WORKING PAPER 459

EVALUATION OF REGIONAL LAND RESOURCES USING GEOGRAPHIC INFORMATION SYSTEMS BASED ON LINEAR QUADTREES

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May 1986

ABSTRACT: Evaluation of regional land resources involves the integration and analysis of geographic data which comes from a variety of different sources and in many different forms. This paper describes results of a pilot study using a computerised geographic informations system (GIS) based on linear quadtrees to integrate and analyse geographic data for evaluation of regional land resources near Matlock in the Peak District of Derbyshire, England. Results are presented which show the response to queries involving set logic operations on binary raster images and are discussed in relation to methods of regional land resources evaluation. The paper concludes that GIS based on linear quadtrees provide a flexible, powerful analytical tool for geographical research involving integration of geographic data from various sources, including remote sensing.

RESUME: L' evaluation des ressources regionales d'i terrain comprend l'integration et l'analyse de donnees geographiques provenant de differentes sources et se presentant sous des formes differentes. Cette recherche decrit les resultats d'une etude-pilote utilisant un systeme d'information geographique sur ordinateur, de facon a etablir une evaluation des resources regionales d'un terrain situe pres de Matlock, dans le Peak District du Derbyshire, en Angleterre. La recherche conclut que le Systeme d'Informations Geographiques est bases sur des "quadtrees" lineaires, et fournit un outil d'analyse flexible et efficace pour la recherche geographique concernant l'integration de donnees geographiques provenant de sources diverses, y compris les images satellites.

INTRODUCTION

Evaluation of land resources involves the study of geographic data from many different sources and in many different forms. Geographic data can be efficiently integrated and analysed using computerised geographic information systems (GIS). These are data base management systems which allow users to store, retrieve, manipulate, analyse and display geographic data at their request. The concept of GIS has evolved over the past two decades (Tomlinson 1984). Its origin lies in the computerised data banks which were created to store locational data such as the coordinates of points for specific applications in surveying and mapping. It has now broadened and expanded rapidly to embrace sophisticated computerised systems for modelling and decision-making in land management (Dangermond, 1984; Estes et. al. 1985).

The purpose of this paper is to describe the characteristics of a pilot GIS that we are developing and to demonstrate its use for land resources evaluation in an area near Matlock in the Peak District National Park, Derbyshire. Results are presented and discussed in relation to traditional methods of land resources evaluation and the need to integrate geographic data from different sources, with various levels of resolution and accuracies.

In order to place the current work in context, we begin by outlining recent changes in the approach to land resources evaluation and trends in the development of integrated GIS. Then we describe a quadtree data model for encoding images and present and discuss results.

LAND RESOURCES EVALUATION

Land resources evaluation is concerned with making assessments about man's potential use of land for purposes such as agriculture, forestry, recreation, urban planning or engineering (Christian and Stewart, 1968). It involves analysis of the capabilities and constraints imposed by the physical characteristics of a region and is usually conducted in support of some decision-making process in land management. It is carried out by scientists from many different fields of study but, in many cases, they adopt a similar approach, though of course the level of detail and specific requirements and methods usually differ (Mitchell, 1973). Moreover they draw typically upon a common core of information about the land. The extent of this common core is usually substantial - all require basic information about topography, geology, soils, climate and land use. While there are usually minor differences in specific requirements, the major difference often lies in the level of detail required.

In conducting land resources evaluations, land is usually characterised by a distinctive assemblage of attributes and interlinking processes in space and time (Townshend, 1983). The attributes include topography, soils, water, climate, vegetation, and fauna as well as the results of human activity. Mitchell (1973) stresses that land evaluation is a broad term which encompasses analysis, classification and appraisal of information from a variety of sources for a potential land use. Analysis involves selecting characteristics which have importance for a particular application and compiling land characteristics. Classification relates to the organisation of characteristics which distinguish one area from another and which characterise each. Appraisal uses these characteristics, along with other properties, to assign a value to a piece of land, expressed either by a numerical value or by a judgement of its worth in qualitative terms.

