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A quantitative method for zoning of protected areas and its spatial ecological implications☆

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Abstract

Zoning is a key prescriptive tool for administration and management of protected areas. However, the lack of zoning is common for most protected areas in developing countries and, as a consequence, many protected areas are not effective in achieving the goals for which they were created. In this work, we introduce a quantitative method to expeditiously zone protected areas and we evaluate its ecological implications on hypothetical zoning cases. A real-world application is reported for the Talampaya National Park, a UNESCO World Heritage Site located in Argentina.

Our method is a modification of the zoning forest model developed by Bos [Bos, J., 1993. Zoning in forest management: a quadratic assignment problem solved by simulated annealing. Journal of Environmental Management 37, 127–145.]. Main innovations involve a quadratic function of distance between land units, non-reciprocal weights for adjacent land uses (mathematically represented by a non-symmetric matrix), and the possibility of imposing a connectivity constraint. Due to its intrinsic spatial dimension, the zoning problem belongs to the NP-hard class, i.e. a solution can only be obtained in non-polynomial time [Nemhausser, G., Wolsey, L., 1988. Integer and Combinatorial Optimization. John Wiley, New York.]. For that purpose, we applied a simulated annealing heuristic implemented as a FORTRAN language routine.

Our innovations were effective in achieving zoning designs more compatible with biological diversity protection. The quadratic distance term facilitated the delineation of core zones for elements of significance; the connectivity constraint minimized fragmentation; non-reciprocal land use weightings contributed to better representing management decisions, and influenced mainly the edge and shape of zones.

This quantitative method can assist the zoning process within protected areas by offering many zonation scheme alternatives with minimum cost, time and effort. This ability provides a new tool to improve zoning within protected areas in developing countries.

Keywords: Zoning; Protected areas; Simulated annealing

1. Introduction

Originally created to promote the enjoyment of scenic beauty, the establishment of protected areas also supports the conservation of species and ecosystem diversity, preservation of ecological processes, promotion of scientific and recreational activities, and limited exploitation of natural resources, among others (McNeely, 1997). Pursuing these diverse objectives frequently leads to conflict because different stakeholders, e.g. water and energy companies, tourism operators, aboriginal communities, tourists, scientists, etc. have different resource expectations (Eagles et al., 2002).

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The assignment of land units to specific uses, known as zoning, is a useful option to mitigate conflicts and a key prescriptive tool for the administration of protected areas (Walther, 1986). Prescriptive zoning is not a descriptive final document but an ongoing process which assures that the management of the area is periodically updated and better planned (USNPS [United States National Park Service], 1998). In spite of such potential benefits, the lack of zoning and effective management prescriptions is common for most protected areas in developing countries and, as a consequence, many protected areas exist only on maps and in legislation. Reasons for such *paper parks* often revolve around shortages of funding, lack of technical ability, and complexity of planning processes (Sabatini, 2003).

We developed a quantitative method for zoning of protected areas (Sabatini, 2003; Vidal, 2003; Verdiell et al., 2005). Since quantitative methods are regarded as fast, reliable and amenable to quick reviews and updates, they can be useful tools for zoning in developing countries where most protected areas are administered under very stringent budgets and few personnel (Sabatini and Rodríguez Iglesias, 2001).

Our quantitative zoning method was structured after the forest zoning model developed by Bos (1993). Bos's model assigns forest units to potential land uses based on land aptitude, priority of use, and the influence of the surrounding area. However, it does not take into account certain high priority biological diversity conservation objectives for protected areas, such as clustering of core zones, connectivity among them (e.g. corridors), and minimizing fragmentation and edges. Such considerations are high-priority objectives for conservation of biological diversity in protected areas. Consequently, we incorporated some innovations into the forest model that allow us to derive zoning designs compatible with those ecological objectives.

Due to its intrinsic spatial dimension, quantitative zoning is a challenging combinatorial optimization quadratic assignment problem (Burkard, 1984); its resolution for other than trivially small problems requires the application of heuristics to estimate a solution (Nicholson, 1971). The application of heuristics to the selection and design of representative biological sites has become an increasingly significant area of research (e.g. Nicholls and Margules, 1993; Underhill, 1994; Ball and Possingham, 2001). However, heuristics have not been applied before for solving zoning problems within protected areas (Sabatini, 2003).

