Problems with Using Overlay Mapping for Planning and Their Implications for Geographic Information Systems

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ABSTRACT / As part of the planning process, maps of natural factors are often superimposed in order to identify areas which are suitable or unsuitable for a particular type of resource management. Overlay maps may also be used to identify analysis areas for predictive modeling of resource productivity and ecological response to management. Current interest in applying computer-assisted mapping technology to making overlay maps is drawing attention to geographic information systems for this purpose. The resultant maps, however, may be so inaccurate or unable to capture significant units of productivity and ecological response that they could lead to imperfect or false conclusions. Recommendations are made on how to proceed in light of these problems.

An increasingly common part of the planning process for wildland areas is the preparation of map overlays to determine the suitability of an area for alternative resource management. Techniques for suitability analysis are presented in a number of papers (Varnes 1974, Larson and others 1977, Hopkins 1977, Ferguson 1981, FAO 1984, Steiner 1983). Maps of natural factors such as bedrock geology, soil, slope, and vegetation are superimposed in order to locate and delineate areas where particular factor combinations occur. This is done either by manually overlaying the factor maps or with an automated geographic information system (GIS). A geographic information system is a computer information system with the capability of handling spatially related data, specifically map-related data such as soil type boundaries and stream networks.

An accurate overlay map would have unquestionable value in identifying types of land that will respond in a coherent and uniform way to the application of a variety of management practices. A mapping system for identifying such land types could be useful in current attempts to model the response of wildland areas. Of these models—for example, FORPLAN (Johnson and others 1986)—most utilize land types which are represented in the model by the component known as an analysis area. Because of their fundamental importance to such models, no mapping system for defining analysis areas should be accepted without a thorough examination of the problems with its application. This subject is addressed here.

KEY WORDS: Land suitability; Geographic information systems; Landscape ecology; Resource planning model

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There are a number of problems in the preparation of map overlays, one of the most obvious being the practical difficulties in manually superimposing a large number of maps. This problem is largely overcome when the overlays are prepared by computer-assisted mapping technology. For this reason, computerized GIS have been advocated for use as tools for land managers and planners (see, for example, Davis 1980, Tomlin and others 1981, Martin 1985, Berry and Sailor 1987, and the recent series of articles in the *Journal of Forestry* August–October 1986). Although GIS have the capability to display and analyze geographic information, this discussion is concerned with their use as tools for making overlay maps more efficiently. This increase in efficiency, however, does not eliminate other problems. The problems that generally pertain to manual systems, such as the limitations of the information on which they operate, also apply to computerized systems. Furthermore, as noted below, use of GIS may create additional problems by creating false perceptions about the quality of the results.

Land management agencies in the United States, including the US Forest Service, are moving forward with the assessment of GIS technology as a tool to support natural resource management. These assessments concentrate on problems associated with making the technology work in a cost-effective manner. Computer hardware and software have received most of the attention. However, these assessments do not address more basic underlying problems such as information

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errors. It is desirable, therefore, to bring these problems forward for consideration, discussion, and, hopefully, ultimate resolution.

This article is intended primarily for planners and managers, especially those with a limited knowledge of GIS technology. While the problems of applying GIS technology are well understood by the specialist (see, for example, Dangermond and others 1982), it is apparent that they have not come fully to the attention of those responsible for making the decision to use such technology or interpret the results.

Inaccuracy

A very significant problem which has received little attention is inaccuracy. In a thorough review of the problem, MacDougall (1975) states, "It is quite possible that overlay maps by their very nature are so inaccurate as to be useless and perhaps misleading for planning." MacDougall does not specify the level of planning to which he is referring. But with emphasis on accuracy, he is probably thinking of levels more detailed than national or regional planning. These more detailed planning levels are most closely related to planning of broad areas such as a national forest or county, or to site-specific projects.

