increase in size of the target polygon (figure 4). The ICI increased directly in proportion to the size increase*. Repeating the ICI calculation twenty times for a variety of densities shows the low-density ICI values having a higher degree of relative variability (figures 5).

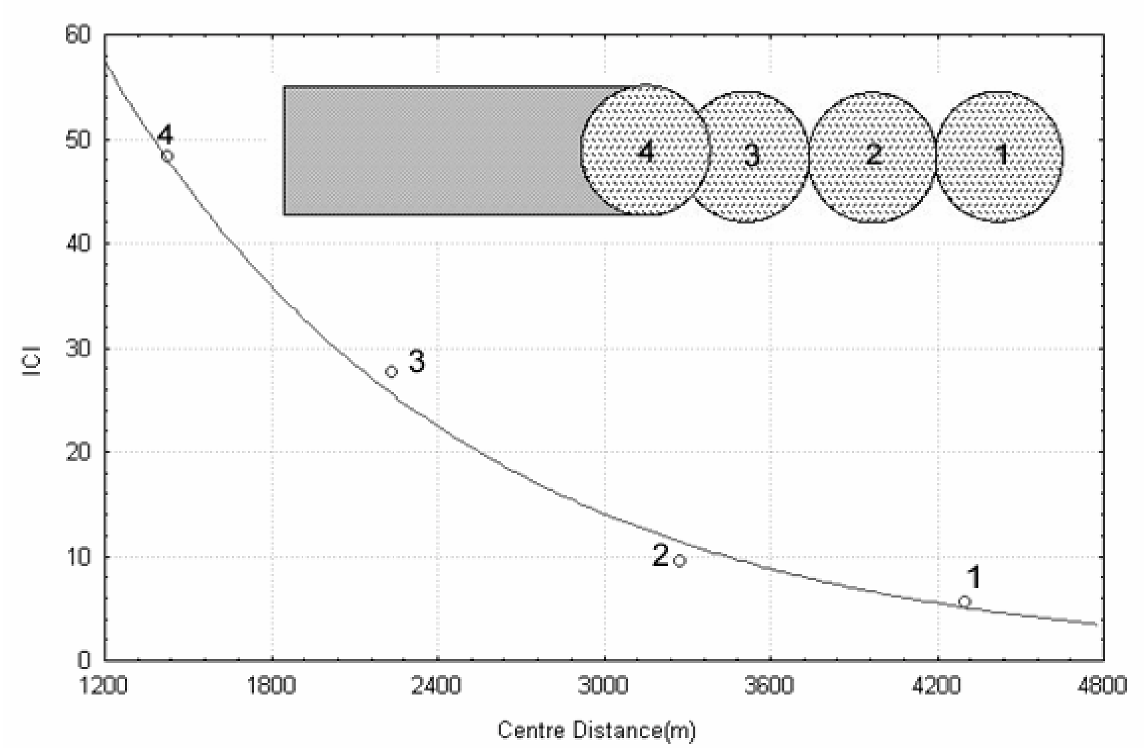

Figure 2. The change in ICI when a target circle (1 →4) approaches a rectangular neighbour as measured by the distance between polygon centres. The graphics are the actual polygons used in the simulation.