The main objective of this work was to evaluate the effects of our innovations on zoning outcomes and their implications for biodiversity conservation. For this purpose, the zoning method was applied using different sets of parameters on a small-sized, hypothetical zoning case. We also developed a real-world application for Talampaya National Park, a UNESCO World Heritage Site located in Argentina.

2. Materials and methods

In order to formulate a quantitative method for solving the zoning problem, the protected area is represented by a rectangular grid of land units, henceforth termed cells, and the demands of different stakeholders are represented by alternative land uses (e.g., strict preservation, recreation, research). In fact, the assignment of each cell to a specific land use will depend on the agreement between the land attributes, physical and ecological, and other factors that dictate certain land uses such as water availability or proximity to roads, while not excluding other constraints that must be considered by managers. The choice of aptitude scale is a management decision, and will depend on each particular situation.

If n is the number of cells and r the total number of uses, the zoning process can be mathematically modelled as follows (Verdiell et al., 2005):

$$\begin{cases} \text{maximise} \quad Q(X) = \sum_{g=1}^{n}\sum_{u=1}^{r} A_{gu}P_uX_{gu} \\ \qquad\qquad +M\sum_{u=1}^{r}\sum_{f=1}^{r}\sum_{\substack{g=1\\ g<h}}^{n}\sum_{h=1}^{n} C_{uf}D_{gh}X_{gu}X_{hf} \\ \text{subject to} \quad \sum_{u=1}^{r} X_{gu} = 1, \quad 1 \le g \le n, \\ \qquad\qquad m_u \le \sum_{g=1}^{n} X_{gu} \le M_u, \quad 1 \le u \le r, \end{cases} \tag{1}$$

where X_{gu} are the decision variables defined as

$$X_{gu} = \begin{cases} 1 & \text{if the cell } g \text{ is assigned to use } u, \\ 0 & \text{otherwise,} \end{cases}$$

A_{gu} represents the suitability of a cell g for a certain use u, P_u is the preference of use u, C_{uf} indicates the compatibility between uses u and f.

$$D_{gh} = \begin{cases} \frac{1}{d(g,h)^2} & \text{if } g \neq h, \\ 0 & \text{otherwise,} \end{cases}$$

where $d(g,h)$ is the Euclidean distance in R^2 in the grid, between g and h, assuming that each cell of the grid is identified by a pair (i,j). M_u and m_u is the maximum and minimum number of cells, respectively, that must be assigned to use u.

The objective function, devised to depict the optimization goal, includes both a linear and a quadratic term. The linear term represents the assignment of land units taking into account only land aptitude (A_{gu}) and preference of use (P_u), while the quadratic term indicates the relative value of the location of use u with respect to the location of use f. The parameter M multiplies the quadratic term in order to weigh it, relative to the linear term.

Since use allocation within a protected area is usually influenced by other land uses in the surrounding area, our zoning model explicitly incorporates this factor into the grid. Cells in the surrounding area are pre-assigned fixed uses; namely, agriculture, roads, lakes, which in turn may influence how cells within the protected area are allocated land uses via the coefficient of compatibility between land uses (C_{uf}).

The simple model developed to solve a protected area zoning problem (1) has some predetermined minimum constraints. Then other types of constraints, e.g. seeking the connection of cells with the same land use, are added.

Researchers prefer connected over isolated designs because connectivity strongly favors the flow of energy, nutrients, water, and disturbances, as well as organisms and their genes. Our zoning model considers connectivity as an optional constraint for each use. Before assigning a cell to a land use, adjacent cells are examined. If at least one adjacent cell shares the same land use, the new assignment is allowed. In order to mathematically represent this constraint, the following sets are defined:

$$V = \left\{u \in N,\ 1 \leq u \leq r:\ \text{the use } u \text{ requires connectivity}\right\},$$

$$W = \left\{i \in N,\ 1 \leq i \leq n:\ \text{cell } i \text{ is not in the surrounding area}\right\}.$$

For each $i \in W$, let

$$I_i = \left\{j \in W : i \neq j \text{ and cells } i,j \text{ are adjacent}\right\}.$$

In this case the constraint set is defined by the assignments that verify:

$$\sum_{j \in I_i} X_{jg} \geq 1 \quad \text{if } X_{ig} = 1,\ i \in W,\ g \in V,$$

$$X_{gu} \in \{0, 1\}\ \ 1 \leq u \leq r,\ \ 1 \leq g \leq n.$$

As mentioned before, our zoning model addresses a complex optimization problem that cannot be solved by exact methods in polynomial time (Nemhausser and Wolsey, 1988). Thus we used a heuristic method based on a simulated annealing procedure, implemented in FORTRAN code.