A land resources evaluation system has several basic requirements. Mitchell (1973) identifies three:

1. a means of answering queries from users;

2. a means of acquiring, storing, analysing and displaying information about the land and its potential uses;

3. a means of retrieving and manipulating information;

The traditional approach to fulfilling requirements for land resources evaluation has been by preparing manually various maps and transparent overlays showing features, such as slope, aspect, soils, drainage and other characterisitcs and by preparing statistical and textual reports. Visual comparison and interpretation of maps and reports leads to an evaluation of regional land resources for a particular application. The basic source of information for all these maps has usually been aerial photographs, though other forms of remote sensing are increasingly being used to aid sub-division of the land. Computers are used increasingly to store, process and retrieve at least some of the data and GIS have been developed using a fixed-cell size grid or polygon respresentation, but much geographic data is still stored in analogue maps because these have provided access much more quickly than existing GIS when large volumes of geographic data are involved.

GEOGRAPHIC INFORMATION SYSTEMS

Marble and Peuquet (1983) describe the development of GIS and observe that a GIS is designed to accept large volumes of spatial data, derived from a variety of sources including remote sensing, and to store, retrieve, manipulate, analyse and display these data. The development of intelligent GIS in which the concepts and techniques of artificial intelligence and database systems are integrated represents a major new field of research (Smith and Pazner, 1984a; 1984b; Smith and Peuquet, 1985; McKeown et al. 1984).

In designing a GIS, a critical decision is the choice of data model. This is the abstraction that is used to represent properties which are considerd to be relevant to the application in the computer. Peuquet(1974) reviews the different types of spatial data models that have been used in GIS and compares their performance. Geographic data have been represented using many different types of data models, but a basic difference is between vector and raster types.

1 Vector type

In this type of data model, the basic logical unit in a geographical context corresponds to a line on a map. It is recorded as a series of x-y coordinates with a heading describing the feature. Vector data is widely used in cartographic GIS and many other types which have been developed for specific projects.

2 Raster type

This type of data model uses a fixed-sized square cell or raster to represent geographic data in a binary array or grey-scale image. The development of data models based on raster has been largely driven by advances in the technology of remote sensing and computing over the past decade (Marble and Peuquet 1983). The use of MSS scanning systems in satellite remote sensing has been a major influence. At the same time, there have been significant advances in the technology of raster scan and video digitising systems. These have accelerated digitising maps and related documents. Because all these systems use a square cell or raster, it is generally agreed that this is the only practical tiling or tessellation. A number of other possibilities exist which may be theoretically better than the regular tessellation (Bell et. al., 1983).

Peuquet (1984b) discussed the main advantages of raster type of data models. Apart from the practical benefits of being able to get massive sets of raster data from satellite remote sensing, and raster scanning of maps, it is compatible with array data structures and various hardware devices for input and output. Peuquet (1984b) and McKeown (1984) argue that existing vector and raster data models are limited however by two basic factors:

1. the rigidity and narrowness in the range of applications and types of geographic data which can be accommodated;

2. the unacceptibly low levels of efficiency for storage and response to queries for the current and anticipated volumes of geographic data.

These factors restrict the potential of automated GIS based on the use of vector or raster data models to cope with the variety of different forms of geographic data and the massive volumes. For these reasons, attention has recently focused on another data model known as the quadtree.

QUADTREE DATA MODEL

A data model which has become increasingly important in recent years is the quadtree, which is based on the concept of recursive decomposition of a grid. The idea of the quadtree was formulated by Klinger (1971) but has been developed by many others, including Klinger and Dyer (1976), Hunter and Steiglitz(1979), and Samet (1980,1981,1984). Research into the theory and applications of quadtrees has broadened and expanded during the 1980's. They have become a major focus of interest in computer science for applications in image processing, graphics, robotics and GIS. Samet (1984) provides a comprehensive review of the quadtree and related hierarchical structures. He points out that there are now many different types of quadtree, such as the point, line, and regional quadtrees, that they are all based on the principle of recursive decomposition of an image but that they do not all share the same properties or ease of implementation. The efficiency of quadtrees for representation of regions and for interchangeability with more common representations such as vectors, chain codes, arrays and rasters has been studied intensively by computer scientists.

