Assessment of Vegetation Change in a Fire-Altered Forest Landscape

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ABSTRACT: This research focused on determining the degree to which differences in burn severity relate to post-fire vegetative cover within a Michigan pine forest. Landsat MSS data from June 1973 and TM data from October 1982 were classified using an unsupervised approach to create pre-fire and post-fire cover maps of the study area. Using a raster-based geographic information system (GIS), the maps were compared and a map of vegetation change was created. An infrared/ red band ratio from a June 1980 Landsat scene was classified to create a map of three degrees of burn severity, which was then compared with the vegetation change map using a GIS. Classification comparisons of pine and deciduous forest classes (1973 to 1982) revealed that the most change in vegetation occurred in areas subjected to the most intense burn. Two classes of regenerating forest comprised the majority of the change, while the remaining change was associated with shrub vegetation or another forest class. Results from this research indicate that vegetation change detection can be accomplished using postclassification comparison within the context of geographic information system analysis.

INTRODUCTION

AN OPERATIONAL FOREST RESOURCE INFORMATION SYSTEM, as part of its task of updating inventories, must be able to identify short-term and long-term changes in the resource base. Examples of short-term change are those caused by damage from fire, insect attack, or logging, while long-term change is from regrowth or regeneration of vegetation (Ahern and Horler, 1986). Numerous studies have evaluated the utility of multispectral Landsat data for change detection in diverse environments. Algorithms and methods employed for this process have included postclassification comparison, change vectors, image rationing, and principal component transformation (Howarth and Wickware, 1981; Weismiller *et al.*, 1977; Jensen, 1986; Pilon *et al.*, 1988). Satellite sensors allow researchers to "step back" and view the forest in a regional perspective, analyzing it as a whole rather than on a tree-by-tree basis (Ahern and Leckie, 1987). Coupled with the multispectral nature of its sensors, this constantly expanding database has made Landsat valuable for detecting Earth feature changes over time. Heller *et al.* (1983) noted "One of the greatest potentials for operational utilization of Landsat satellite data...involves the capability to monitor changes in the forest resource-base"

The great volume of data produced by Earth resources satellites is of little value if the information cannot be accessed and analyzed in an orderly and timely manner. Geographic information systems (GIS) provide a means by which this information can be organized, integrated with ancillary data, and analyzed for forest monitoring. Geographic information systems permit an analyst to maintain the spatial and temporal individuality of multiple data sets, which facilitates analysis of vegetation change and regrowth after a forest fire.

The intent of the research was to map the extent and nature of vegetation change after a forest fire, and to link the observed changes to differences in the severity of the burn. Previous studies on the subject have not identified the specific relationship of burn severity to vegetation recovery. Thus, the study will address this deficiency by investigating the degree of vegetation change induced by a major forest fire in a northern pines ecosystem. Pre-fire Landsat MSS digital data (1973) and post-fire Landsat Thematic Mapper (TM) data (1982) were classified and then analyzed by means of a geographic information system to determine if the changes in vegetation cover were associated with the 1980 fire. The changes identified were related to the severity of burn experienced, as identified through analysis of Landsat ratio MSS data acquired approximately six weeks after the fire.

STUDY AREA

The study area is located on a Pleistocene glacial outwash plain in the Huron National Forest of northern lower Michigan (Figure 1). Topographically, the area is a flat basin, with elevational relief of less than ten metres per kilometre, and is characterized by poorly developed drainage. Sandy, well-drained soils support a mixture of hardwoods and softwoods across the region.

The Mack Lake Fire began as a small prescribed burn on the morning of 5 May 1980. Approximately 80 hectares of logging slash were to be burned and then replanted with jack pine seedlings to create nesting habitat for the endangered Kirtland's Warbler. Just after noon, in conditions of high heat, low humidity, and increasing winds, the fire escaped from the prescribed burn area and went out of control, eventually destroying over 9000 hectares of pine and deciduous forest. Twelve hours later, the fire was effectively under control. This fire was one of the most intense one-day wildfires in recent history, with flame heights estimated at 10 to 15 metres and a top speed calculated at 10 to 15 kilometres per hour (Simard *et al.*, 1983).