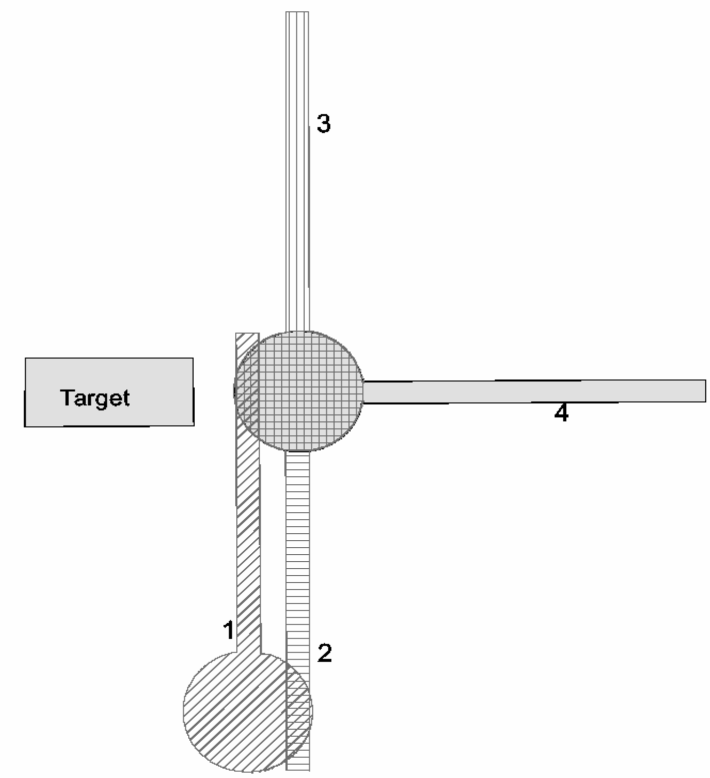

Figure XX. Rotating a polygon whilst maintaining constant edge-to-edge distance.

Table 7.Results of rotating and moving a polygon to maintain a constant edge to edge distance