The basis for this hypothesis of significant error is as follows. Maps used to assemble an overlay are almost always those which identify uniform regions. These maps of regions have been compiled and drawn to meet two kinds of accuracy standards: the allowable error in the positioning of boundary lines (horizontal accuracy), and the degree of uniformity or purity of the region.

The possible magnitude of error at the level of broad area planning can be large. For example, MacDougall (1975) reports that in an overlay of six maps, each with an allowable horizontal error of 0.5 mm (approximate US National Map Standards for well-defined points) and a purity of 80% (a good soils map), the possible error in the location of boundaries is 3 mm, and the purity of the overlay is 21%. On the basis of purity alone, MacDougall concluded that this overlay map is not significantly different from a random map. This is an extreme case, but it illustrates the possible magnitude of the problem.

The horizontal error of a boundary line has two parts: error in the original source map, and error introduced in the preparation of the final map. Modern cartographic techniques can keep the latter to a minimum. Errors in source maps can be considerably greater. This is because most natural factors vary along a continuum and are not composed of discrete natural regions. The boundaries between regions reflect gradual changes and tend to be indistinct and arbitrary. Therefore, the line represented on a map is actually representing a zone of transition. Two cases where this commonly occurs are maps of soil and vegetation—two of the most commonly used factors in overlays for suitability analysis (see Figure 1).

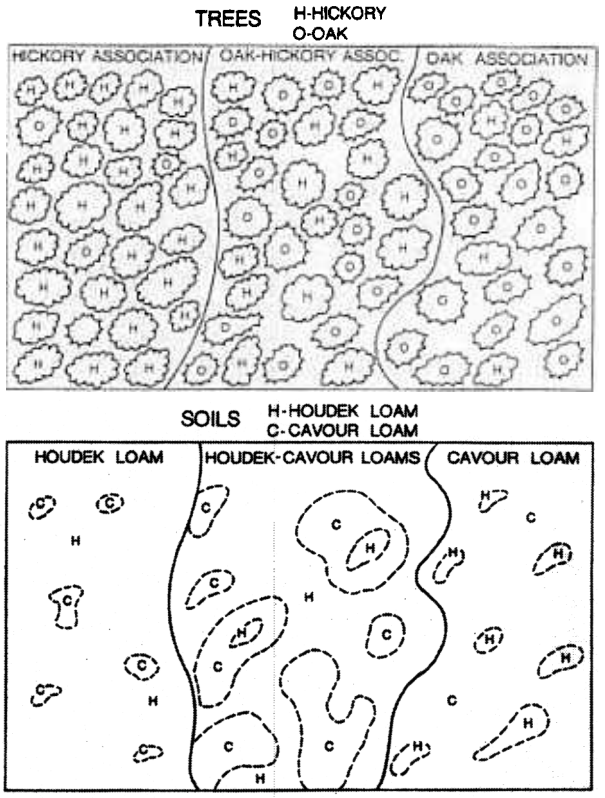

Figure 1. Transition zones between regions. After Aandahl and Herrwagen 1964.

Generalization is an integral and inescapable part of all mapping, and as a result mapping units have varying purity or uniformity. The generalization process may involve simplifying boundaries between regions or allowing atypical conditions to be included in the region. This process is illustrated in Figure 2. Depending on the scale of the map and its purpose, mapping units may contain quite different conditions. This also varies with the complexity of the landscape. Maps of mountainous terrain usually contain higher percentages of impurities than less rugged terrain. When impurities which are included in each region tend to coincide spatially with impurities in the matching region on other factor maps, the result is error compounding error.