Nearly half of the forest destroyed by the fire was near-uniform stands of jack pine (*Pinus banksiana*), a fire-dependent species requiring high heat to open the resinous cones (Kozlowski and Ahlgren, 1974). Other species common to the area include red pine (*Pinus resinosa*), white pine (*Pinus strobus*), quaking aspen (*Populus tremuloides*), paper birch (*Betula Papyrifera*), and oaks (*Quercus spp.*), as well as understory vegetation common to a northern pine forest (blueberry (*Vaccinium spp.*), sedge (*Carex Spp.*), and bracken (*Pteridium aquilinum*). Tamarack (*Larix laricina*), black spruce (*Picea mariana*), and white cedar (*Thuja occidentalis*) are found in the numerous small bogs that dot the

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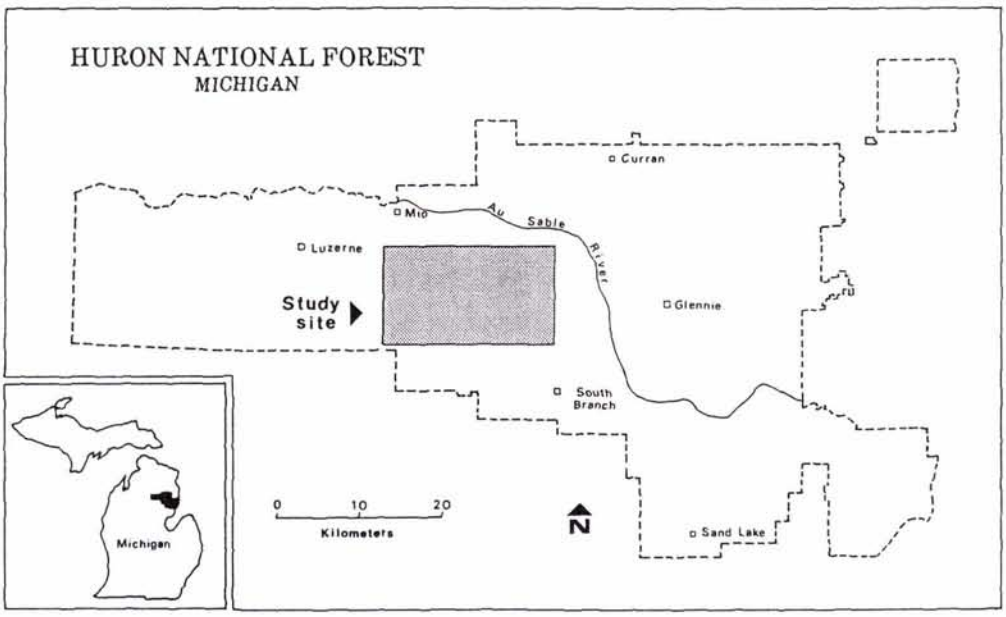


FIG. 1. Location of the study area within the Huron National Forest of Michigan.

eastern and southern perimeters of the study area (Abrams and Dickman, 1982).

DATA DESCRIPTION

A Landsat 1 MSS scene from 9 June 1973 (Scene I.D. 1321–15581) was used for the pre-fire classification, allowing optimum differentiation between classes due to the summer date of the data. A Landsat 2 MSS scene acquired on 17 June 1980 (Scene I.D. 21973–15443) was used for the post-fire burn severity assessment. Anderson *et al.* (1982) effectively used, in part, imagery acquired more than nine months after the Walsh Ditch fire to develop five degrees of burn severity. Imagery acquired several weeks after a fire may be superior to data acquired within a few days of the fire, allowing the vegetation time to die and drop foliage.