Polygon ID	ICI
1	34.32
2	50.77
3	47.36
4	40.76

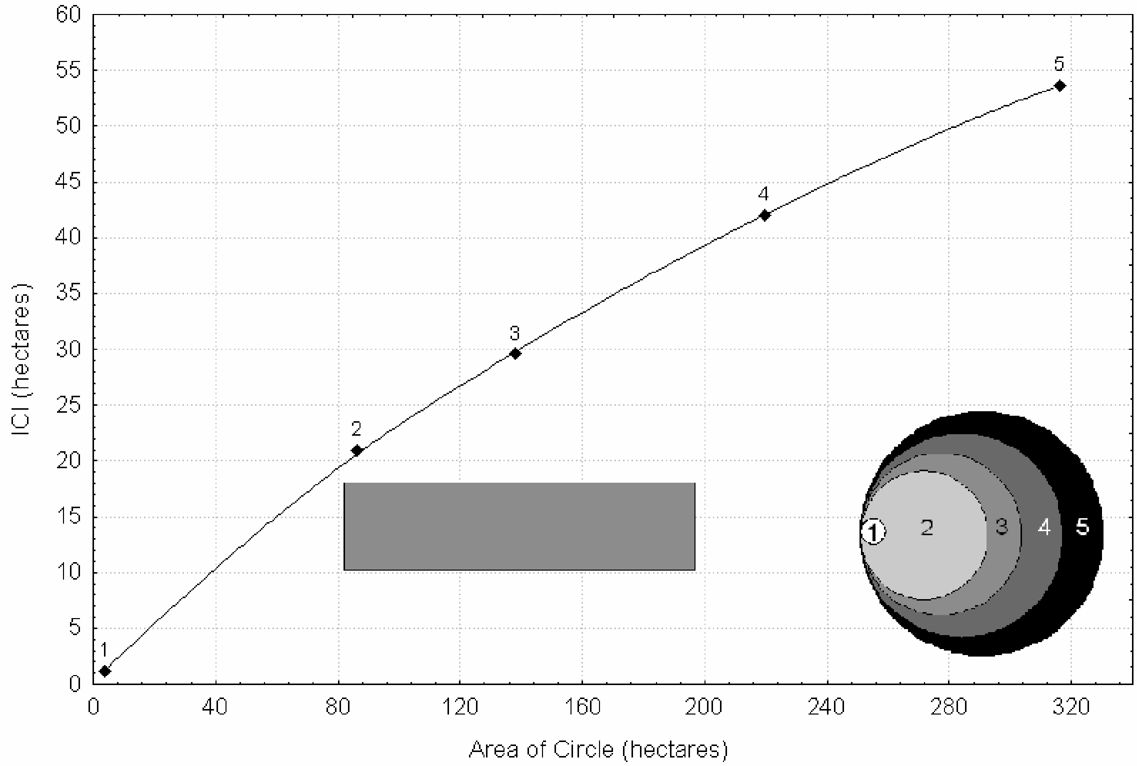

Figure 4. The change in ICI when the circle (1 to 5) size increases whilst maintaining the same separation distance near a rectangular neighbour. The graphics are the actual polygons used in the simulation. ICI calculated with no shape or force penalty and at a density of 3 points per hectare.

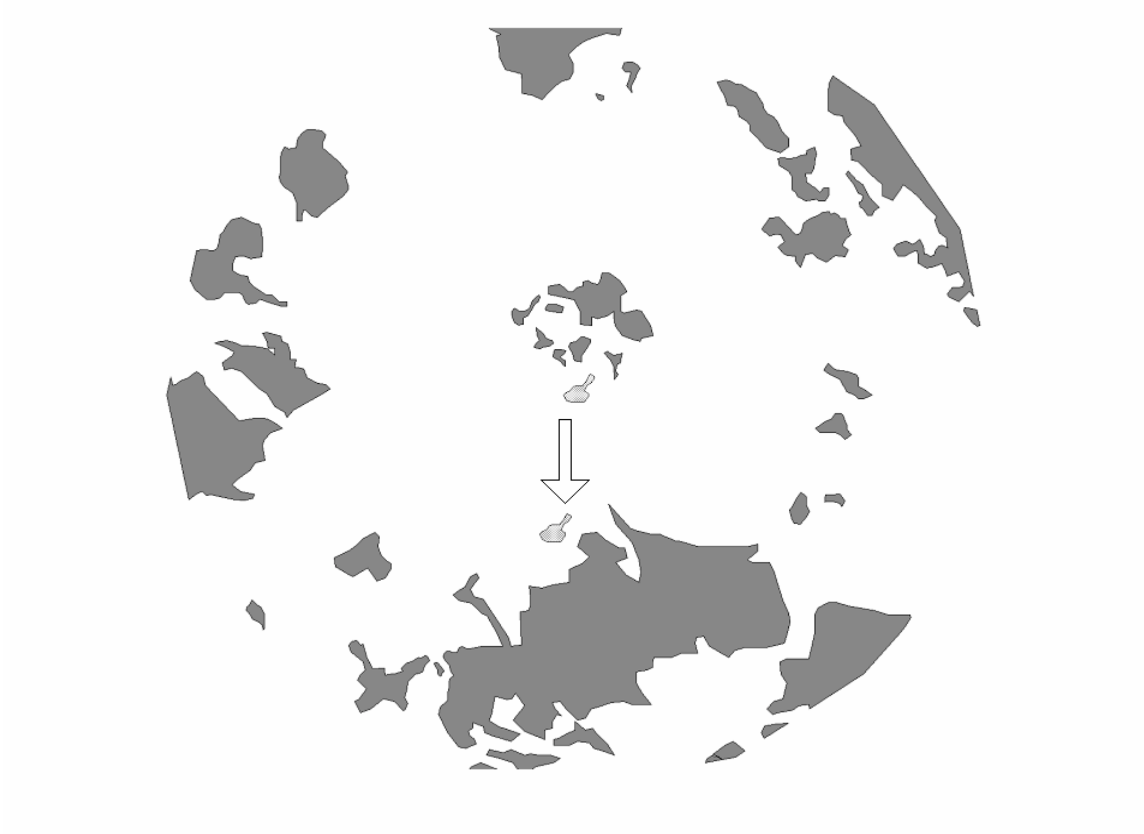

Figure XX. Moving an isolated fragment from a cluster to a large neighbour keeping the same distance apart. (D= 5, No shape, no force, dist = 196m, target = 5.96ha, 37 neighbours)

The ICI value for the fragment close to the cluster of small fragments is 11.33 hectares and the ICI when close to the large neighbour is 22.12 hectares.