Errors of this sort are most likely to occur when maps of different scale with dissimilar degrees of gen-

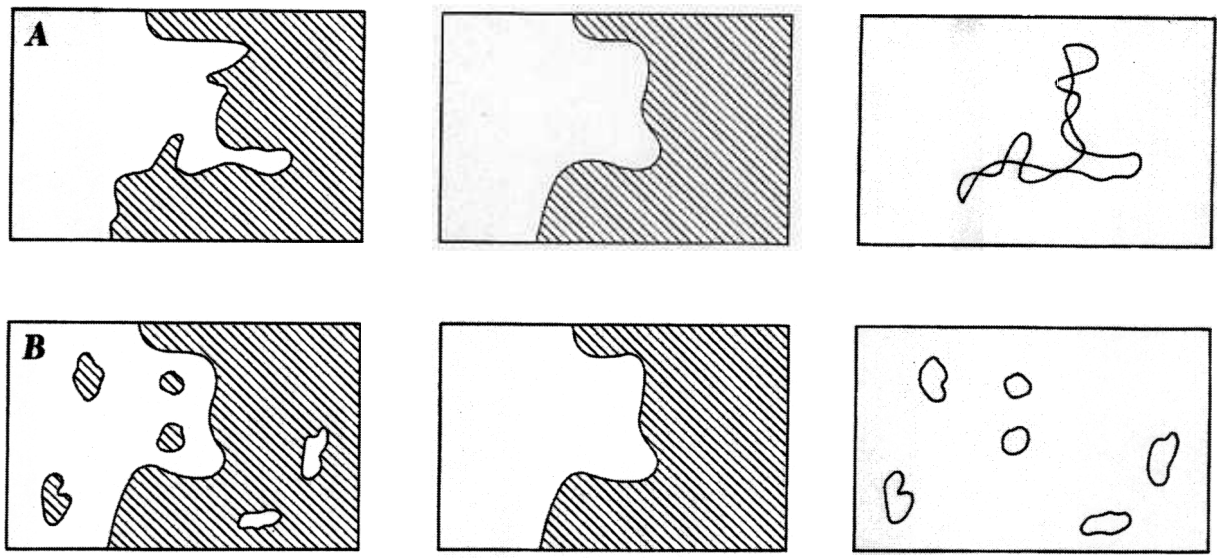

Figure 2. Idealized examples of generalization of soil patterns. Each row shows a small section of a hypothetical soil pattern in its original detailed form (left), after generalization (center), and with generalization errors identified (right); **A** line smoothing; **B** deletion of boundaries. From Hole and Campbell 1985; redrawn with permission from Rowman and Allanheld.

eralization are overlaid. To overlay, for example, the highly generalized boundaries of a system of climates plotted on a regional or global scale onto a pattern of vegetation plotted in detail almost invariably results in considerable errors.

Other sources of error stem from geometrical differences among maps. Maps are prepared according to projections which accommodate curvature of the earth's surface. Distortion is a necessary part of all these projections, because it is impossible to resolve perfectly a spherical surface onto a plane. Caution is necessary when one or more maps in the overlay have been prepared in a different projection. Depending on the particular projection used, it is quite possible that there could be significant error introduced into the overlay. Use of computers can reduce the possibility of such errors.

The principal source of error in the assembly of the factor maps into an overlay is in the enlargement or reduction of maps so that they are all of the same scale. Use of computers can minimize these problems. However, the entry of the maps into the computer can be a potential source of error. Various techniques are available for entry of the maps into the computer, including electronic scanning. The most common is to use a device to translate boundary lines of areas or polygons into coordinates, and have the operator trace the boundaries with a digitizer. The accuracy of the procedure depends on the care used in tracing the boundaries. In another technique, the mapped areas are represented by grid cells. The disadvantage of grid-cell representation is that details can be missed unless cell size is very small (Figure 3). Gridding tends to underestimate areas that are small or irregular (particularly sinuous areas, such as narrow floodplains); in many planning situations, these are generally the areas of principal interest because of their infrequency.