The TM scene used for the longterm post-fire recovery mapping was acquired by Landsat 4 on 27 October 1982 (Scene I.D. 4010–15494). Vegetation in the study area would therefore have had three growing seasons between the two dates. Although this date is not optimal, a complete leaf-off condition does not exist within the imaged scene. Discussions with a botanist and local residents indicate that different species of trees within the area are in varied stages of senescence, and a substantial percentage of trees within the study area (especially oaks) retain their leaves well into early winter. Additionally, National High Altitude Project (NHAP) photos flown three days prior to the TM data acquisition indicate that differences in coniferous and deciduous species and type are clearly discernible.

All Landsat digital data sets were registered to a common Universal Transverse Mercator projection by control points and resampled using a nearest-neighbor algorithm to a common pixel size of 30 by 30 metres. Accurate registration of the three data sets to a common coordinate system was essential to the change detection process, ensuring that identical locations in each scene were compared. As part of the registration process, a data subset measuring 20 by 13 kilometres was created, encompassing the fire zone and surrounding vegetation.

Supporting information relevant to the study includes detailed pre-fire land-cover maps prepared by the Michigan Department of Natural Resources listing type, species, and density of the forest, and stand/compartment maps produced by the Forest Service. Conventional photographic support includes 1978 pre-fire airphotos, a photomosaic prepared by the Michigan Department of Transportation from photos flown after the fire, and photos from two dates of the NHAP, flown in 1982 and 1983.

METHODOLOGY

The methodology adopted for this study involved classifying two dates of Landsat data into general land-cover classes using a minimum-distance-to-means classifier. These classifications were then analyzed for change using a matrix operation within the GIS. The resulting vegetation change map was then compared to a map of burn severity developed from a band ratio of a third data set acquired immediately after the fire.

In this study, some "common ground" must be reached between data sets of differing spatial resolution to allow a comparison to be made (Archibald, 1987). For the purposes of this study, it was determined that a comparison of several data sets was valid, provided that (a) comparison was made after classification; (b) comparison was made at a land-cover classification level no finer than could be accurately determined by the lowest resolution sensor (Level II for Landsat MSS); and (c) appropriate generalization of the finer resolution data was carried out.

Comparison of the data sets after classification removes much of the effect of the differing properties of the two sensors (MSS and TM). Using a postclassification comparison allows each date of data to be classified into desired land-cover classes based on the inherent characteristics of the data. Additionally, this removes the need to normalize images to each other, and holds any inherent data defects within the single data set (Ahern and Horler, 1987; Weismiller *et al.*, 1977; Howarth and Wickware, 1981). This may in part compensate for the differing condition of the vegetation during the two seasons imaged.

An unsupervised approach using a minimum-distance-to-means classifier was chosen for the analysis of the 1973 and 1982 data. Analysis of supporting documentation and color composites of the data revealed that a minimum of five and a maximum of ten cover types were discernible. Clusters generated by the classifier were pooled into general cover classes, based on reference data, spectral signature, and association with other clusters. Six classes were developed for the 1973 data,

including pine forest, aspen-birch forest, oak-hardwood forest, shrub vegetation, non-forested herbaceous vegetation, and water. A seventh class representing vegetation class boundaries and shadow effects was included as mixed vegetation (Plate 1a).

Based on previous investigations using TM data for vegetation classification (Sadowski *et al.*, 1983; Hopkins *et al.*, 1988; Horler and Ahern, 1986), the optimum TM bands for the unsupervised classification were determined to be 3, 4, 5, and 7, encompassing the visible red, the near-infrared, and the mid-infrared portions of the spectrum. Analysis was similar to that of the 1973 data, pooling the classes generated by the unsupervised classifier into eight cover classes: pine forest, aspen-birch forest, oak-hardwood forest, non-forested herbaceous vegetation, shrub vegetation, water, and bare soil. Although bare soil was not discernible in the 1973 data, it was added in the 1982 analysis, appearing as a result of limited logging activity carried out within the fire zone.

