A GIS-BASED MULTICRITERIA APPROACHES TO LAND USE SUITABILITY ASSESSMENT AND ALLOCATION

Guillermo A. Mendoza[1]

ABSTRACT. —Land suitability assessment in a Geographic Information System (GIS) environment is formulated as a multi-criteria decision making (MCDM) problem. Different MCDM approaches are developed to combine factors in a suitability analysis of land for potential land uses. These MCDM approaches are used to develop a generic suitability index. Approaches include both qualitative and quantitative techniques. Results from the MCDM analysis are then linked to a GIS for more detailed spatial analysis. Besides land suitability evaluation, an MCDM framework is also developed for land use allocation. The framework captures the multi-criteria nature of land suitability analysis and at the same time allocates land by maximizing the overall suitability of a land area.

INTRODUCTION

This paper addresses two critical issues in land use planning; land use suitability and land use allocations. Land use suitability is a generic term associating a combination of factors and their impacts with respect to potential land uses. Land allocation, on the other hand, involves the process of designing an optimal mix of land uses based on their estimated suitability and perceived management objective.

The objectives of this paper are: 1) to develop multi-criteria approaches in evaluating land use suitability; and 2) to use different measures of land use suitability as guides to optimally allocate lands to their most suitable uses. Moreover, the paper also aims to develop an integrated model that accommodates these objectives in a spatially explicit planning and decision making environment through the use of a Geographic Information System (GIS).

An integrated GIS-based multi-criteria approach to land suitability analysis and allocation offers significant advantages. The GIS environment enables the spatially explicit evaluation of site suitability and the assignment of various measures of suitabilities to specific sites or geographic areas. The integration also allows area allocations at specific spatial or geographic locations. Hence, the integrated GIS-based model combines the spatial capabilities of GIS, with the analytical power of multi-criteria analyses. That is, the GIS-based integrated model permits both analytical planning and optimization of land use decisions at different levels, namely; 1) site suitability assessments based on different factors and specific land uses; 2) generation of suitability indices based on combinations of different factors (i.e. composite index/measure of site suitability); and 3) generation of an optimal land use plan that simultaneously considers the individual site suitabilities, and the optimal allocation to the most suitable land use (i.e., mix of land uses that yields the “highest” overall cumulative suitability.

SITE (LAND) SUITABILITY ASSESSMENTS

There is significant amount of literature dealing with land suitability assessments. Anderson (1987) surveyed different methods of land capability/suitability analysis ranging in degrees of computational and analytical sophistication. Hopkins (1977) reported a comparative evaluation of alternative methods of assessing land use

[1] Associate Professor, Department of Natural Resources and Environmental Sciences, University of Illinois, Urbana, Illinois. This study is supported in part by the International Arid Lands Consortium through a cooperative Agreement between the University of Illinois and the University of Arizona. The participation of Prof. Phillip Guertin, University of Arizona, is also acknowledged.

suitabilities. More recently, Steiner (1983, 1987) reviewed land evaluation and site assessment (LESA) using USDA-recommended standards.

Site suitability assessment is inherently a multi-criteria problem. That is, land suitability analysis is an evaluation/decision problem involving several factors. In general, a generic model of site/land suitability can be described as:

$$S = f\ (x_1,\ x_{2,}\ldots,\ x_n)) \qquad (1)$$

where S = suitability measure; x_1., x_2, …, x_n = are the factors affecting the suitability of the site/land.

The principal problem of suitability analysis is to measure both the individual and cumulative effects of the different factors; x_1, …, x_n. In other words, suitability analysis generally involves determining an appropriate approach to combine these factors. Some approaches to combining these factors include: 1) composite rating, including weighted composite ratings (Anderson 1987); 2) weighted factor method (Hopkins 1977); 3) various forms of multi-criteria approaches such as compromise programming (Pereira and Duckstein 1993); Prioritized Land Use Suitability (PLUS) by Xiang and Whitley (1994); use of effectiveness matrix (Jankowski and Richard 1994); modified weighted factor (Diamond and Wright 1988); and 4) the heuristic rules of combination expressed through verbal logic rather than in numeric terms (Hopkins 1977).

Another classical site suitability analysis approach is through formal functional relationships of the different factors. Most notable among these approaches is regression analysis. Wildlife habitat suitability assessments, for example, commonly use regression analysis procedures to estimate habitat suitability indices (Pereira and Itami 1993).