Table 1. Summery of the simple metrics and the scenarios.

Metric	Enlarging circle (figure 4)	Multiple Patches	orientation	Shape change ???	Moving circle (figure 2)
ICI	√	√	√	√	√
Shape	×	×	×	√	×
Area	√	×	×	×	×
Separation Dist	×	×	×	×	√

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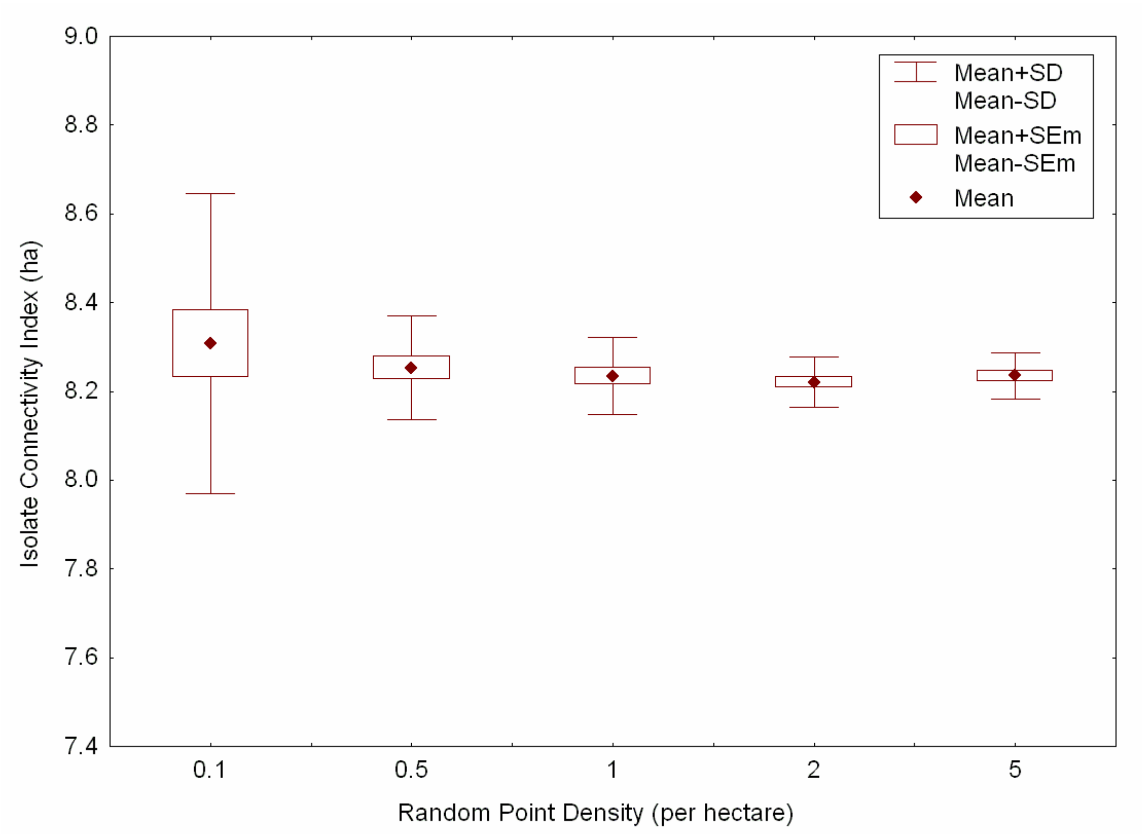

Figure 5. Variation in ICI, over 20 repetitions, for changes in density when applied to a 6 hectare isolated patch. Densities were 0.1, 0.5, 1, 2 and 5 points per hectare.