The final assembly of maps by manual means into an overlay tends to reduce horizontal error. This occurs because the individual who traces boundary lines is acutely aware of inconsistencies in their boundaries. In cases where boundary lines on two maps parallel one another but are separated by 1 or 2 mm, the map compiler will almost certainly represent them by a single line in the overlay halfway between them. The compiler is adjusting the lines with knowledge of the correlation amoung factors, factor map reliability, and so on. In this way, small sliver errors in boundary location are reduced in the overlay map and, more important, the number of regions representing factor combinations that do not actually exist is minimized. Sliver errors are small errors created by overlapping of coincident boundaries (Figure 4).

It is important to recognize that this editing procedure does not occur when an overlay is prepared with an automated system. Unless rules are specified to eliminate slivers, regions are produced in a purely mechanical way wherever different factor combinations are identified by the computer, regardless of size or location.

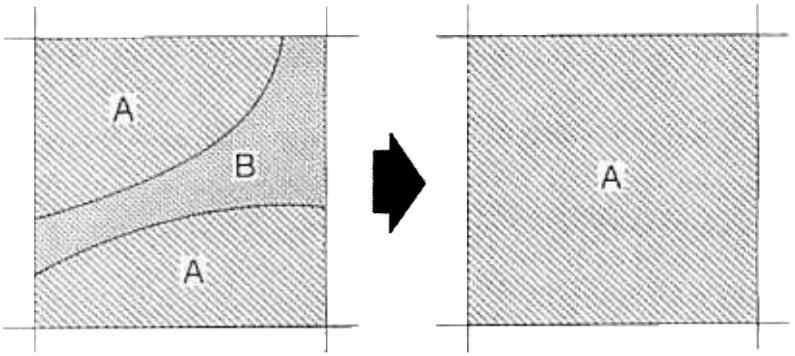

Figure 3. Mapped areas represented by grid cells. A single category is assigned to the cell by selecting the category that occupies the largest area within the cell. **A** valley sideslope; **B** floodplain. From Hole and Campbell 1985.

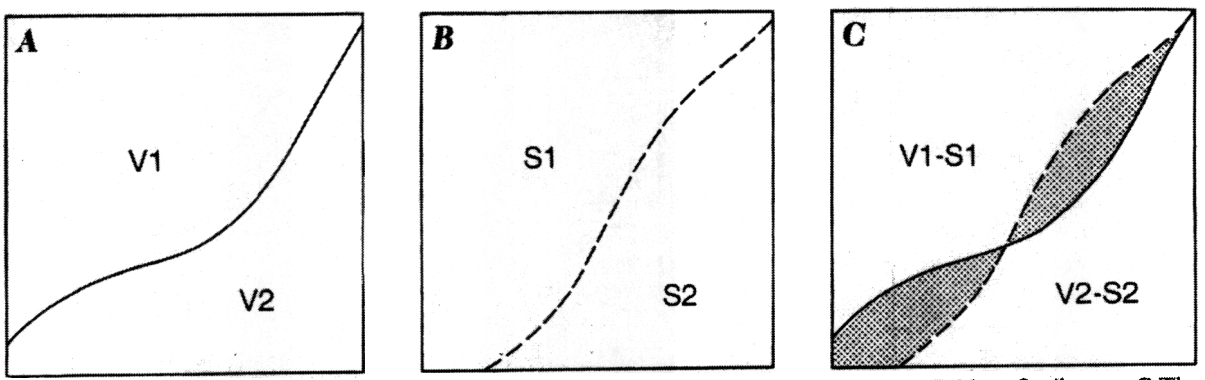

Figure 4. Sliver errors (shaded) resulting from overlaying two maps. **A** Map of vegetation types. **B** Map of soil types. **C** The overlay.

Assumption Underlying the Approach

Inaccuracy aside, there are other problems that relate to the map overlay approach to suitability analysis. The determination of suitability requires an understanding of the effects of management practices and prescriptions on the quantity and quality of resource outputs. This, in turn, depends on a sound knowledge of ecological processes, such as erosion and vegetative succession. The kind and magnitude of expected response is the result of many complex and interacting factors which control ecological processes. Various combinations (or integrations) of factors and related processes occur throughout a wildland area. Making predictions about ecological behavior requires information about the nature of this integration and its variation from place to place. A useful tool for this purpose must be capable of identifying units of land displaying more or less homogeneous integration of factors, particularly in ways that may affect their ecological response to management.