SUITABILITY ANALYSIS AND ANALYTIC HIERARCHY PROCESS

This paper proposes an alternative approach to site suitability analysis. Most of the suitability analysis techniques described above rely on significant amount of information to be useful, applicable, and effective. Regression analysis, for example, will require a cross-sectional database covering the wide range of suitability conditions as affected by the different factors individually and collectively. If such data are available, formal analysis of the composite function in (1) such as regression analysis, is warranted and also offers an accurate way to evaluate site suitability. If, on the other hand, data are incomplete, or if significant information gaps exist in the cross-sectional database, then it may be more appropriate, practical, or convenient to adopt an alternative approach that does not rely on complete or comprehensive databases. One such approach is the Analytic Hierarchy Process (AHP).

AHP offers some advantages over the classical site suitability analysis techniques. First, it provides a structured approach to measuring suitability by “decomposing” the suitability analysis problem into hierarchical units and levels. This allows a systematic and more in-depth analysis of the factors which may be better understood when “de-coupled” or “deconstructed” into their lower and more specific forms or indicators. Second, AHP relies less on the completeness of the data set, and more on “expert” opinions or observations about the different factors and their perceived effects on site suitability. Third, the approach is more transparent and hence more likely to be accepted especially when the suitability analysis will ultimately serve as a basis for land allocation. Fourth, AHP allows for the participation of both experts and stakeholders in providing the suitability measure of a site relative to a proposed land use. Such framework allows the incorporation and accommodation of both qualitative and quantitative criteria for assessing site suitabilities.

AHP is well documented in a significant number of published literature (Mendoza 1989,1997; Saaty 1980,1995; Kangas 1992,1993; Peterson et al. 1994; Reynolds and Holsten 1994; Pukkala and Kangas 1996) and will not be described in this paper. AHP applications to suitability analysis are reported in Banai-Kashani (1989); Eastman et al. (1992, 1993); and Xiang and Whitley (1994).

GIS-BASED MULTI-CRITERIA METHODS

GIS is a computer-based system that offers a convenient and powerful platform for performing land suitability analysis and allocation. As pointed out earlier, the integration of multi-criteria methods of suitability assessments and allocation methods into a GIS system offers both the spatial capabilities of GIS and the analytical power of formal multi-criteria decision making tools.

The site suitability analysis approach proposed in this paper takes a generalized form of (1) as follows:

$$S = \sum_{j=1}^{n} c_j x_j \qquad (2)$$

where x_j = are the factors affecting suitability; c_j = are "parameters" associated with each factor

Note that the simple model described in (2) is linear. Given a sufficient dataset, the c_j's can be easily estimated, and subsequently determine S. However, in many suitability analysis cases, a complete crossectional database for all x_j's are not available, nonexistent, fraught with errors or uncertainty, and difficult, costly, or even impossible to generate. Alternatively, one could estimate the c_j's not through an information-intensive procedure like regression, but through systematic analysis of information obtained from experts, users, and other stakeholders who are most informed about the site and its suitability for a potential land use. Such information is generated through structured questioning designed to elicit the experts' judgment and opinion. Results from this structured questioning and the resultant matrix of information that reflect the experts' judgment and opinions form the basis for estimating the parameters in c_j. Hence, c_j's are viewed not as technical coefficient associated to each factor; instead, they represent the relative importance or degree of influence of each factor to the overall measure of site suitability. In this case, c_j are estimated not through formal parameter estimation procedures like least squares in regression, but through AHP. It should be noted also that the c_j's estimated by AHP reflect the relative weights of each factor which are scaled and normalized. Hence, they are somewhat analogous to the set of scaled and normalized set of regression coefficients.

The model described in (2) can be easily transformed and implemented in a raster GIS environment (Eastman, et al. 1995). Current GIS functionalities and capabilities can computationally operationalize the model in (2) using Map Algebra.

GIS Suitability-based Land Allocation

The proposed integrated GIS-based model can provide more than site-specific and spatially explicit map of site suitabilities. The integrated model can also use these site suitabilities to serve as a guide to subsequent allocation of land to potential uses. This allocation process is performed and implemented under a raster GIS environment.