For the Atherton Tablelands example, applying a force of 1, 2 and 3 to a small patch for the eight major points on a compass produced a maximum ICI when the force originated from the east (figure 6). To the east of the target patch is a large patch (651 hectares), which increases the ICI value with the application of an easterly force. A 40 hectare patch lies to the west but the shadow effect of a westerly force is negated by the 'down-wind' reduction of the larger easterly patch. When the force increases, the large distant patches begin to influence the ICI value. Open spaces to the north and south ensure minimal change in ICI for forces originating from these cleared areas.

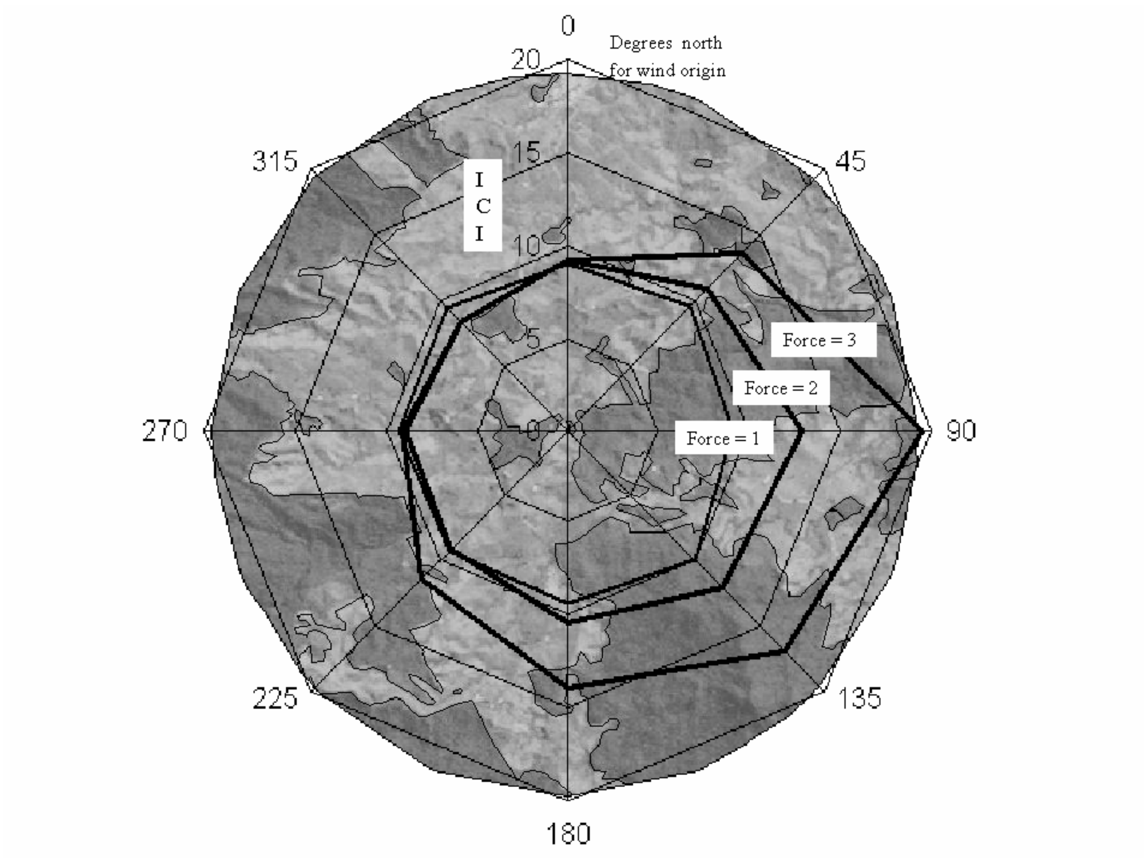

Figure 6. Changes in ICI when a force, such as wind, of magnitude 1, 2 and 3 originating from the eight major compass points is applied to a small patch. The radial distances indicate the ICI value for the target patch while the perimeter numbers indicate the angle relative to north. The background image is a Landsat TM derivation with dark areas and light areas representing rainforest and pasture respectively.