Quadtree encoding

A quadtree is constructed from a square binary array of pixels which represent an image. We refer to the set of black pixels in the image as the region. If we assume that an image comprises a $2^n \times 2^n$ binary array of pixels, then a quadtree encoding represents this image by recursively sub-dividing it into four quadrants until no further sub-division is necessary. This occurs when we obtain square blocks (possibly single pixels) which are homogeneous in value (i.e. either all black or all white) or when we reach the level of resolution that we require. This process is represented by a tree with four branches or sons in which the root node corresponds to the entire binary array of pixels or image, the four sons of the root node correspond to the four quadrants, which in our case are labelled North West, North East, South West and South East. The terminal or leaf nodes of the quadtree correspond to the homogeneous blocks for which no further sub-division is necessary. The nodes at level n (if any) represent square blocks of size $2^n \times 2^n$. Thus, a node at level 0 corresponds to a single pixel in the image, whereas a node at level n is the root node of the quadtree. An example is given to illustrate these concepts in Fig 1. The region in Fig 1a is represented by the binary array in Fig 1b. The resulting square blocks for Fig 1b are shown in Fig 1c and the tree in Fig 1d.

Initial work on regional quadtrees was carried out using pointers to represent the tree structure. Each node was represented by a record which consisted of five pointers: four to sons, one to an ancestor and a field for the colour of the node. This technique was used by Rosenfeld et.al.(1982,1983,1984). Although quick search times may be achieved using pointer based structures, a large amount of storage is taken up by the pointers. According to Stewart (1986), assuming that each pointer uses 16 bits of memory and the node descriptor 8 bits, then the pointers take up nearly 90% of the memory space used.

Regional representation using linear quadtrees

Gargantini(1982) proposed a data structure to represent quadtrees which was more economical in its requirements for memory space. Known as a linear quadtree, it is in the form of a linear list consisting of the quadtree nodes in some order of traversal of the tree. A number of different forms of keys is available to map a set of ancestors to a numeric key (Gargantini 1982; Abel and Smith 1983). In our case, we follow the form proposed by Gargantini(1982) but number the quadtrants 1, 2, 3 and 4. Thus nodes are arranged so that the quadrants are in order 1,2,3,4 corresponding to the NW, NE, SW, SE quadrants of an image. Only black nodes are recorded. Thus a region in an image corresponds to a node which has a unique key derived from its ordered list of ancestors (Fig 2).

Linear quadtrees offer several advantages over quadtrees based on use of pointers. Gargantini(1982) demonstrates how arithmetic operations on the key of the node can be evaluated to determine various properties such as determining the relative x, y coordinates of a node, adjacency of nodes, ancestor or descendent relationships and translation and rotation of images. Where disk resident quadtrees must be considered, the linear quadtree can readily be indexed to a B-tree memory management system to provide efficient access to nodes for such elemental operations as examinations of the neighbours of a given node (Abel 1984).

IMPLEMENTATION OF GIS USING LINEAR QUADTREES

As a part of a one year pilot study, we are developing a GIS based on linear quadtrees to determine its potential for geographical research in a range of different applications. Programs have been written in the C programming language on a VAX 11/750 computer running Berkeley UNIX 4.2.

Although we are continuing to develop and expand the range of functions that are available to the user, we have functions for input, manipulation, analysis and display of images. Input can be from binary array images, vector polygons or vector segments, the last two being converted to binary arrays. We are also implementing an algorithm for direct vector to quadtree encoding which was devised by Mark and Abel (1985). Analysis functions include traversing an image, finding the colour of a node, finding a neighbour to a node, finding the perimeter of regions, measuring distances, labelling the separate regions or components, determining geometric properties of regions such as size, shape or orientation, forming windows into an image at larger scales, generation of statistics about number of nodes, areas involved and correlations between geographic features and set logic operations on quadtrees (union, intersection, complement) (Mark and Abel, 1985). These functions allow users to perform the two basic operations on GIS identified by Smith and Peuquet(1985):

1. find what is at a specified location;

2. find all occurrences of a specified entity or subset of entities.

Functions for output allow users to file results, plot maps and generate printed output of statistics and related diagnostic information about the number of nodes involved in operations.