Recently, there have been attempts to combine GIS with optimized land allocation techniques. In most of these, integration is achieve sequentially or in a linear fashion; that is, optimized allocation is performed independently using various types of optimization models, then the results of the optimization is exported to a GIS for mapping and display (Jones et al. 1995; Church et al. 1995; Chuvieco 1993; Campbell et al. 1992; Carver 1991; Diamond and Wright 1988). While this approach is plausible in some applications, an alternative approach is to impose the integration simultaneously rather than sequentially. That is, the site suitability estimates serve as the defining variables for land allocation. Hence, optimized allocation is done internally within the GIS system.

Before describing the multiple land use allocation model proposed in this paper, the discussion below outlines the methodology for land allocation under a raster-based GIS platform considering one land use. That is, individual cells/pixels are allocated to a single land use given their land suitability values. The model can be described as:

$$\text{Maximize } \Sigma S_k \quad \text{for all } k \qquad (3)$$
$$\text{Subject to: } \Sigma a_k = A$$

where S_k is the suitability index for pixel/cell k, a_k is the area of cell k, and A is target area allocation.

This seemingly simple model is quite difficult to implement within a GIS system. To accomplish this, Eastman et al. (1995) devised a heuristic procedure that achieves the optimized allocation in (3). The procedure simply involves ranking of all the pixels/cells based on their S_k values. In other words, an image (i.e. derived map) can be generated containing the "ranked" values of each cell. That is, the values of each cell in the image (S'_k) is "transformed" from each original suitability value (S_K) where the transformed value reflects its "rank" among all cells. The number of cells to allocate to the land use (according to its suitability value) will depend on the target allocation, A, and the resolution of the pixel/cell. But, the "optimized allocation" is made by systematically selecting from highest ranked cells to lower ranked cells.

The model described in (3) allocates cells/pixels based on their suitability values for a single land use. The real problem in land use planning, however, involves the allocation of tracts of lands or sites into alternative land uses. This becomes most problematic when the land could be allocated to various land uses some of which are complementary while others may be competing. Further complicating the allocation problem is the involvement and potential pressure exerted by interest groups or stakeholders with vested interests on how the land is allocated. Thus, the allocation problem becomes not only a multi-factorial land use suitability problem, but also a multiple-objective, multi-decision maker land allocation problem.

A multiple land use allocation model based on suitability values can be formulated by expanding the model described in (2). Clearly, for a given land use, one could implement models (1) and (2) to generate a suitability map for the particular land use. Hence, suitability maps reflecting the suitability values of each pixel relative to a particular land use can be generated using (2) and (3). The use of AHP insures that the suitability maps are comparable for all land uses (i.e., they are scaled and standardized because the c_j's in (2) are normalized.)

Allocation of land to alternative uses must address the following issues: 1) Each pixel/cell has different suitability value associated to a particular land use; 2) Land uses are either complementary (i.e., compatible) or competing (i.e., exclusive); and 3) Stakeholders, interest groups, or decision makers value each land use differently.

Suitability maps as described above addresses the first issue. These reflects the suitability values of each pixel/cell calculated by (2) given the c_j's estimated by AHP. The second issue actually involves two interrelated problems. The first problem must consider the fact that land uses have different degrees of importance, or relative values to different interest groups or stakeholders. The second problem involves the manner of "combining" these different valuations of relative importance for each land use. Hence, the second issue then requires some mechanism to, not only evaluate the relative importance of each land use, but also to collectively arrive at a compromise valuation that is consistent and acceptable to the stakeholders. These two problems and the proposed mechanism to solve them are described in more detail in the next section. Again, in this context, the AHP offers a transparent and convenient procedure for achieving both.

The third issue relates to the participation of various stakeholders in the evaluation of land uses and subsequent land allocation. Studies have shown that land use planning and allocation are best achieved under a participatory framework where stakeholders play significant roles in the decision making process. The AHP approach offers both structural and procedural features that accommodates the evaluation and decision making requirements of such a participative framework.