2.1. Our proposal

One of the problems that managers face is how to assign land uses within a protected area that is already affected by other land uses derived from adjacent units. In the objective function, compatibility between uses is considered through the C_{uf} coefficient. If uses u and f are compatible (e.g. ecotourism and scientific research), C_{uf} should be greater than zero. However, if uses u and f were incompatible (e.g. ecotourism and timber), C_{uf} should be given some negative value. It is also important to note that the compatibility of land uses in protected areas is generally not reciprocal. For example, ecotourism can be severely affected by adjacent logging but the opposite may not be true. Thus, the C matrix in our proposal is, in general, a non-symmetric matrix. However, it is not difficult to prove that C could be replaced by a symmetric matrix C^{new} following the simple transformation $C^{\text{new}}_{uf} = C^{\text{new}}_{fu} = \frac{1}{2}(C_{uf} + C_{fu})$ without any change in the objective function.

The compatibility coefficients (C_{uf}), on the other hand, are multiplied by the inverse of the squared Euclidean distance between cells $1/d(g,h)^2$ because it is usually desirable that conflicting uses are not in close proximity to each other, while compatible uses can be allowed to cluster together. A quadratic instead of a linear dilution of the influence of neighboring cells yields quicker clustering of a zone, and clustering has ecological and economical implications. For example, clustering minimizes zone boundary perimeter and yields a more compact shape. Since zone boundaries may need to be maintained or patrolled, longer boundaries usually mean more time, effort, and money.

2.2. Metrics for assessing zoning design

Metrics can be used to evaluate how effectively a particular land use pattern contributes to the maintenance of species and gene flow between landscapes and over time (e.g. Schumaker, 1996; Ahmad, 2001). We used five metrics (Table 1) to evaluate quantitative zoning outcomes, calculated using the FRAGSTATS 3.3 software (McGarigal et al., 2002).

2.3. Zoning scenarios

We tested all parameters of the zoning model on hypothetical zoning scenarios and on one real-world situation (Sabatini, 2003; Vidal, 2003; Verdiell et al., 2005). However, we only report here results which allow an evaluation of our model innovations in comparison to Bos's model, and highlight biodiversity conservation implications.

For the hypothetical case we report here, the protected area and its surrounding region was represented by an array of 36×36 cells. Aptitude scores for alternative uses of each cell are shown in Fig. 1. Other inputs (i.e. weighting factors for candidate uses, compatibility scores among uses, weighting parameters for tuning the relative influence of the linear and the quadratic terms, limits and values for numeric and spatial constraints) are shown in Table 2.

Our real-world application was developed on Talampaya National Park. Located in Northwestern Argentina, the park was created in 1975; its 215,000 ha were declared a World Heritage Site by UNESCO in 2000. Main heritage features include an extremely rich fossil record, geological features, archaeological cave paintings, and natural ecosystems containing several endangered species (Dellafiore and Sylvester, 2000). For this investigation, the Talampaya National Park and its surrounding area were represented by an array of 30×30 cells. Aptitude data (Fig. 2) were assembled from land aptitude maps by Dellafiore and Sylvester (2000). Remaining input scores are shown in Table 3.

Table 1
Selected metrics for assessing zoning design

Name	Symbol	Value	Descriptions
Number of patches	NP	$1<$ NP $<N_{\max}$ (1 when the zoning contains only 1 patch)	Number of patches of a particular use.
Aggregation index	AI	$0<$ AI <100 (0 when the patch uses are maximally disaggregated, 100 when the zoning consists of a single patch)	Ratio of actual edge to total amount of possible edge.
Connectance index	CONNECT	$0<$ CONNECT <100 (0 when none of the patches in the zoning are connected, 100 when every patch in the zoning is connected).	Percentage of the maximum possible connectance given the number of patches.
Total edge	TE	TE >0, without limit (units = cells).	Sum of the lengths of all edge segments involving the corresponding patch use.
Number of core areas	NCORE	NCORE $>=0$, without limit (0 when CORE $=0$, i.e. every location within the patch is within the specified depth-of-edge distance from the patch perimeter, >1 when, because of shape, the patch contains disjoint core areas)	Area in the patch greater than the specified depth-of-edge distance from the perimeter (here we use edge depth $=3$).