The interface to the user is by a query language which allows users to issue a range of commands in abbreviated form. For example, if we wish to find the intersection of grit and land above 500 feet, we enter the query:

grit I N(height300_400 U height400_500)

where grit, height300_400 and height400_500 are the names of quadtree encoded files representing specific geographic features, and the operators I, U and N stand for intersection, union and complement (logical NOT) respectively. The results can be formed into a new quadtree file or sent directly to the printer. Alternatively, there is a menu driven interface which allows the detailed study of one quadtree. This can be used to find the colour of a point, traverse a line across the image or find a neighbour to a point.

Work is now being done to integrate the GIS into a relational data base management system for storing regions and objects. A B-tree memory management system is being developed to store very large quadtrees (Abel, 1984).

LAND EVALUATION IN THE PEAK DISTRICT

To illustrate the potential of the GIS based on linear quadtrees for regional evaluation of land resources, a data base was created by digitising geographic data from maps and aerial photographs. Landsat MSS imagery was classified to provide land cover at a much coarser level and is being included in the GIS.

Description of study area

A study area was selected close to Matlock, Derbyshire. This was chosen because of the variety of geology, relief, soils and land use in a relatively small area. The region lies on a boundary of Carboniferous limestone and Millstone grit. There is a range of relief from valleys below 100 m to summits over 350 m. An interesting change in land use occurs from the relatively fertile alluvial valleys which support intensive use (orchards, arable, settlements., etc), to the upland areas characterised by extensive uses, such as rough grazing and forestry. Soils change from alluvium on the valley floor, through surface water gleys to brown earths on valley sides, with podsols occurring on the highest ground. The region therefore represents a relatively rich source of geographic variation and contains many identifiable sub-regions suitable for illustrating land resources evaluation by GIS.

The area of approximately 25 sq km was chosen for compatibility with existing mapsheets, and so that the resolution after digitising would be sufficient for the type of queries received. The square region selected corresponded to O.S. mapsheet SK 26 SE at 1:10560 scale. This was one of the older O.S. maps produced in 1971 so heights were recorded in feet. The resulting raster grid of 256 x 256 pixels lead to a ground resolution of about 20 x 20 m, whilst the LANDSAT MSS data was resampled to give a ground resolution of 80 x 80 m pixels.

Data Capture

Two different methods were used to build arrays of spatial data for quadtree encoding:

1. Manual Digitising

A GTCO digitiser linked to an IBM PC/XT was used to digitise selected features from the O.S. map at a scale of 1:10560. A series of functions for polygon to raster conversion form part of the GIS. These allow vector data to be mapped on to an array of a specified size. Functions for filling regions then produce binary array images. A set of 10 binary array images of size 256 x 256 were made for images of geology, soils, land use and climatic data.

2. Video digitising.

A video digitising system was used to produce 256 x 256 8 bit images of contours from the O.S. map. The contours were first traced onto transparent overlays and each contour interval was coloured by hand to produce a grey scale image. This was then captured by the video digitiser and frame grabber then transformed to fit a square 256 x 256 array. The result was 10 binary array images of relief.

All the binary array images were then quadtree encoded to produce a database for the area for testing various operations on quadtrees and land evaluation.

RESULTS

Figures 3-8 show selected results from a land resources evaluation for the Matlock area. Parameters considerd were geology, elevation, soils and land use. Although several more parameters are to be included into the database, this example indicates how a GIS approach could be used to identify areas most suitable for agriculture.

Fig (3) shows those areas where there is grit parent material. This large area highlights the way in which the quadtree representation saves space by storing maximal blocks at different levels within the tree. The northern three quarters of Fig (3) is stored as only 6 quadtree nodes for the 6 maximal blocks. The complex boundary of the grit area requires considerably more nodes to be accurately represented. A characteristic feature of quadtree encoded images is the tendency for smaller blocks at the edges of regions, and larger ones towards the centre.

Fig (4) shows land below 800 ft above sea level. This map was produced by the union of all height maps for intervals above 800 ft, to produce the map 'height_above800'; this was then complemented to produce areas not above 800 ft. Following each union operation, maximal blocks are formed, since four small blocks with a common ancestor may be produced. Because the combined image often contains more space-saving larger blocks, the union image of Fig (4) need not necessarily contain more nodes than any single image from which it is derived. Fig (4) contains many larger blocks, showing how the quadtree stores large regions compactly, while being accurate enough to closely approximate the contours which bound the region.

