Thematic Mapper Data for Forest Resource Allocation

Abstract
A technique for classifying a Landsat Thematic Mapper image was demonstrated on the Wayne National Forest of southeastern Ohio. The classified image was integrated into a geographic information system database, and prescriptive forest land use allocation models were developed using the techniques of cartographic modeling. Timber harvest sites and accompanying haul roads were allocated.

Introduction
The United States Forest Service (USFS) is responsible for managing a land area of more than 769,000 square kilometres (United States Department of Agriculture, 1986), routinely making decisions regarding its use and the allocation of resources. In the past, land-use and resource allocation decisions have relied heavily on professional expertise and judgment from within the agency. Over the past several decades, however, traditional methods of decision making have been seriously challenged by an increasingly concerned and involved public. Such challenges have arisen from an increase in demand for available public lands by a wide variety of forest users.

Congress has responded to increased demands on the Forest Service by attempting to institutionalize the process of national forest planning. The Multiple Use Sustained Yield Act of 1960 (MUSY) mandated that the Forest Service manage its land for a variety of uses and with a sustained yield of goods and services for the benefit of all forest users. The Renewable Resources Planning Act of 1974 (RPA) and a subsequent amendment, The National Forest Management Act of 1976 (NFMA), were an attempt to set forth specific guidelines for land-use planning in national forests.

These laws have had a direct and pervasive impact on resource planning throughout the Forest Service. Forest resource goals are initially established in Washington, D.C., to determine, for example, how much timber should be harvested nationwide and how much land should be set aside for recreation. Under the NFMA, all national forests are then required to develop integrated land-use management plans responding to these nationwide goals. Ultimately, the planning process will involve forest managers, government personnel, public interest groups, private industry, and a number of other interested parties.

The first phase of the land-use plan development process addresses the relative importance of activities such as timber harvest and recreation. The next phase of the forest planning process moves from conceptual planning to actual implementation (Shands, 1989). Public input is particularly important in the implementation phase, because agreeing in principle to a clear-cut is much different from seeing it planned through one's favorite hiking spot. As management plans get closer to implementation, the Forest Service is increasingly held accountable for its land allocation decisions and must therefore be able to clearly document its decision-making process.

This study describes a method for land-use allocation in a national forest using an automated land-use allocation technique. Landsat Thematic Mapper (TM) data were classified and integrated with an existing geographic information system (GIS) database to provide current and readily available land-cover information. A classification technique was demonstrated that maximized the use of spectral information provided by the TM sensor while also providing the analyst a method for checking the validity of the final classification. Cartographic models were developed to allocate timber harvest areas and timber haul roads. The models provide forest managers a method for incorporating a variety of physical site factors with their own professional judgment and to estimate costs of these plans.

Background
The Forest Service has been experimenting with image processing and GIS technology to support its planning efforts for several years. Forest managers in the Okanogan National Forest in north central Washington used the technology for the development of a fire management plan (Gum, 1989). Operational and planning decisions were made based on information provided by the GIS database. Several studies have identified land-cover features through the use of remotely sensed data (Hutchinson, 1982; Satterwaite *et al.*, 1984; Fox *et al.*, 1985; Walsh *et al.*, 1990). Other research efforts have also used image processing and GIS technology to study various aspects of forest management. Landsat TM data were used to differentiate among forest species and age groups in the Kisatchie National Forest of central Louisiana (Coleman *et al.*, 1990) and to map forest understory (Stenback and Congalton, 1990).

Computer-based resource simulation models have been used for road network allocation and harvest scheduling. The IRAS (Integrated Resource Analysis System), PASS (Project Area Scheduling System), and SNAP (Scheduling and Network Analysis Program) models are examples of computer-based models that have varying levels of sophistication and are already used by the Forest Service (Leefers, 1989).

Methods
The study area for this project was located in the Athens Purchase Unit of the Wayne National Forest. It is an area of approximately 1.5 square kilometres and is located in eastern

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Hocking County just north of Nelsonville, Ohio (Figure 1). The landscape is one of moderately steep, rugged hillsides typical of those found throughout the unglaciated Appalachian plateau of southeastern Ohio. Narrow, sloping ridgetops are bisected by rivers that form equally narrow valleys, while non-bisected uplands are generally rounded. Vegetation is primarily deciduous, although eastern white pine has been planted throughout the area, and scattered shrubs are apparent. Evidence of oil, gas, and coal mining is also apparent, with abandoned mine shafts, active and inactive oil wells, and bare soil. Acid mine drainage occurs in many of the streams.