See McGarigal et al. (2002) for detailed descriptions and metrics formulae.

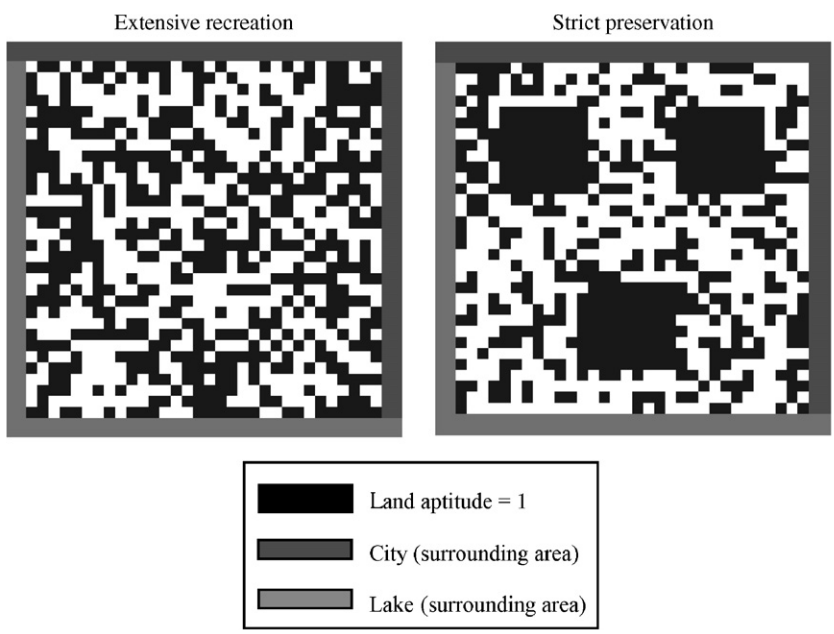

Fig. 1. Hypothetical case of land use aptitude and its surrounding area. Land aptitude is depicted using a 0 (no aptitude, white) or 1 (with aptitude, black) for extensive recreation and strict preservation.

3. Results

3.1. Hypothetical simulated scenarios

As expected, when Euclidean distance was squared, the connectivity constraint enforced, and a non-reciprocal compatibility among uses selected, the resulting zoning showed both core areas and corridors (Fig. 3a). In contrast, a more fragmented spatial pattern emerged when the connectivity constraint was set off (Fig. 3b). On the other hand, the original land aptitude pattern was hardly mimicked when a linear Euclidean distance (Fig. 3c) or a symmetric (either negative or positive) compatibility matrix were used (Fig. 3d and e).

Spatial metrics calculated from zoning results were in agreement with intuitive expectations for spatial relationships. Thus, for instance, the number of patches (NP) was highest and the percentage of connection (CONNECT) lowest, when the connectivity constraint was off (Table 4). Both total edge (TE) and the ratio of achieved edge relative to total possible edge (AI) reached extreme values when either positive or negative reciprocal compatibility matrices were used (Table 4). Selecting a non-symmetric matrix of compatibility among uses produced intermediate results. A

Table 2
Parameters for the hypothetical zoning scenarios

Parameter in objective function	Value
Number of cells of the grid (n in zoning model):	1296 (36×36);
To be assigned	1024;
Surrounding area	272.
Number of uses (s in zoning model):	4,
To be assigned	2. Extensive recreation. Strict preservation;
Fixed (surrounding area)	2. Lake. City.
Land aptitude (A_{gu} in zoning model)	0 (no aptitude), 1 (with aptitude); see Fig. 1.
Use preference (P_u in zoning model)	$P_u = 1$ for both uses.
Weighting parameter (M in zoning model)	$M = 0.15$.
Compatibility of uses (C_{uv} in zoning model)	Between uses to be assigned:
	Extensive recreation−Extensive recreation = 0.25; Strict preservation−Strict preservation = 1.25; Extensive recreation−Strict preservation = 1; Strict preservation−Extensive recreation = −1.
	Between uses to be assigned and uses of surrounding area: Extensive recreation−Lake = 1; Extensive recreation−City = 1; Strict preservation−Lake = 1; Strict preservation−City = −1.
Distance between cells (d_{gh} in zoning model)	Euclidean distance squared.
Connectivity constraint (W_{ij} in zoning model)	Extensive recreation = no;
	Strict preservation = yes.
Minimum and maximum number of cells constraint (m_u and M_u in zoning model)	Extensive recreation = 500, 700;
	Strict preservation = 300, 400.

correct identification of the three existent core areas (NCORE), (Fig. 1), was only achieved when the Euclidean distance term was squared (Table 4).