On the premise that many factor maps are interrelated and correlated with the others, the map overlay approach attempts to identify on a single map zones where factor boundaries correspond to each other. Areas bounded by perceived correspondence in boundaries are thought to represent ecological response units. Typically, heavy or sole reliance is placed on available maps for this purpose.

While overlays may be useful in identifying ecological response units, there are potential shortcomings with such an approach. To begin with, unit boundaries on different factor maps rarely correspond to each other. This is because each factor has been studied independently by different professionals with different purposes in mind and at different times. Different principles and methods, levels of detail, and errors in source maps all combine to detract from an integrated ecologic picture. Boundaries of ecological significance emerge from study that reveal corresponding changes in the natural factors. This is different from attempting to synthesize ecological response units by the addition of factors or components initially defined as things in themselves, with no whole unit in mind. Moreover, the problems of boundary line location and the impurity of mapping units generated by over-

laying maps create some time-consuming, if not impossible, difficulties for the person who must interpret and overcome the erroneous factor combinations that result from trying to combine independently derived information.

There are a couple of other reasons why the use of available factor maps may not work well when it comes to identifying ecological response units. First, the same factor may indicate different process rates depending on where it is observed. For example, studies have shown that the productivity of the same soil series varies considerably throughout its range (Gersmehl 1980). Second, factor maps reflect a classification. The class boundaries selected for the map may not be relevant to the initiation of a process. For example, the slope angle that indicates an erosion threshold for a particular geologic material varies depending on the regional climate in which the slope is located. Slope maps typically do not account for this variation.

Another problem is lack of information. Some factors do not exist in map form; yet they may be critical to understanding a process. For example, the degree to which a landscape is dissected by streams is critical to understanding the process of sediment transport. But this information does not commonly exist as maps showing various dissection classes. While analysis could be performed to obtain such information, most often it is not done because of the practical necessity to use available maps.

The rationale behind the overlay mapping technique is the notion that significant ecological response units can be captured by synthesizing, or integrating, available factor maps. The implicit assumption is that the derived units reflect differences in potential response to management and resource productivity. That the commonly synthesized factors are the most appropriate for expressing these differences has often been assumed without validation. As yet, this synthesis has developed little beyond an empirical description that provides no explanation of processes which produced the units identified. This limits the ability to predict productivity and the consequences of environmental impact. To be effective, such an environmental synthesis must be shown to have directly applicable links to process (see the review by Moss 1985).

Similar problems are encountered in the application of multivariate clustering to classify land by grid cells (Omi and others 1979). In this approach, an arbitrary grid of cells is imposed on the surface to be mapped. The cells are then described by selected attributes and the information entered into a GIS. This information is then used to classify cells by numerical taxonomic methods, such as cluster analysis. A map is produced by drawing lines around cells of similar class. However, as Rowe (1980) points out, the units derived from such a process are not necessarily ecological. Ecological units can be apprehended only as wholes that have some process significance. For example, a floodplain is a pattern of spatially associated, but unlike, component land units (cells).

A related approach, with the same limitations, is digital-image processing. This is a sophisticated grid approach, where the cell size is very small. Maps are created directly from photoimagery such as that from satellite or aerial photographs. Again, clustering of cells on the basis of their appearance from the imagery does not necessarily result in the identification of ecological units. This is because cells which have different spectral signatures frequently occur in the same ecological unit.

Implications

Map overlays may be so inaccurate or unable to capture significant units of productivity and ecological response as to be of questionable value for planning. Automating the map overlay process will not solve these problems. The machine processing of poor quality information will not produce better information upon which to base management decisions; but that is an information problem, not a technology problem. Users of GIS must know and understand that if the information is poor to begin with, technology of any kind will do nothing to correct that.