A GIS database was developed for Dorr Run, the most prominent feature of the study area, and included nine map layers. Elevation, hydrology, soils, roads, forest type, forest density, buildings, and oil wells were digitized at a 1:24,000 map scale. Landsat TM data from 23 April 1986 were also obtained for the study area to derive a map of the most current land-cover classification. Aerial photographs taken on 2 March 1983 were used for additional ancillary information.

When classifying satellite imagery, supervised or unsupervised classification techniques alone are often not enough to effectively classify an image. Selecting representative training sets is critical for a reliable final supervised classification, and the basic approaches of either supervised or unsupervised classification do not necessarily result in the best classification (Chuvieco and Congalton, 1988). In this study, a classification technique was sought that would not only use the spectral information provided by the TM sensor but also take advantage of a user's familiarity with local land-cover characteristics. This technique would provide a method for checking the validity of the final classification scheme, as it relates to those land-cover features that best represent the distribution of ground features. To get the best results in training sets for the classification, a hybrid technique using both the unsupervised and supervised approach was developed.

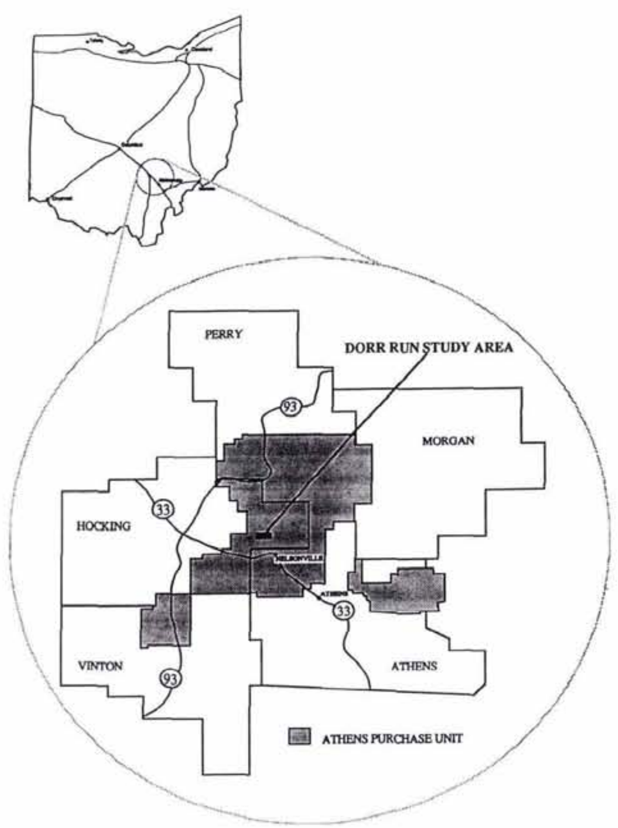


Fig. 1. Location maps of the Dorr Run study area.

This technique was implemented using ERDAS, REVISION 7.3 image processing software. A clustering algorithm was used to derive the training sets such that a maximum number of spectrally and spatially unique clusters were found. The algorithm was executed such that a 3- by 3-pixel window roamed the image, grouping similar pixels based on their spectral similarity, as well as their spatial configuration. Thus, the clustering technique took advantage of all the information in the TM image (Richards, 1986).

In the first iteration of the classification procedure, the maximum-likelihood classifier was used. The classification was compared with the ground truth information and a familiarity with the study area. Based on our analysis, the 24 resulting clusters did not capture the critical features of the study area.To retain the maximum number of clusters that best represented the study area, a minimum-distance classifier was tested and found to provide more meaningful results. The training sets derived from the minimum-distance classifier were then used to classify the TM image, resulting in a data layer of 100 land-cover classes. Two methods were used in tandem to reduce the 100 land-cover classes to best represent the land cover of the area. Initially, the spectral mean for each cluster using two spectral bands was used to generate a spectral plot (Figure 2) (the red band (0.63 to 0.69 μm) and the near-infrared band (0.76 to 0.90 μm)). The red and near-infrared bands produce the most contrast between land-cover features (Jensen, 1986). Ideally, points located in a similar area on the plot should be in the same land-cover class. By using the TM image as a backdrop, the GIS data layer of 100 classes was displayed "above" the image such that both layers could be simultaneously viewed, studied, and compared with the spectral plot. This step took advantage of prior knowledge of the study area and knowledge of the spectral and spatial content of the 100 GIS categories. The 100 classes were reduced to six classes that represented the major land-cover features of the study area. If clusters seemed out of place on the spectral plot, they were viewed and compared with the TM image, and assigned to a new category, if appropriate. Finally, the classified TM image was converted into a format compatible with the other GIS data layers. The TM layer was resampled to 10 metres to match the cell size of the GIS data base.