3.2. Talampaya National Park

Our quantitative zoning of Talampaya (Fig. 4a) was quite similar to the actual current zoning (Fig. 4b) produced by Dellafiore and Sylvester (2000) on the basis of expert knowledge and field experience. The oval drawn in Fig. 4a. encloses the only area of marked disagreement between the two maps. That is an area which was highly degraded by human activities before its incorporation to the park. Its inclusion as part of the strict preservation area was motivated by the expectation that strict preservation will contribute towards restoration (F. Sylvester, personal communication).

We ran the Talampaya zoning problem on a 2.04 GHz Pentium 4 platform with 512 Kb of RAM memory. CPU time ($\pm$standard deviation) for a single run averaged 113 ± 0.23 s ($n = 30$).

4. Discussion

Spatial patterns strongly influence ecological processes (Noss and Harris, 1986; Turner, 1989). Disruption of spatial patterns may endanger functional integrity by interfering with critical ecological processes necessary for population persistence, and maintenance of biodiversity and ecosystem integrity (With, 1997; Debinsky and Holt, 1999). For instance, in altered landscapes, there is considerable evidence of disrupted plant–pollinator mutualisms. Possible causes vary from lack of nesting sites for key insect pollinators to a decline in pollinator visits when plant population sizes become reduced by fragmentation. This results in reduced seed production, which limits seedling recruitment and may push populations towards extinction (Harris and Johnson, 2004). It is essential, therefore, that zoning methods for protected areas produce zoning patterns that are congruent with landscape ecological patterns.

A conceptual model of core areas connected by corridors was proposed by Noss and Harris (1986) as a mean to preserve species in protected areas over the long run. Their model can also be applied to within-reserve zoning. Zoning designs with interconnected areas should be preferred over designs that impose habitat isolation. The three main innovations (squaring Euclidean distance, allowing for non-symmetric compatibility scores, allowing the enforcement of connectance) we introduced into the forest zoning model proposed by Bos (1993) were aimed at both making possible a closer match between land aptitude patterns and zoning spatial patterns, and promoting spatial structures of ecological significance. Our simulation results showed that those three elements have potential for reducing fragmentation, limiting edges, and producing better defined core areas and corridors.

The conservation value of a site may be due to historic, biological, aesthetic, or social reasons (e.g. habitat for endangered species, threatened ecosystems, paleontological or aboriginal sacred sites). The identification of areas of conservation significance is essential for delineating core zones. Different species may frequent different habitats, some may complete stages of their life cycles in different ecosystems. On the other hand, delineating a single core area within a protected area may be risky because disturbance events such as fire, predation, brood parasitism, disease, among others, could eliminate an entire population. In a variety of cases, therefore, several core areas are recommended for zoning designs. Using a