Fig (5) indicates areas of acid brown earth soils, which occur in two regions on the valley sides. Note that four smaller blocks are not always merged into a single large block, if they do not have a common ancestor in the quadtree structure.

Fig (6) indicates woodland areas. This is a fairly complex image since it contains a large number of small polygons. A relatively large number of nodes are required to store this image, many of which are nodes at the lowest level. This results in the quadtree structure being less efficient at storing many small regions, rather than a few extensive areas.

Fig (7) shows only those areas which possess all the above characteristics. It displays only regions with grit geology and brown earth soils which are within the height limit, and which are not covered by woodland. This map was produced by the GIS query:

P brown_earth I grit I height_below800 I N woods

The P operator stands for Plot map. The N operator produces the complement of the woods map, since we are interested in those areas not covered by woods; this is then intersected with the height map, the result of this is intersected with grit geology areas, and finally an intersection is made with the soils map. At each stage those areas which do not share all the attributes are excluded. One of the main advantages of using linear quadtrees is the speed at which set operations such as these are performed; the above query taking only a few seconds.

Fig (8) shows areas between 300 and 400 ft generalised by omitting some details. In this case the smallest size blocks, present in the other images, are omitted. This illustrates the variable resolution of the quadtree structure, since it is equivalent to a descent of the tree which stops one level above the terminal or 'leaf' nodes. The smallest blocks in Fig (8) have a ground size 80m square, and the coarseness of the picture is readily apparent. This is the level of resolution of Landsat imagery, which is being integrated into the database at this level. This shows how the quadtree structure accommodates data of different resolutions.

DISCUSSION

The above example showed how a user can query the GIS to identify areas most suitable for agriculture in the study region. Brown earth soils have the best drainage, water retention and textural characteristics of the soils present in the study region. The podsolic soils are too acid and poorly drained, whilst lower level gleys are very badly drained and have a massive structure making them difficult for agriculture. The valley floor alluvial soils are shallow and have poor water retention characteristics.

The height limit of 800 ft was selected to exclude areas considered to be too high for agriculture, because of exposure of crops and increasing rainfall likely to produce leaching or erosion.

Areas of grit geology were selected because this parent material permits relatively free drainage while allowing reasonable soil development. Shales occurring in the region tend to impede drainage, while limestone areas in the southern part of the image usually promote shallow soils and stony surfaces, which are suitable only for grazing purposes.

The result of this example land evaluation shows (Fig 7) that areas with the above characteristics are found in several locations on both valley sides. They occur mostly not as small residual areas, but as identifiable regions which could be productively used as field units. The total and individual areas of these land units can be calculated by block summation. The fact that after several intersections, the resulting areas still have reasonable size, shows there is quite a common area of overlap between all four images. This is being studied further, together with climatic and remote sensing data, as it suggests a correlation between the parameters.

CONCLUSIONS

The approach to land resources evaluation using GIS based on linear quadtrees has been discussed in relation to a study of the Matlock area, Derbyshire. Results show that linear quadtrees have an important practical and analytical role to play in regional resources evaluation. The practical role relates to (1) the integration of spatial data from a variety of different sources in one database which can be interrogated by users and (2) the production of land information at scales which suit the needs of users. The analytical role relates to spatial analysis of selected parameters and the generation of new information and reports about regional resources from information stored in the GIS. The ease, speed and efficiency with which this can be carried out on large volumes of geographic data is a major advantage of the use of the linear quadtree.

Results from this study have not only helped to clarify concepts and demonstrate the potential of the GIS based on linear quadtrees but have shown that they are a flexible analytical tool for geographic research which deserves further study.

ACKNOWLEDGEMENTS

Maps used in this study were based upon the 1971 Ordnance Survey 1/10560 map with the permission of the HMSO, Crown Copyright Reserved. The University of Leeds provided a research grant for M. Gahegan and a post-graduate studentship for N. Stuart to facilitate this research.