The classified image is shown in Figure 3. When examining this map, the majority of categories reflect leaf-off deciduous vegetation, stratified by topography. The remaining categories included other vegetation present — primarily white pine — as well as some bare soil that are the result of prior strip mining activity, shown in white.

The next phase of this study called for the allocation of haul roads from selected timber harvest sites in the Dorr Run study area. The techniques employed to incorporate physical site factors, the professional expertise of the forester, and, potentially, public input were those of "cartographic modeling" (Tomlin, 1990), a geographic analysis methodology in which data and data-processing tasks are respectively decomposed into algebra-like variables and functions that can then be recomposed with great flexibility. Each of these functions falls into one of four categories. Local functions compute a new value for each individual cell as a function

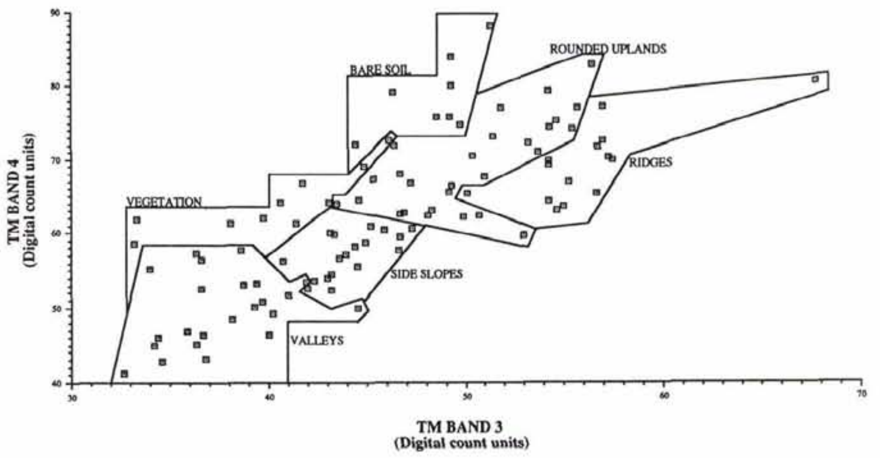


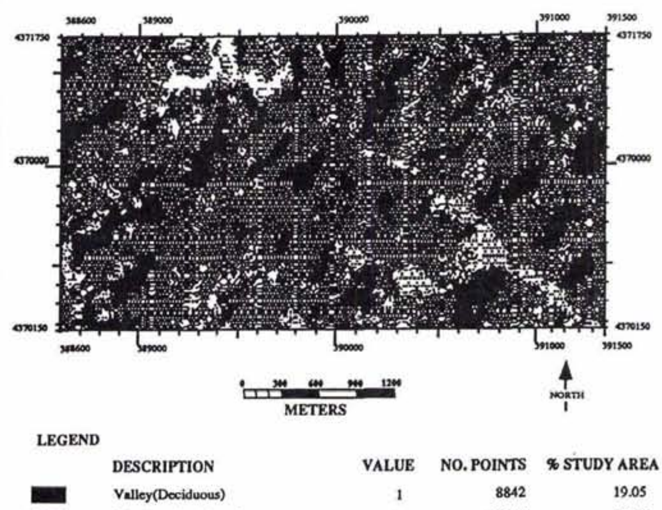
Fig. 2. Digital count values of TM bands 3 and 4. The location of digital count values on this plot helped determine land-cover classes.

of one or more existing values associated with that cell on one or more map layers. Zonal operations compute each cell's new value as a function of the values of all cells that occur in that cell's zone. Focal operations compute a new value for each cell as a function of the value, distance, or direction of neighboring cells. Finally, incremental operations characterize the form of each cell as an increment of one-, two-, or three-dimensional cartographic form in the first, second, or third dimension relative to its adjacent neighbors.