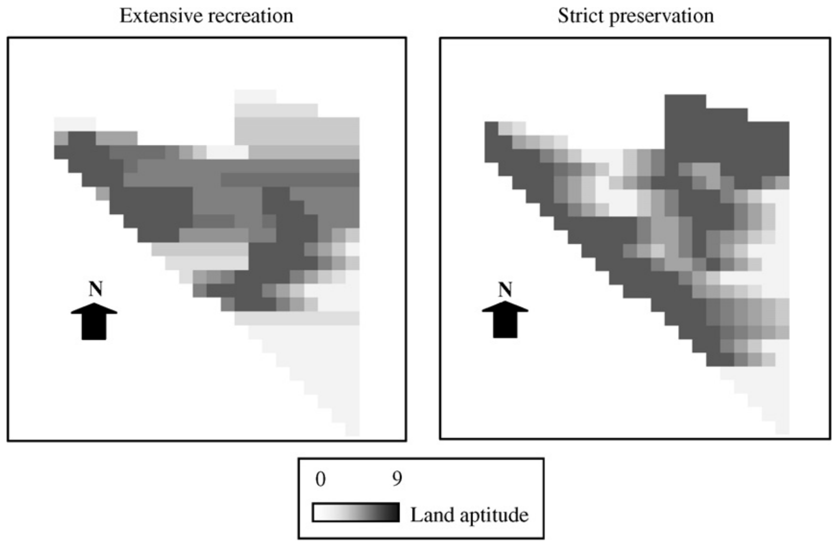

Fig. 2. Talampaya land use aptitude. Land aptitude scale is from 0 (no aptitude, white) to 9 (maximum aptitude, black).

Table 3
Parameters for Talampaya National Park

Parameter in objective function	Value
Number of cells of the grid:	900 (30×30),
To be assigned	278,
Surrounding area	622,
Number of uses	4,
To be assigned	(1) Extensive recreation, (2) Strict preservation;
Fixed (surrounding area)	(3) Ischigualasto Park, (4) Extensive ranching,
Land aptitude	See Fig. 2.
Use preference	Extensive recreation = 0.25; Strict preservation = 0.75.
Weighting parameter	$M = 0.075$.
Compatibility of uses (C_{uv} in zoning model)	Between uses to be assigned: Extensive recreation–Extensive recreation = 0.25; Strict preservation–Strict preservation = 2; Extensive recreation–Strict preservation = 2; Strict preservation–Extensive recreation = −2. Between uses to be assigned and uses of surrounding area: Extensive recreation–Ischigualasto Park = 1; Extensive recreation–Extensive ranching = −1; Strict preservation–Ischigualasto Park = 2; Strict preservation–Extensive ranching = −1.
Distance between cells	Euclidean distance squared.
Connectivity constraint	Extensive recreation = no; Strict preservation = yes.
Minimum and maximum number of cells constraint	Extensive recreation = 1,278; Strict preservation = 70, 170.

squared instead of a linear term of Euclidean distance has the effect of promoting clustering of cells allocated to compatible uses (Verdiell et al., 2005). The ecological importance of this behaviour is that more than one area of conservation significance may emerge for zone delineation as shown in Fig. 3a.

When comparing protected areas of similar size, vulnerability to disturbances is usually higher for areas with more edges and longer perimeters. Edges may have negative consequences for wildlife through an increased incidence of nest predation and parasitism (Yahner and Scott, 1988), and by altering species distribution and dispersal (Fagan et al., 2003). Alien plants frequently gain a foothold on new areas by invading edge habitats. Competition with invasive species, in turn, may lead to reduced seed production in native species, thus threatening biodiversity (Fagan et al., 1999). Edge considerations are, therefore, important for zoning of protected areas. Zones with a high edge:area ratio are undesirable (i.e. fewer, larger zones are to be preferred over numerous, smaller ones). Round zones, on the other hand, should be preferred over longer, narrower zones. Our simulation results showed that reciprocal positive values of compatibility among uses maximize edge length and minimize aggregation, both undesirable ecological results. In contrast, when reciprocal negative values were used, edge length was minimized and clustering maximized. However, the use of reciprocal negative values had the undesirable consequence of producing a single core area (Fig. 3d). Thus, a non-symmetric compatibility matrix probably represents the best compromise between clustering of land units with similar land aptitude and minimization of the edge:area ratio.

Habitat fragmentation is one of the most pressing problems in wildlife management and biodiversity conservation (Shafer, 1990); it generally leads to smaller, more isolated animal populations. Smaller populations, in turn, become vulnerable to local extinction due to stochastic