Briefly, AHP can be used to generate the relative weights or degree of importance of each land use. Given these weights, one could formulate a general optimization problem as:

$$\text{Max } \mathbf{Z} = g\,(S_1.\ S_2.\ \ldots,.Sp) \qquad (4)$$
$$\text{s.t. } x \ \varepsilon\ X$$

where **Z** is an indicator of overall cumulative suitability; S_1. S_2, **…**, Sp are the generic measure of suitability for each land use (i.e. suitability maps). Clearly **Z** could be a vector, or a scalar depending on how land use utilities are combined in an attempt to forge a compromise valuation of all land uses. The simplest case would be to devise a "composite measure" where **Z** is a single value denoting the overall cumulative utility. That is;

$$Z = \Sigma w_k \; Z_k \qquad (5)$$

where w_k, are the relative weights generated by AHP for each land use.

Optimizing Land Use Allocation within GIS

The procedure for optimizing land use allocation will depend on whether the land uses are compatible or conflicting. First, consider the case when the land uses are compatible. This is a simple land allocation case because technically, if all the land uses are compatible, then there is no pressure to allocate the land for alternative land uses. The allocation is simply based on a descending measure of overall (i.e. composite) or cumulative suitability for the compatible land uses. Procedurally, this is similar to allocation when there is only one land use. In other words, the ranked-based allocation will be based on the cumulative measure Z described in (5) which actually combines the individual suitabilities for each land use as described in (3).

The models described in (2)–(5) achieve optimal single land use allocation within GIS through the heuristic procedure based on ranking of each cell according to their suitability values. The constraint set in (4) is essentially target allocations as described in (2). However, in many cases, there are other constraints that must be satisfied simultaneously. While this is easy to perform in most mathematical programming models, achieving this spatial allocation optimally while considering all constraints simultaneously, is a more difficult task. Another heuristic procedure developed by Eastman et al (1995) achieves this simultaneous constraint satisfaction by modifying the suitability measure as described below:

$$Z = \Sigma w_j \; x_j \; * \Pi_i \, c_i \qquad (6)$$

where the cj's are the constraint "scores" which are either zero-or-one. In other words, Boolean images could be created to represent each constraint, where the Boolean image has a value 1 for reclassified cells that satisfies the constraint, and 0 otherwise. By "modeling" these Boolean images representing the constraints, only those cells that satisfies all constraints (non-zero), will be considered in the allocation. Those cells that have at least one zero value (because of at least one constraint not being satisfied), will have a zero multiplicative value, and hence, it is assigned a zero suitability.

The optimal land use allocation procedure is a bit more complicated when the objectives are conflicting. In this case, land use allocations are exclusionary; that is, a piece of land can be allocated to only one land use. There are two possible ways to solve the problem. One is trough a "prioritized allocation." That is, the land uses are compared in terms of priority. Single land use allocation is done first to the land use rated as the highest priority following the procedures described previously. Then, allocation of remaining cells is done for lower priority land uses. This approach assumes that higher ranked land uses are infinitely more important, and that no trade-off between land uses is allowed.

The other approach is to develop some "compromise allocation" based on some versions of compromise programming. The simplest approach would be to use the method developed by Eastman et al. (1995) where allocation to competing land uses is done through the "minimum" Euclidean distance to the "ideal". That is, a "metric" is devised representing the distance of the suitability of each cell relative to the maximum suitability of the different land uses. Cells are allocated to the land use "closest" to the ideal value of each land use.

LITERATURE CITED

ANDERSON, L.T. 1987. Seven methods for calculating land capability/suitability. *Planning Advisory Service* (PAS) Report No. 402.

BANAI-KASHANI, R. 1989. a new method for site suitability analysis: The analytic hierarchy process. *Environmental Management*.

CAMPBELL, J.C., J. RADTKE, J.T. GLESS, AND R.M. WIRTSHAFTER. 1992. An application of linear programming and geographic information systems: Cropland allocation in Antigua. *Environment and Planning.* 24: 535–49.

CARVER, S.J. 1991. Integrating multi-criteria evaluation with geographical information systems. *Int. J. of Geographical Information Systems* 5: 321–39.

CHUVIECO, E. 1993. Integration of linear programming and GIS in land use planning. *Int. J. of Geographical Information Systems* 7(1):71–83.

CHURCH, R.L., A. MURRAY, AND K. BARBER. 1995. A spatial decision support system for doing hierarchical habitat planning. In *Analysis in support of ecosystem management,* ed. J. Thompson. USDA. Forest Service.

DIAMOND, J.T., AND J. WRIGHT. 1988. Design of an integrated spatial information system for multiobjective land use planning. *Environment and Planning B: Planning and Design* 15:205–14.