A diagram of the modeling process is shown in Figure 4. First, descriptive "site suitability" models were developed and used to assess the suitability of the study area to sustain each land use. Prescriptive "land-use allocation" models were developed to site land uses where deemed most suitable. The descriptive cartographic models for timber harvest and timber haul roads ultimately resulted in a site suitability map for each land use. Tables 1 and 2 show the criteria used in constructing the site suitability models for timber harvest and timber haul roads, respectively. The information was implemented in the models using the professional judgment of the authors.

The timber harvest and timber haul road site suitability models are diagramed in Figures 5 and 6. The models show the modeling operations used with the required map layers needed to assess suitability. The original data layers are shown on the left with the final map produced on the right. Figure 7 shows the site suitability map for timber harvest and Figure 8 shows the site suitability map for timber haul road construction. Each map is the result of the execution of the respective commands shown in Figures 5 and 6. The commands were implemented in an academic GIS modeling package (OSU *Map-for-the-PC*, 1989). Suitability values were ranked on a relative scale from 1 to 16, with 1 considered the most suitable and a 16 the least suitable. The darker areas in Figures 7 and 8 represent the areas of high suitability, while light areas highlight the least suitable areas.

The suitability maps served as the basis both for the selection of timber to be harvested and for a refinement of the haul road model. By selecting only the most highly suitable cells on the timber harvest suitability map, only the most highly suitable timber would be cut. If more timber needed to be cut, cells having a lower value could be selected. This is the type of decision that would be made by the forest manager. Final site selection for timber harvest was made by examining contiguous cells. Conterminous areas of less than 100 cells were eliminated as they were rejected as being too



LEGEND

	DESCRIPTION	VALUE	NO. POINTS	% STUDY AREA
	Valley(Deciduous)	1	8842	19.05
	Sideslope(Deciduous)	2	13670	29.46
	Rounded upland(Deciduous)	3	18054	38.90
	Ridge(Deciduous)	4	3593	7.74
	Vegetation(Shrub/coniferous)	5	1764	3.80
	Bare soil	6	477	1.05
	TOTAL		46400	100

Fig. 3. Land-cover map of the Dorr Run study area produced from the TM image.

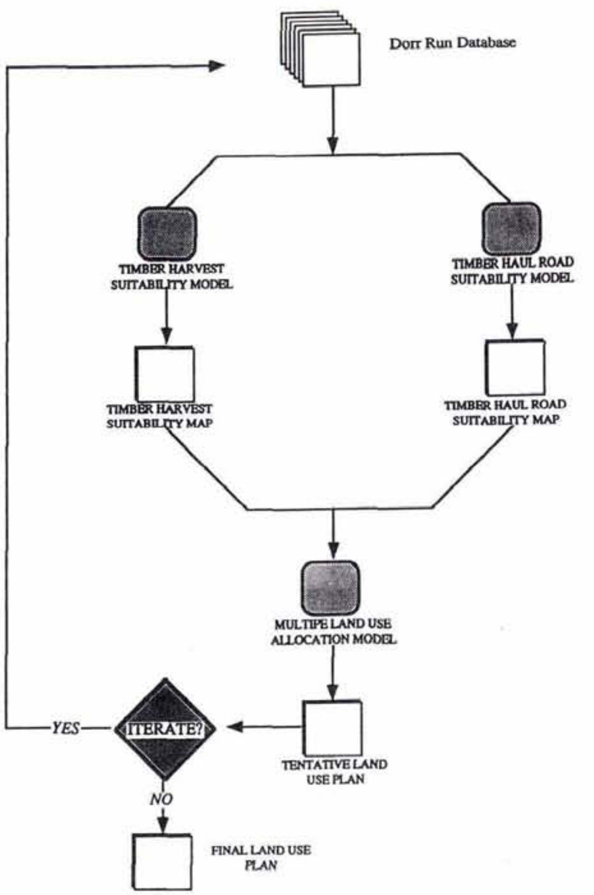


Fig. 4. Diagram of the land allocation model developed in this study.

small for economical harvesting (P. Perry, pers. communication, 1990).

On the haul road suitability map (Figure 8), the 16 categories were collapsed into five suitability levels, primarily due to software limitations. Reassignments were made based on the following characteristics: highly suitable cells were those showing characteristics such as the presence of an existing road, absence of any streams, mild slopes, suitable soil, and the presence of a ridge; less suitable areas were composed of less dense or older tress, unsuitable soils, or steeper slopes; and least suitable areas were cells having severe soil limitations, extremely high slopes, or in a valley or an oil well.