The computation of the ICI consisted of summing the sub-ICI values that were generated between the target and a sequential list of neighbour polygons. The sub-ICI values for each neighbour were retained in the new neighbourhood coverage. When displayed, as for a 65 hectare patch in figure 7, the user can ascertain the contribution from each neighbour polygon.

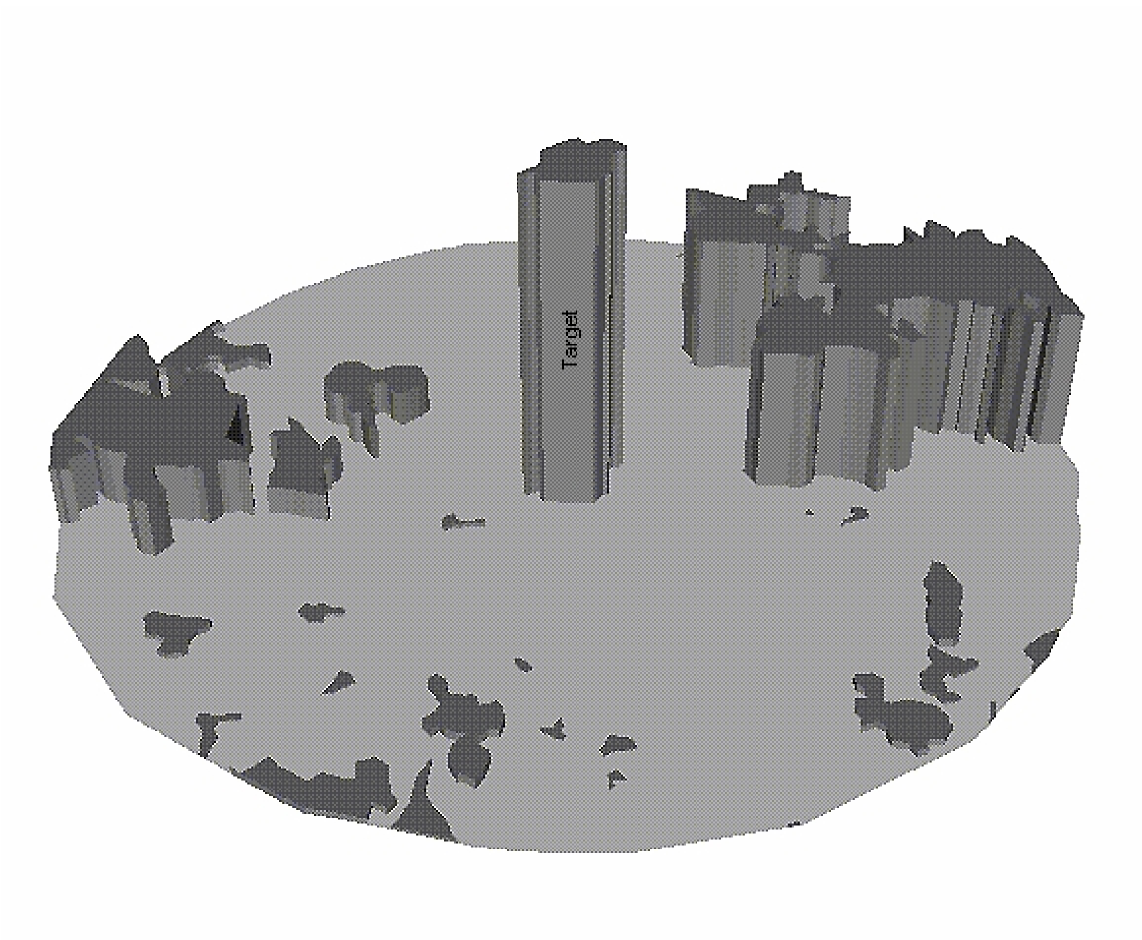

Figure 7. Individual neighbour ICI contributions, shown by extruded height, with relation to centre target patch. The higher the neighbour patches the greater the ICI value. This implies that the higher patches have a higher ecological exchange with the target patch than the lower patches. The target patch is also extruded to the sum of the ICI for all the neighbour patches. Neighbourhood selection horizon of 5 kilometres is shown as the ground layer. The view is facing north with illumination at 30 degree elevation from the south east. This particular ICI was calculated with 2 points per hectare and no force.

4. Discussion

The ICI, in this early stage of exploration, appears to provide a suitable measure of the connectivity of a particular patch to neighbouring patches. The ICI changes observed between the manipulated polygons for proximity, size and shape are consistent with the theme that patches that are large, close to neighbours, and compact are more likely to be ecologically interactive than small, distant, dispersed fragments (Forman 1995; Bastin and Thomas 1999). This index is designed to provide an indication of the interaction between isolated fragments.

The behaviour of the ICI in artificially constructed spatial configurations is predictably governed by the formulae used to construct the index. The increase in ICI as two polygons converge is a direct result of the inverse square law applied to the distances between random points. Increases in target patch size produced a linear increase in ICI, as determined by the inclusion of patch areas in the formulae. The shape-weighting present in the ICI is a combination of linear increases resulting from divergence from the center point and the inverse square law applied to the additional distance penalty. Further research is required to align these formulas with ecological reality.