EASTMAN, J.R. ,W. JIN, P. KYEM, AND J. TOLEDANO. 1992. Participatory procedures for multi-criteria evaluations in GIS. *Proceedings, in GIS'92,* pp. 281–88. Buffalo, N.Y.

EASTMAN, J.R., P. KYEM, AND J. TOLEDANO. 1993. A procedure for multi-objective decision making in GIS under conditions of multiple objectives. *Proceedings, EGIS'93*, pp. 438–47.

EASTMAN, J.R. ,W. JIN, P. KYEM, AND J. TOLEDANO. 1995. GIS in Decision Making. UNITAR. Vol. 4. *Explorations in Geographic Information Systems Technology*. Clark University.

EASTMAN, J.R., W. JIN, W. KYEM, AND P. TOLEDANO. 1995. Raster procedures for multi-criteria? Multi-objective decisions. *Photogrammetric Enginnering & Remote Sensing*. 61(5): 539–47.

HOPKINS, L.D. 1977. Methods of generating land suitability maps: A comparative evaluation. *J. of American Institute of Planners*. 43(4):386–400.

JANKOWSKI, P., AND L. RICHARD. 1994. Integration of GIS-based suitability analysis and multicriteria evaluation ina spatial decision support system for route selection. *Environment and planning B: Planning and Design*. 21: 323–40.

JONES, J.G., J. CHEW, M.D. SWEET, K. WALL, AND L. WELDON. 1995. Bitterfoot Ecosystem Management: Landscape analysis to support ecosystem management. In *Analysis in support of ecosystem management*, ed. J.E. Thompson. USDA Forest Service.

KANGAS, J. 1992. Multiple-use planning of forest resources by using the Analytic Hierarchy Process. *Scand. J. of For. Research*. 7:259–68.

KANGAS, J. 1993. A multi-attribute preference model for evaluating the reforestation alternatives of a forest stand. *Forest Ecology and Management*. 59: 271–88.

MENDOZA, G.A. AND W. SPROUSE. 1989. Forest planning and decision making under fuzzy environments: An overview and analysis. *Forest Science* 35(2): 481–502.

MENDOZA, G.A. 1997. Introduction to Analytic Hierarchy process: Theory and applications to Natural Resources Management. In *Proceedings of 1997 ACSM/ASPRS Annual Convention*. Vol 4. Resource Technology. April 7–10. Seattle, WA. pp.130–39.

PEREIRA, J.M., AND L. DUCKSTEIN. 1993. A multiple criteria decision-making approach to GIS-based land suitability analysis. *Int. J. Geographical Information Systems*. 7:407–24.

PEREIRA, J.M., AND R. ITAMI. 1991. GIS-based habitat modeling using logistic multiple regression: A study of the Mt. Graham Red Squirrel. *Photogrammetric Engineering & Remote Sensing*. 57(11):1475–86.

PETERSON, D.L., D. SILSBEE, AND D. L. SCHMOLDT. 1994. A case study of resource management planning with multiple objectives*.* *Environmental Management*. 18(5): 729–42.

PUKKALA, T., AND J. KANGAS. 1996. A method of integrating risk and attitude toward risk into forest planning. *Forest Science*. 42(2): 198–205.

REYNOLDS, K.M., AND E. HOLSTEN. 1994. Relative importance of risk factors for spruce beetle outbreaks. *Can. J. of For. Research*. 24(19):2089–95.

SAATY, T.L. 1980. *The Analytic Hierarchy Process*. New York: McGraw-Hill.

SAATY, T.L. 1995. *Decision making for leaders: The analytic hierarchy process for decisions in a complex world* RWS Publication, PA. 3rd Edition.

STEINER, F. 1983. Resource suitability: Methods for analysis. *Environmental Management*. 7(5): 401–20.

STEINER, F. 1987. Agricultural land evaluation and site assessment in the United States: An introduction. *Environmental Management.* 11(3): 375–77.

THOMAS, D.A., AND X. SUN. 1995. (Rangeland) production: use of models incorporating aggregated knowledge and fuzzy construction. *Journal of Arid environments*. 30: 479–94.

XIANG, W. AND D.L. WHITLEY. 1994. Weighting land suitability factors by the PLUS Method. *Environment and Planning B: Planning and Design*. 21:273–304.