For haul road allocation, it was assumed any haul road originated at a selected timber harvest site and terminated at a major road. The technique chosen was first demonstrated for use in timber harvest scheduling in the Onawa Lake area of central Maine (Tomlin, 1981). To incorporate the distance from each timber harvest site to a major road, zones of proximity from existing roads were generated. This was done using the haul road suitability map as a "friction layer," such that the resulting map layer indicated distance from existing roads, not only in terms of physical proximity, but also in terms of haul road construction costs, as defined by relative suitability values. Using the selected timber harvest sites to represent the origin of haul roads, the roads were then allocated over the haul road suitability layer. The new road cells will automatically trace continuous paths of lowest cost, or lowest value on the map layer.

Plan 1 resulted from the first iteration of this process (Figure 9). Although each individual road cell has taken the cheapest path, or path of least resistance, there is not an optimization in the overall road network. One indication of this is that haul roads are running parallel. It is obviously not cost effective to build several roads running parallel within 40 metres of each other. It was, therefore, necessary to run

TABLE 1. SITE SUITABILITY CRITERIA FOR TIMBER HARVEST.

–North- and east-facing slopes are most productive
–Convex-shaped slopes are most productive
–Pole timber (age 40-50 years) is ideal for harvest
–Red or black oak should be harvested individually
–Thinning is recommended for white pine seedlings

(P. Perry, pers. comm., 1990)

TABLE 2. SITE SUITABILITY CRITERIA FOR HAUL ROADS.

–A lower degree of slope is more suitable
–Ridgetops are most suitable
–Vegetative density should be ranked based on a combination of age and stocking rate
–WrF (Westmoreland-Guernsey silt loam) soils with 40-70% slope have a severe limitation due to steep slopes
–Bethesda channery loam soils with 20-40% slopes and Westmoreland silt loam soils with 15-25% slopes have a moderate limitation due to slope and texture
–Existing roads have no limitations; other types of roads can be upgraded

(U.S. Department of Agriculture, 1989)

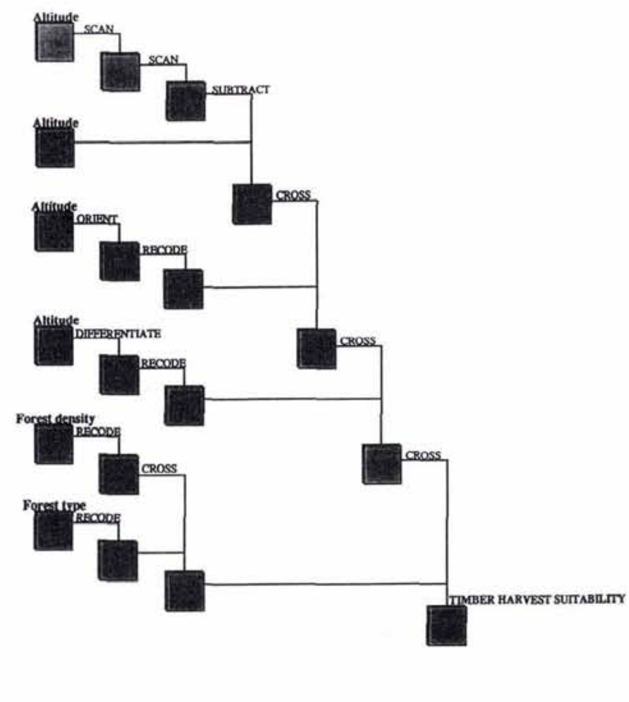


Fig. 5. Schematic of the timber harvest suitabiity model.