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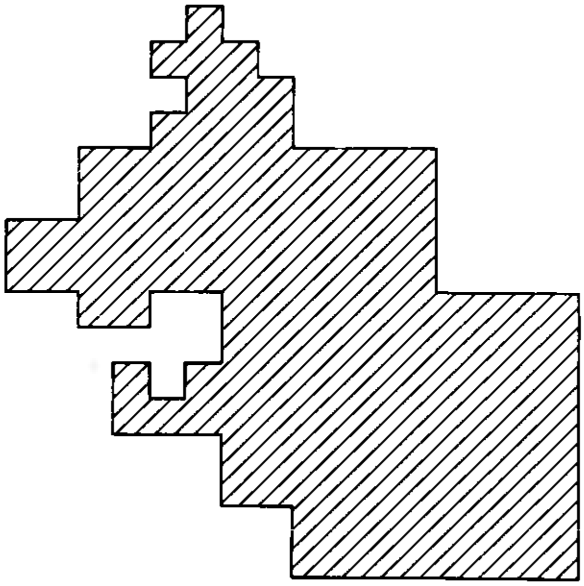
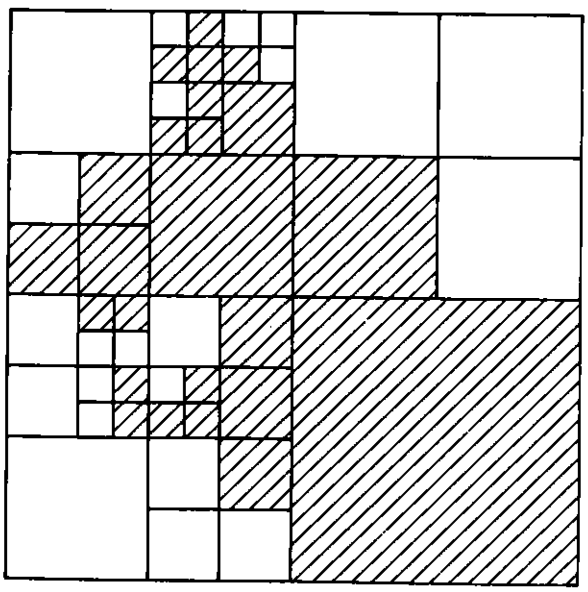
(a) Region.



(b) Binary array.

0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0
0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0
0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0
0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0
0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1
0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1

c) Block decomposition of region in (a).



(d) Quadtree representation of the blocks in (c).

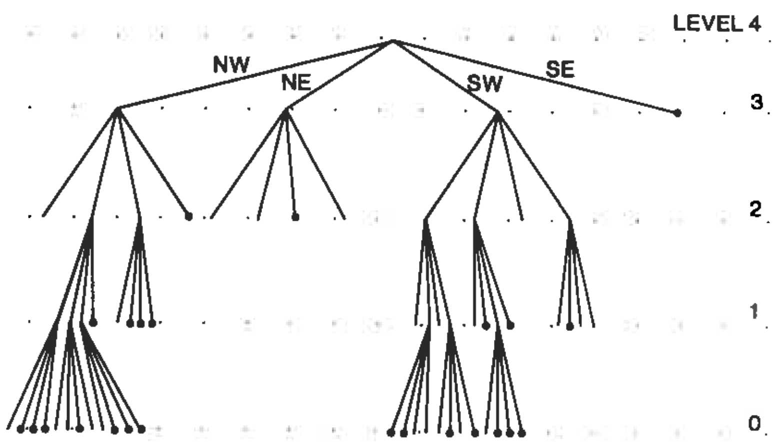


Fig (1) Quadtree region representation.

x-axis

NW (y-axis)	0	1	2	3	4	5	6	7 NE
0	111	112	121	122	211	212	221	222
1	113	114	123	124	213	214	223	224
2	131	132	141	142	231	232	241	242
3	133	134	143	144	233	234	243	244
4	313	314	321	322	411	412	421	422
5	315	316	323	324	413	414	423	424
6	331	332	341	342	431	432	441	442
7	333	334	343	344	433	434	443	444