In addition, two classes (1982 classification) appearing almost exclusively within the fire zone were added, designated fire zone 1 and fire zone 2. Analysis of the spectral signatures of these two classes and comparisons of classification maps to information from field investigations indicated these classes represented transitional stages in the regrowth of the pine forest. The two classes are differentiated by the amount of regrowth occurring in a burned area. Fire zone 1 includes areas of small pine seedlings interspersed with open areas of short grasses and forbs, while fire zone 2 represents a more advanced stage of regrowth, with relatively larger stands of pine and fewer open areas. Spectrally, fire zone 1 is brighter in all bands than either fire zone 2 or pine forest, most likely because of the lush, young vegetation and the greater proportion of open space within these areas. These two classes could not justifiably be grouped with any of the previously identified cover classes without a loss of information through overgeneralization (Plate 1b). A 3 by 3 majority class filter was applied to the classified TM data set prior to accuracy assessment and subsetting. This algorithm, similar to that used by Todd *et al.* (1980), Walker et al. (1986), and Hopkins *et al.* (1988), served to generalize the data to the level of the MSS and reduce spurious isolated pixels created by shadowing.

Three degrees of burn severity were defined, based on Forest Service reports, photographic documentation, and definitions of burn severity from previous papers on forest fire damage (Tanaka *et al.*, 1983; Lachowski and Anderson, 1979). A severe burn was defined as an area where fire has destroyed both crown and understory foilage, killing the trees and reducing the ground vegetation back to the level of the forest floor (Simard *et al.*, 1983). A moderate burn was defined as where either the crown or the understory vegetation is destroyed by the fire, and the area is only partially burned. A light burn occurred where the fire dropped from a crown fire to a ground fire, with mature trees essentially untouched and understory vegetation only slightly damaged. Unburned vegetation within the fire zone was also grouped into this class (Plate 1c).

An MSS 7/5 ratio was used to delineate the burn area and extract degrees of burn severity for the 1980 data through exploiting the near-reversal of the standard vegetation reflectance spectral curve caused by the destruction of forest vegetation by the fire. Normally, green vegetation has a low reflectance in the red portion of the spectrum and high reflectance in the infrared, but the effect of the fire reduces the infrared in direct relation to the intensity of the fire (Figure 2). Several researchers have observed this effect and utilized it to outline burn boundaries and develop degrees of burn severity (Issacson *et al.*, 1981; Milne, 1986; Minick and Shain, 1981; Tanaka *et al.*, 1983).

Accuracy assessment was made utilizing a cluster sampling technique (Roller and Visser, 1980; Todd *et al.*, 1980), which

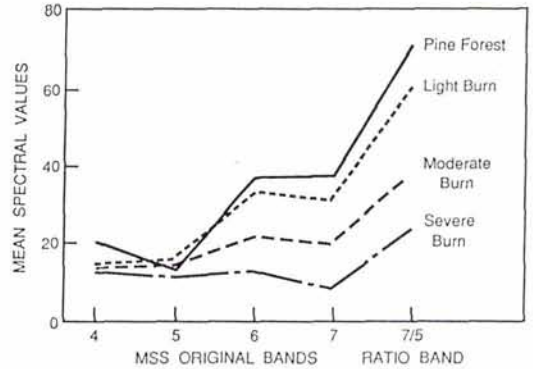


FIG. 2. Change in pine forest mean spectral values with increasing burn severity.

compared the classified data against known class locations derived from airphotos and other reference material described previously. The fire zone area was extracted as a subset from each classification, using a binary mask digitized from Forest Service fire reports (Simard *et al.*, 1983). All classes outside of the fire zone were recoded to zero, restricting further analysis to the area affected by the fire.