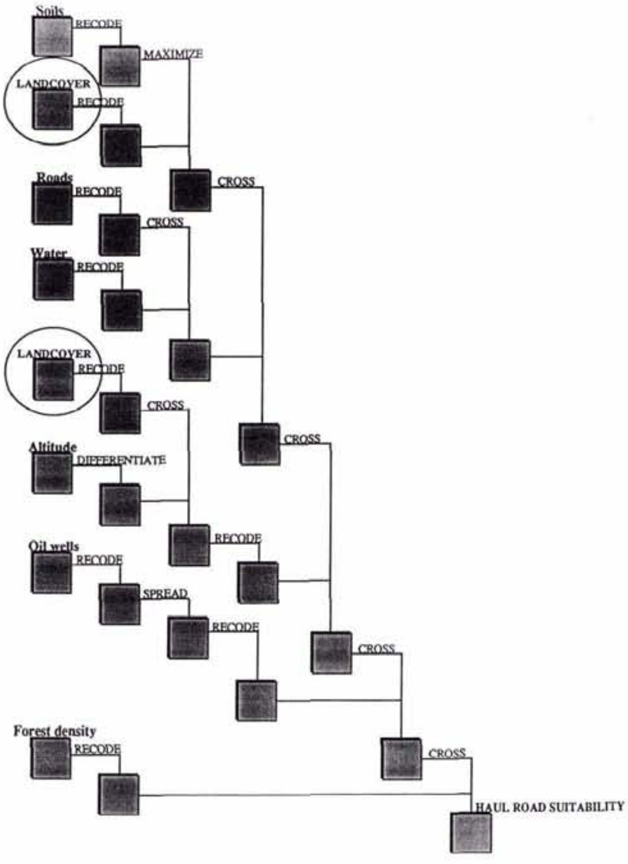


Fig. 6. Schematic of the timber haul road suitability model.

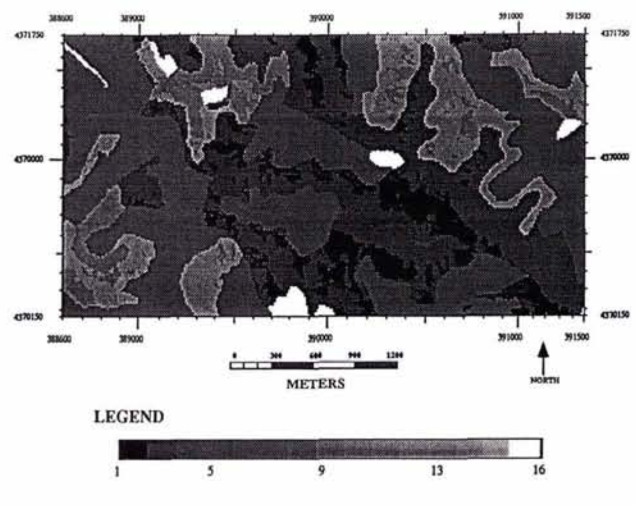


Fig. 7. Timber harvest suitability map. The highly suitable areas are shown in black and the least suitable areas are shown in white.

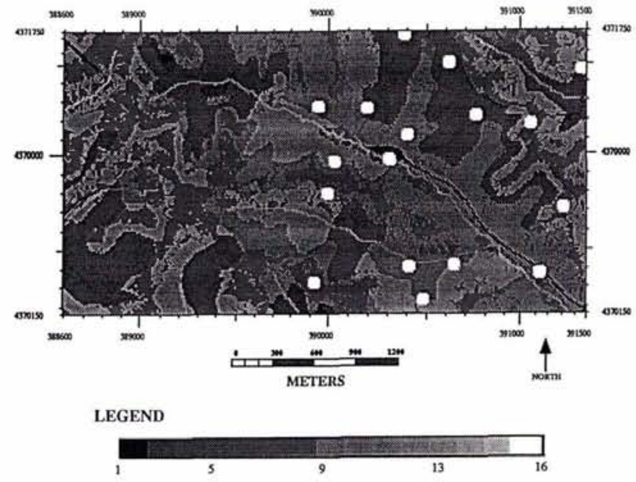


Fig. 8. Haul road suitability map. Existing roads are the most suitable and are shown in black. White areas are the least suitable with shades of gray representing areas in between.

the model again to eliminate such redundancies. To encourage roads to diverge into a single route, any cell that was part of the previously allocated road network was assumed to have a lower value than any other cell on the haul road suitability map. Thus, the presence of a cell in the road network after the first allocation gave it priority on the next allocation.