SW SE

Fig (2) Addressing scheme for locational keys

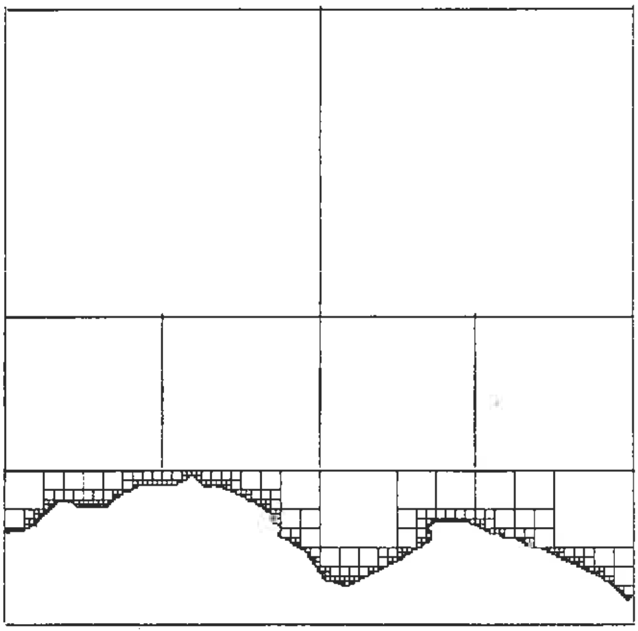


Fig (3) Areas underlain by grit.

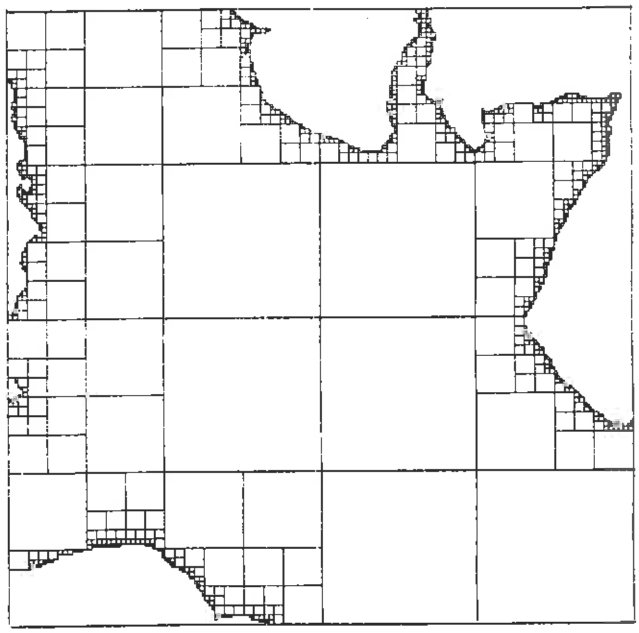


Fig (4) Land below 800 ft.

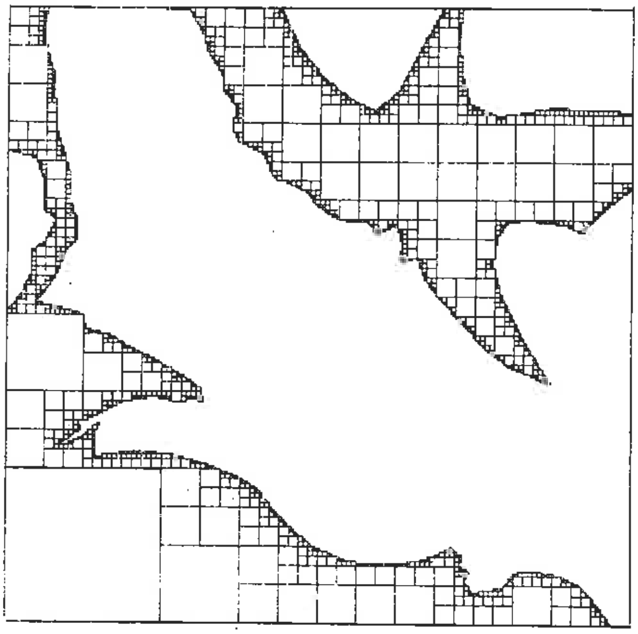


Fig (5) Brown Earth soils.