The user of the ICI program has the opportunity to vary a number of variables. The greatest consumer of computing power for the ICI calculation is the density level of random points. The values of ICI remain consistent for a variety of density levels, however the ICI variability is more evident at lower densities. With increasing density, the ICI will more precisely describe the structural configurations, such as fine extrusions. Averaging the ICI values, for a number of program runs, will maximise the descriptive precision of this metric and provide an indication of variability. Given the processing involved, a more economical method might be to increase the density to a level of acceptable variability.

The user also has the option of specifying if a force such as wind or water current affects the region. The force weighting serves to promote the ‘upwind’ neighbour’s influence and decrease the ‘downwind’ influences. The force in this respect is not representing the structural damage caused by increased wind velocity but rather an additional factor in the vector size for ecological dispersal. Forces, such as wind, can alter the rate and range of dispersing resources (i.e., seeds, insects, birds, soil) (Saunders, Hobbs et al. 1991) and the ICI is designed to capture this. Orientation of a polygon to a force can have critical consequences to ecological functionality (Miller, Lin et al. 1991; Gutzwiller and Anderson 1992; Forman 1995; Laurance, Bierregaard et al. 1997; Turton and Freiburger 1997) and the ICI partially describes this structural aspect. The programming design was for no change in ICI unless the neighbour configuration was polarised in sectors. Evenly distributed neighbours should experience no sum change in ICI since the gain by ‘upwind’ neighbours should be equally offset by reductions in ‘downwind’ neighbour connectivity. The use of force creates distortions in the ICI values that effectively measure the clustering of neighbour patches around a target patch. Increasing the force intensity will increase the contribution of distant neighbouring polygons that are ‘upwind’ and decrease the contribution of ‘downwind’ neighbours. Thus in a study area like a river the upstream structures would be more influential than the downstream structures especially in periods of high water flow. Presently we are aware of no other metric that describes angular forces, such as wind, on ecological connectivity. The difficulties in designing more suitable models for force effects are considerable. Further evaluation of the programming design is required to accurately depict the application of force in a landscape.