Four iterations of this process resulted in a final allocation of timber harvest sites and accompanying haul roads. The same technique was used with each iteration in terms of taking into consideration the allocation from the previous iteration as well as the relative suitability of the remainder of the study area. Table 3 provides data reflecting the relative

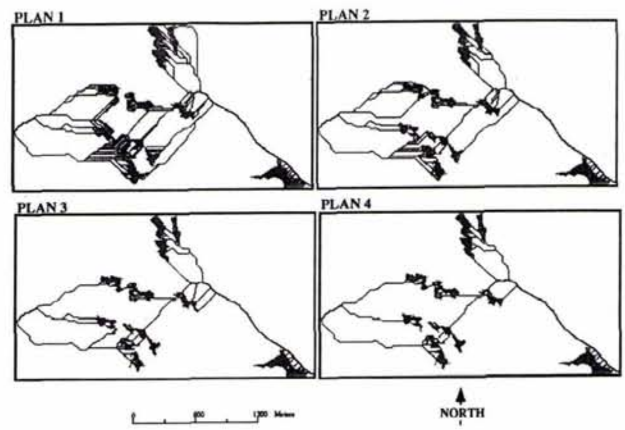


Fig. 9. Haul road allocation maps for four subsequent iterations of the allocation model. The network is optimized from Plan 1 to Plan 4.

TABLE 3. THE RELATIVE COST OF EACH PLAN BASED ON THE SITE SUITABILITY EVALUATIONS. BASED ON A RELATIVE $1 COST PER CELL, THE COST OF THE ROAD NETWORK RANGES FROM $16,524 FOR PLAN 1 TO $5,411 FOR PLAN 4.

	Plan 1		Plan 2		Plan 3		Plan 4	
Relative cost/cell	Number of cells	Cost per cell	Number of cells	Cost per cell	Number of cells	Cost per cell	Number of cells	Cost per cell
1	0	0	0	0	0	0	0	0
2	111	222	75	150	46	92	27	54
3	108	324	68	204	28	84	23	69
4	104	416	77	308	56	224	50	200
5	36	180	23	115	17	85	16	80
6	66	396	38	228	28	168	28	168
7	362	2534	190	1330	106	742	91	637
8	265	2120	136	1088	94	752	83	664
9	206	1854	111	999	80	720	67	603
10	100	1000	72	720	45	450	34	340
11	91	1001	52	572	38	418	33	363
12	178	2136	116	1392	78	936	65	780
13	94	1222	61	793	44	572	32	416
14	204	2856	125	1750	85	1190	63	882
15	9	135	5	75	4	60	5	75
16	8	128	7	112	7	112	5	80
	1942	$16524	1156	$9836	756	$6605	662	$5411

cost of building a road network for each plan. Relative final costs are a function of the number of cells in each network and their cost based on the cell's suitability on the original 1 to 16 scale.

Assuming a relative cost of $1.00 per cell, the total cost for building the road network in Plan 1 from the selected timber harvest sites would cost $16,524. Moving from Plan 1 to Plan 4, cost decreases as the road network is optimized. Compared to $5,411 derived for Plan 4, Plan 4 was deemed the most optimal plan in terms of network efficiency, as well as being sensitive to the environmental factors considered in the haul road suitability model.

Conclusions

The land-cover map derived from the TM image provided information to the haul road and timber harvest models developed in this study. The soils data layer in the GIS provided information about soil type, including soils with both moderate and severe limitations to road construction. The TM image provided land-cover information, identifying areas with or without vegetative cover. The classified TM scene also provided topographic information by producing a stratified map of deciduous vegetation. By combining the locations of ridges and valleys from the TM image with the slope information derived from elevation data in the GIS, ridges and valleys with steep or gentle slopes could be identified as factors in the haul road suitability model. In the timber harvest model, elevation data from the GIS were used to derive convex and concave slopes. Both techniques for determining slope are useful, as an alternative method is often needed when data layers for a particular study area are unavailable.

The utility of having a current land-cover map was demonstrated in this study. However, due to the small size of the study area and the time of year of the imagery, its full potential was not realized. Using a larger footprint of the Earth's surface, additional features could have been delineated in the classification. Furthermore, if the TM scene were taken during leaf-on conditions, additional information on existing timber conditions could have made a valuable contribution to the timber harvest model.

For future applications of this approach, the framework for a modeling process has been developed that is both robust and flexible. Using a more powerful hardware platform, the models could be run and re-run in real-time, allowing for instantaneous feedback and iterative modifications, as well as the processing of a larger geographic area. Using similar modeling techniques, potential impacts of the allocated land uses, such as soil erosion from the roads or views of potential harvest areas from around the study area, could be assessed. Similar techniques could also be used to allocate other forest land uses such as recreation areas and trails. Academic modeling software allowed this technique to be demonstrated adequately; a more sophisticated software package can be developed to provide an interactive user interface for operational use of these models.

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