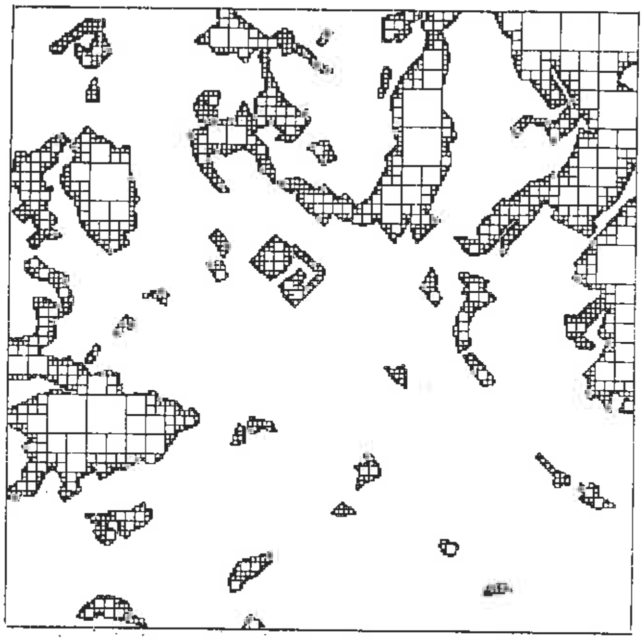


Fig (6) Areas of woodland

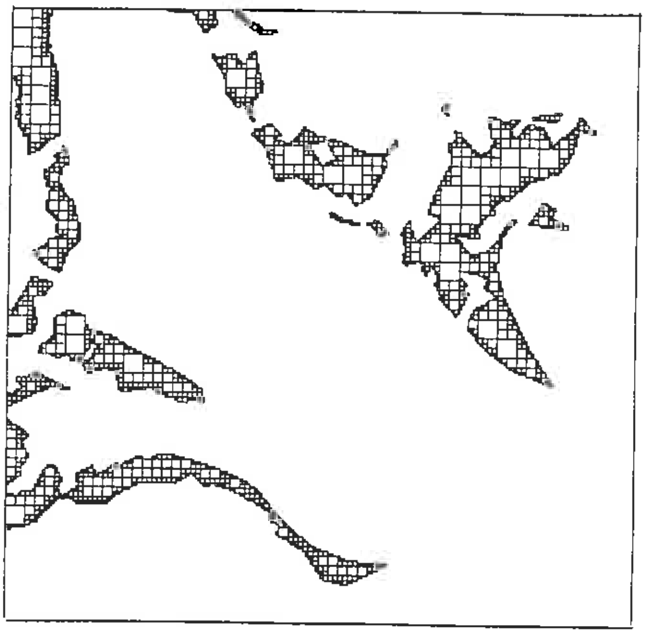


Fig (7) Brown earth soils below 800 ft., over grit, not covered by woodland.

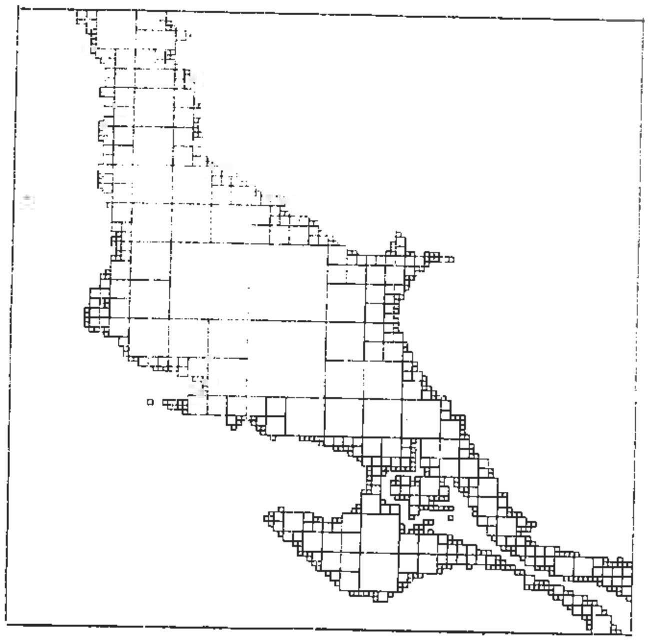


Fig (8) 300-400 ft. elevation, generalised to 128x128 resolution