Measurement of the separation distances is by Euclidean geometry and ignores the heterogeneity of resources between patches. Studies of organism behaviour show evidence of dispersal patterns that do not adhere to the Euclidean distance rule (Lavorel, Gardner et al. 1995; Rickers, Queen et al. 1995; Vos and Stumpel 1995; Farina 1997; Jansson and Anglestam 1999). The channelling effects of stepping stones (Keitt, Urban et al. 1997) and asymmetrical transfers (Gustafson and Gardner 1996; Kindvall and Petersson 2000) combined with habitat gradients (Henein and Merriam 1990; Wiegand, Moloney et al. 1999) meant that separation distances alone rarely gave an accurate representation of the processes in question. The calculation of influence, within the ICI, measures the Euclidean point-to-point vectors. Realistically, ecological flow will be based on species specific travel-cost surfaces (Soule and Gilpin 1991; La Polla and Barrett 1993; Riffell and Gutzwiller 1996; Bowne, Peles et al. 1999; McIntyre and Wiens 1999). Bats have been observed to modify the paths flown in order to remain close to vegetation patches and thus avoid open areas (Law and Lean 2000). The inclusion of travel-cost surfaces will account for particular species preferences and future programming effort will explore incorporating alternative flow patterns. This modification may also compensate for the lack of interaction between neighbours within the ICI routine. The present routine considers the neighbour patches as independent patches when clearly interactions are occurring between all patches (Keitt, Urban et al. 1997). In particular, when neighbour patches are closely located there will be an increased level of interaction that will modify the individual interaction with the target patch. By incorporating the ecological interactions between neighbour patches the ICI index will more accurately measure the connectivity. Travel-cost surfaces or landscape graphs are potential spatial tools in this quest.

In the natural landscapes, the vegetation remnants are often composed of a mixture of vegetation types and this compounds the interaction complexity (Gustafson and Gardner 1996; With, Gardner et al. 1997). Bridgewater (1987) comments that the connectivity effectiveness of corridors is based on the structural differences to the surrounding matrix rather than the smaller differences between connecting heterogeneous vegetation. Heterogeneous native ecological communities interact in a manner that is measurably different to the interactions with the imposed agricultural matrix (Bridgewater 1987). However the failure of many spatial metrics to recognise heterogeneity or habitat gradients combined with landscape models based on binary frameworks reduces the effectiveness for understanding ecological processes (Henein and Merriam 1990; Wiegand, Moloney et al. 1999). Compounding the complexity of heterogeneity are the secondary effects of anthropogenic fragmentation on habitat quality (Mac Nally, Bennett et al. 2000). The ICI currently treats all neighbour patches as homogeneous and exploration into the ecological influences of different communities is required.

Defining the criteria by which neighbours are included or excluded from the analysis is conveniently avoided in the ICI program. All polygons in a selected coverage are processed. Selecting polygons using specified distance horizons requires the analyst to prepare the neighbour polygons before processing. The choice of horizon dimensions greatly influences the processing time and considerable thought is required to balance the density of points with the size of the neighbourhood. As the distance increases, the point-to-point contribution diminishes to where there is no significant change in ICI. Opportunity exists to incorporate a user-specified threshold distance value that ensures only those points able to significantly alter the ICI are processed. With Euclidean distances, this would do little more than create a radial buffer but for least-cost distances, the analytical horizon selected could be highly convoluted.

The ICI can provide guidance towards the restoration of habitats where fragmentation is indicated to be detrimental. Increasing the connectivity can be modelled with simple corridor extrusions, size increases, shape modifiers and 'upwind' protection and enhancement. The ICI can be reapplied to the adjusted patch boundary to explore the ecological changes possible. Caution about the ability of any metric to conclusively guide fine restoration changes must be exercised (Li, Franklin et al. 1993). Field data that measures the demographics of species in landscapes that have been dissected, incised, dissipated, shrunk, attributed, perforated (Jaeger 2000) or modified in quality by human activity and constructions are required in order to further evaluate the ability of the ICI to measure connectivity. The potential to offer a metric that can provide patch scale insights based on principles that are readily understandable is long overdue (Gustafson 1998; Ahern 1999).

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