POSTCLASSIFICATION COMPARISON ANALYSIS

A two-dimensional matrix was created using the classified 1973 and 1982 data within a GIS by performing pixel-by-pixel comparison of Level II land-cover types (as defined in the Michigan Land Use/Land Cover Classification System (MLCUCS), 1976) between the two data sets. Change detection was facilitated by use of the GIS matrix, as it allows each class within a data set to be individually considered for nature and degree of change. Additionally, it permits certain errors of classification of either date to be considered as a separate class, and similar types of change may be pooled by recoding as specified by an analyst. While postclassification comparison has been a tool in image processing for many years (Weismiller *et al.*, 1977), performing it within a GIS maintains finer control over the data and allows greater flexibility in combining related classes.

For example, it was desired for the purposes of this research to group together all unchanged vegetation into a single class. The fact that the vegetation was unchanged is more important than the specific vegetation type, whether it may have been pine forest, deciduous forest, or shrub vegetation. Through a simple recording operation, ten matrix classes representing several types of unchanged vegetation were reduced to a single class of no change.

Sixty-three pairwise combinations were developed from the seven 1973 classes and nine 1982 classes (Figure 3A) and recoded into 16 specific change classes (Figure 3B). Recoding served both to reduce the original number of classes created by the matrix operation and to establish the comparison at Level II of the MLCUCS (1976). For example, change from pine forest to deciduous forest involved recoding two classes (2 and 3) into a single class, grouping change to aspen-birch forest and to oak-hardwood forest as one class. Similar recodes were performed for change from deciduous forest and from shrub vegetation. Categories of change created by the matrix are described below in relative order of importance to this study.

The most important form of change was a change to a class different from the original; for example, pine forest changing to deciduous forest, or shrub/herbaceous vegetation changing to a forest class. These changes represent dramatic differences in vegetation type, because a shift has occurred at the first or second levels of the Michigan Land Use/Cover Classification

(A)

1973 CLASSES \ 1982 CLASSES	PF	AB	OH	NFH	SV	W	BS	FZ1	FZ2
PF	1	2	3	4	5	6	7	8	9
AB	10	11	12	13	14	15	16	17	18
OH	19	20	21	22	23	24	25	26	27
SV	28	29	30	31	32	33	34	35	36
NFH	37	38	39	40	41	42	43	44	45
MX	46	47	48	49	50	51	52	53	54
W	55	56	57	58	59	60	61	62	63

(B)

1973 CLASSES \ 1982 CLASSES	PF	AB	OH	NFH	SV	W	BS	FZ1	FZ2
PF	10	1	1	2	2	9	7	11	12
AB	3	10	10	4	4	9	7	13	14
OH	3	10	10	4	4	9	7	13	14
SV	6	5	5	10	10	9	7	15	16
NFH	6	5	5	10	10	9	7	15	16
MX	8	8	8	8	8	8	8	8	8
W	9	9	9	9	9	10	9	9	9

KEY: PF - Pine Forest; AB - Aspen/Birch Forest; OH - Oak Hardwood Forest; NFH - Non-forested Herbaceous; SV - Shrub Vegetation; W - Water; BS - Bare Soil; FZ1 - Fire Zone 1; FZ2 - Fire Zone 2

FIG. 3. (A) Sixty-three classes created from pairwise combinations of the seven 1973 (pre-fire) classes and nine 1982 (post-fire) classes. (B) Sixteen change classes created by merging of related classes into specified change classes. For example, change from pine forest to deciduous forest was treated as a single change class by merging original classes 2 and 3 into change class 1.

System (1976). Second in importance is a grouping of all classes where no change has taken place, or none that can be sufficiently resolved by the satellite sensor. This class is an important one, because little to no change is expected in the lightly burned areas. No differentiation was made between specific classes within this category, combining all unchanged classes into one class of zero apparent change.

Six change classes were created to accommodate the change of the three Level II vegetation types (pine forest, deciduous forest, and shrub vegetation) to the two fire zone classes. The fire zone classes were not pooled for matrix analysis, as they represent two stages in the regrowth of the forest, and this difference was deemed important enough to be preserved in the analysis.