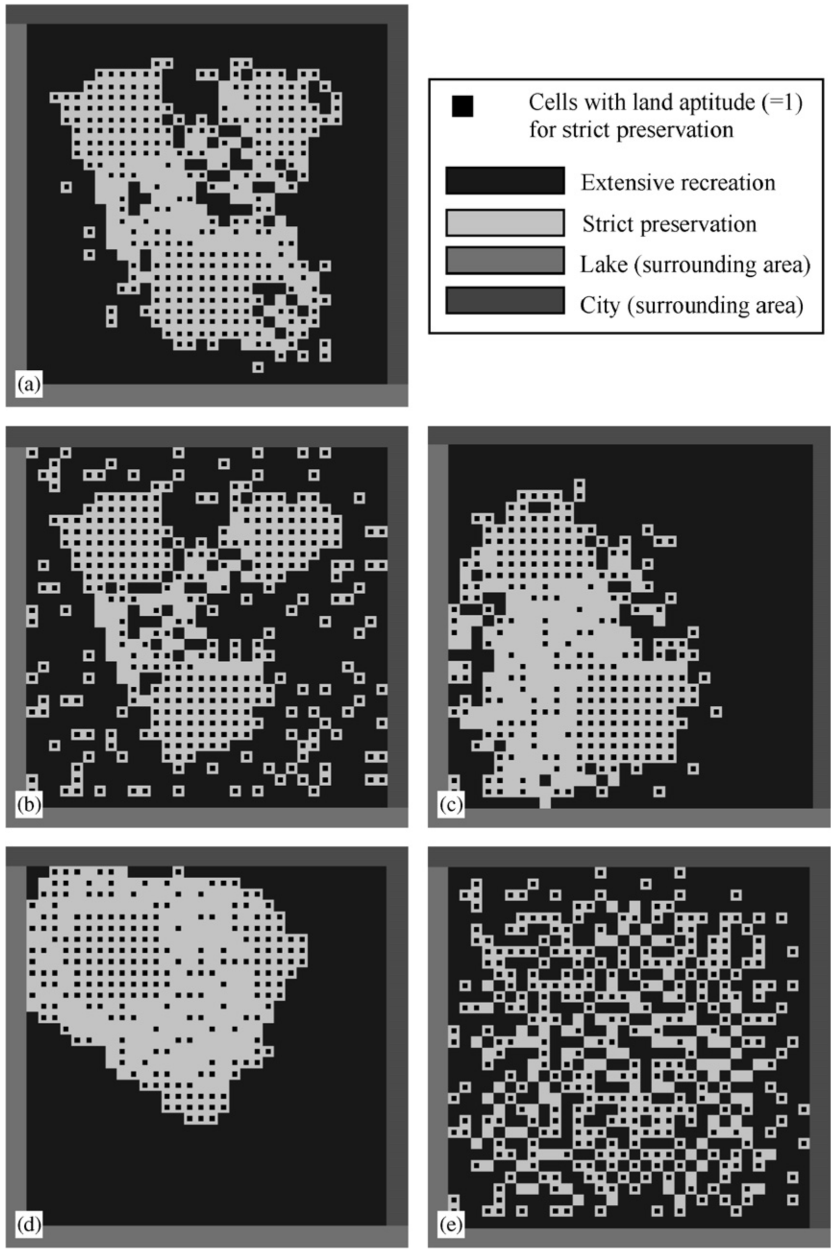

Fig. 3. Alternative zonings obtained with different assumptions for key parameters: distance between cells, connectivity constraint, and symmetry of compatibility coefficients; see text for further explanation. (a) Squared Euclidean distance, connectivity constraint for the strict preservation use and non reciprocal compatibility between uses (extensive recreation–strict preservation $= +1$, strict preservation–extensive recreation $= -1$); other parameters as in Table 2. (b) Without connectivity constraint for strict preservation; other parameters as in a). (c) Linear Euclidean distance; other parameters as in (a). (d) Reciprocal compatibility (-1) between extensive recreation and strict preservation; other parameters as in (a). (e) Reciprocal compatibility ($+1$) between extensive recreation and strict preservation; other parameters as in (a).

events and to the negative effects of inbreeding depression. Maintaining connectivity across the landscape is heralded as a key conservation factor to facilitate species movements and interbreeding (Noss and Harris, 1986; Shafer, 1990; With et al., 1997). Imposing a connectivity restriction for the assignment of land units to uses reduced fragmentation, favouring aggregation around clusters of compatible uses (compare Figs. 3a and b).

As in many other ecological applications, the issue of scale cannot be overlooked when considering zoning of protected areas. Our quantitative method may provide decision support for zoning at different scales, from a remote sensing perspective down to a site-specific scale. However, implementation of real-world problems will often be limited by available information rather than by methodological restrictions.