Before making a decision to use GIS technology, it should be recognized that expectations about such technology may be unfounded and unwarranted. It would be an advantage to place less attention on the technology and more on getting better information.

Conclusions and Recommendations

Most overlay maps contain more errors than their compilers or users probably realize. Sensible suggestions for improved accuracy are made by MacDougall (1975). For instance, there is little that can be done with inaccuracy due to low purity of regions, other than prepare a new map with higher purity standards. Horizontal error, however, can be minimized by a study of each factor map to identify indistinct boundaries, and by using care in any enlargement or reduction and some judicious editing in the assembly of the overlay. Most important, the compilers of overlay maps should attempt to estimate their accuracy, and present this in the legend or accompanying text. Users

Table 1 Summary of overlay mapping problems.[a]

Common situations	Problems in map overlay
Map boundaries reflect gradational change	Sliver errors
Multiple scales of maps can be accurate but inconsistent when changed to common scale	Sliver errors; resolution inconsistencies
Attributes of landscape are interrelated	Inconsistent map classes; sliver errors
Integration of landscape attributes control ecological process and productivity	Unable to capture significant units of productivity and ecological response

[a]Adapted from Dangermond and others, 1982, with additional information by author.

should keep in mind that the errors can be large enough to lead to imperfect or false conclusions.

Moreover, it should be recognized that even if errors can be kept to a minimum, there is still the problem of the assumption underlying the approach. Unless, as recommended below, ways are found to insert ecological processes into map overlay systems (including GIS), the assumption that such systems can capture significant ecological response units for planning purposes is questionable.

While this approach has been used to subdivide land into ecological units, little attempt has been made to assess the results objectively by measuring resource variability within the units. Knowledge of this variability is important, since effective resource management requires that resources be distributed in a manner similar to the ecological response units used. Too much variability may lead to significant errors in predicting productivity, with profound implications for plan implementation and national assessments of productivity. It is concluded that any assessment of land suitability that is based on such errors may lead to significant misallocation of public resources.

Two recommendations follow from this conclusion. First, detailed studies should be conducted with actual resource data to determine how well ecological maps produced with the overlay approach represent the distribution of natural resources. In this way, the utility of such maps for planning can be assessed. Second, those considering this approach should also explore other alternatives. Some of those faced with inaccuracies and the staggering complexity of boundary patterns when the map-overlaying approach is used have concluded that some form of selection, or simplification, is necessary. In other words, it is necessary to reduce the number of factors to be used. As an alternative to the overlay approach, another approach is based upon the dominance or greater relevance of one particular environmental factor. By this approach, certain key factors, such as climate and landform, are recognized to exert a strong influence on the ecological processes of the land and hence on resource management. These factors are used to partition the landscape into ecological units for planning analysis at different spatial scales. The logic and criteria for subdividing a landscape based on this approach are reviewed by Bailey (1985, 1987).

The ecological units which are derived by this alternative approach could be used as a layer with other factor maps. This layer, defined in terms of process, would constitute the basic ecological framework for analysis which can then be described by reference to the other layers.

Summary

Overlay maps may be inaccurate due to map class inconsistencies, indistinct boundaries, scale/resolution inconsistencies, and sliver errors. Furthermore, the assumption that such maps are capable of capturing significant units of productivity and ecological response may be incorrect. Table 1 summarizes some of the basic principles which underlie problems encountered from map overlays that use existing factor maps.

Automating the map overlay process through use of a GIS will not solve these problems, and could lead to false perceptions about the quality of the results. To guard against this, efforts should be made to improve accuracy of map information. Where this is not possible, the map user should be made aware of the possibility of errors. With regard to the use of overlay maps to identify productivity/ecological units, testing is recommended to assess the significance of such units. Other approaches to unit identification should also be explored.

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