The last category includes those classes which represent a change to or from a non-vegetation class, or from non-specific vegetation. Within this category are grouped three specific change classes: to or from water, from a cover type to bare soil, and from mixed (i.e., non-specific) vegetation to any other class. Theses classes were excluded from the final analysis after the second matrix operation was performed, as the focus of the research was on changes between specific vegetation classes only.

VEGETATION CHANGE AND BURN SEVERITY

A second matrix operation was performed using the classified 1980 data and the file of vegetation change in order to link observed vegetation change to differences in burn severity across the study area. Sixty-four classes (four 1980 classes times 16 change classes) were created by this operation, relating changes to the three degrees of burn severity. Initially, no recoding was performed on the resultant GIS file, and much of the change analysis was conducted using tabular output. Change class statistics for each degree of burn severity were generated, giving the total amount of change experienced by a cover type for each class of burn (Table 1). In Table 1, the total number of hectares for each change class is listed for each burn class, allowing differences in change classes to be linked to differences in burn severity.

RESULTS AND DISCUSSION

Although all 16 change classes were input to the matrix comparing change classes to burn severity, only the resultant classes relating to vegetation change were analyzed in depth. Vegetation change classes relating to burn severity, excluding the no-change class, were subdivided on the basis of original vegetation type (pine forest, deciduous forest, shrub vegetation). These were further subdivided on the basis of burn severity, producing as examples, final classes of severely burned pine-to-deciduous forest, or lightly burned deciduous forest-to-shrub vegetation (Table 1). It is important to note that the vegetation change classes and the no-change class contain over 94 percent of the total area within the fire zone study area, with non-vegetation change and other classes making up the remaining six percent. Overall, the two forest classes showed increasing change with increasing severity of burn, while the shrub vegetation showed the opposite effect, with the greatest change in the lightly burned areas (Figure 4). It is important to note that changes observed within the fire zone are a result of both the impact of the fire and successional changes occurring within the vegetation.

CHANGES WITHIN THE PINE FOREST CLASS

The amount of change experienced by pine forest declined with decreasing burn severity. Eighty-three percent of all severely burned pine forest changed to another type of cover, while 71 percent of the moderately burned pine forest and 40 percent of the lightly burned pine forest changed. The majority of change undergone by pine forest in all categories of burn severity was to one of the two fire zone classes. Sixty-seven percent of all change within severely burned pine forest was to a fire zone class, and this dropped to 43 percent in the moderately burned and 21 percent in the lightly burned (Plate 2a).

CHANGE WITHIN THE DECIDUOUS FOREST CLASS

Deciduous forest underwent a greater percentage of change than pine forest in all categories. The dominant class of change by deciduous forest in all degrees of burn was to pine forest, accounting for over 31 percent in the severe burn and 29 percent in the moderate and light burn categories (Plate 2b). Other changes for deciduous forest were to the two fire zone classes, with these two accounting for a summed total of 50 percent of all change in the severe burn, 45 percent in the moderate burn, and 17 percent in the light burn. This sharp dropoff in total percentage for the light burn may be explained by one or a combination of several factors. First, the partial leaf-off nature of the TM data set may be allowing some low coniferous growth to be imaged by the satellite, thereby increasing the apparent change in the moderately burned class; second, a moderate burn may be as effective as a severe burn for effecting a change in the deciduous forest; and third, this may be an expression of the burn divisions, where moderate burn is overlapping the severe and light burn classes.