5. Conclusions

The quantitative method proposed can be implemented for assisting the process of developing prescriptive, participative zoning of protected areas. Agreeing upon

Table 4
Spatial metrics computed for comparing results from alternative hypothetical scenarios using FRAGSTATS

Case	Number of patches (NP)[a]	Aggregation index (AI)[a]	Connectivity (CONNECT)[a]	Total edge (TE)[a]	Number of core areas (NCORE)[b]
Our zoning model(Fig. 3a)	11	84.67	37.04	326	3
Without connectivity constraint (Fig. 3b)	57	71.12	6.13	591	3
Linear distance (Fig. 3c)	13	87.84	33.32	264	1
Reciprocal negative compatibility between uses (Fig. 3d)	4	97.15	33.34	82	1
Reciprocal positive compatibility between uses (Fig. 3e)	26	48.67	11.19	1030	0

[a]At whole zoning level.
[b]At strict preservation use level.

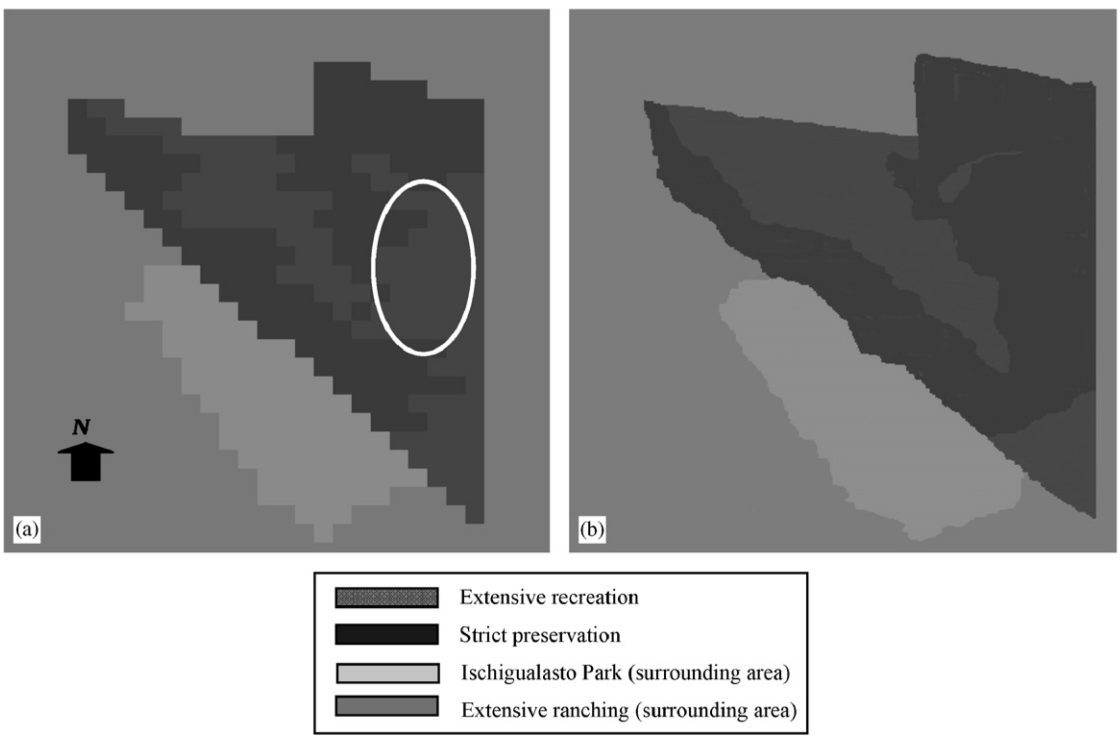

Fig. 4. Qualitative (right), and quantitative (left) zoning of Talampaya National Park. The oval encloses an area of marked disagreement between zonings; see text for further explanation. (a) Quantitative zoning. (b) Qualitative zoning by Dellafiore and Sylvester (2000).

input data, constraints, weighting factors and land use compatibilities would require a concerted, and no doubt difficult, effort from experts and stakeholders. However, once agreement is reached on key input information, a wide spectrum of alternative zoning plans could be easily generated for consideration and discussion. Translating the objectives and vision of different stakeholders into model parameters and constraints may prove difficult. Nonetheless, it may still be rewarding because most biases and conflicts of interest will be explicitly exposed, which could facilitate the task of finding common ground.

Although our quantitative method may not be the definite answer for zoning protected areas, it is a fast, inexpensive, and useful tool for supporting land use planning, illuminating possible land use conflicts and, thus, hopefully, minimizing poor planning.

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