CHANGES WITHIN THE SHRUB VEGETATION CLASS

Shrub vegetation had the least amount of change of the three vegetation change groups (pine forest, deciduous forest, and shrub vegetation), in all categories of burn severity. Thirty-six percent of all severely burned shrub vegetation changed to another vegetation class, 38 percent in the moderately burned

TABLE 1. VEGETATION CHANGE CLASS TOTALS WITHIN EACH BURN CLASS

Change Class	Vegetation Change From (1973)	To (1982)	Burn Classes (from 1980 Data)* Severe	Moderate	Light
(1)	Pine Forest	Deciduous Forest	270.7	379.5	84.6
(2)	Pine Forest	Shrub Vegetation	195.9	286.3	66.9
(3)	Deciduous Forest	Pine Forest	31.1	160.2	623.5
(4)	Deciduous Forest	Shrub Vegetation	4.8	49.4	201.5
(5)	Shrub Vegetation	Deciduous Forest	41.1	97.4	37.6
(6)	Shrub Vegetation	Pine Forest	1.6	6.5	6.6
(11)+	Pine Forest	Fire Zone 1	1117.9	653.4	98.5
(12)	Pine Forest	Fire Zone 2	854.8	398.8	63.0
(13)	Deciduous Forest	Fire Zone 1	29.6	154.7	258.1
(14)	Deciduous Forest	Fire Zone 2	21.3	93.5	102.9
(15)	Shrub Vegetation	Fire Zone 1	14.1	20.0	6.8
(16)	Shrub Vegetation	Fire Zone 2	1.3	1.9	0.9

* All units for burn severity classes in hectares.
+ Classes 7-9 are non-vegetation change classes. Class 10 includes all unchanged classes

category, and 64 percent changed in the lightly burned category. The change from shrub to deciduous forest contained the majority of percent change in each burn category. This change class accounted for 25 percent of all severely burned shrub vegetation, nearly 30 percent of the moderately burned, and over 46 percent of the lightly burned. In effect, the lighter the burn, the greater the apparent change.

The likely cause for the reversal of the expected direction of fire-related change is the intervening ten growing seasons between the 1973 acquisition of the MSS data and the 1982 acquisition of the TM data. As defined by the Michigan Land Cover/Land Use Classification System (MLCUCS), shrub vegetation is "...areas supporting early stages of plant succession ... such areas are soon dominated by young tree growth." (MLCUCS, 1976).

In effect, the areas classified as shrub vegetation in 1973 changed (in part) to forest in 1980. This change to seedlings and saplings was sufficiently vigorous to be classified as forest in the 1982 classification. Where the fire was severe, these smaller trees were killed being more vulnerable to fire than a mature tree, and the area so exposed was only beginning to regenerate, effectively setting back the natural succession of shrub vegetation to deciduous forest. Where the burn was less severe, the small trees were less affected, and were classified as forest in the 1982 data. This effect is dominated by deciduous forest as the end class of succession, as the percentage of shrub changed to pine forest is negligible. Changes to fire zone classes are similarly low (Plate 2c).

CLASSES WITH NO APPARENT CHANGE

This category was created to group all classes unchanged by the fire into one class of zero apparent change. The percentage of unchanged classes increased in every class of burn severity, from 17 percent unchanged in the severely burned areas, to 27 percent in the moderately burned areas, to 42 percent of all classes unchanged in the lightly burned areas (Figure 5). This class of no change also includes changes within a Level II vegatation type (e.g., from aspen-birch forest to oak-hickory forest and conversely), whether they be actual changes observable on the ground or simply differing classifications in the two dates of data. Water is not included in these percentages, as any change experienced by water bodies does not directly relate to burn severity.

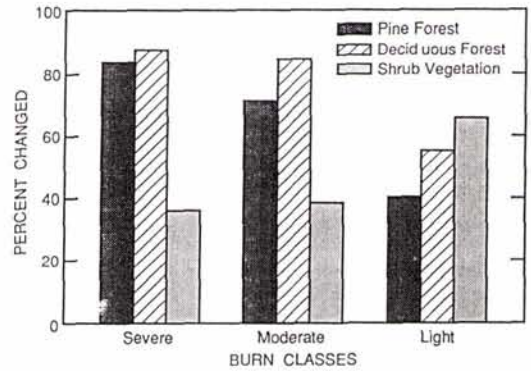


FIG. 4. Total percent change for each vegetation class in each category of burn severity.

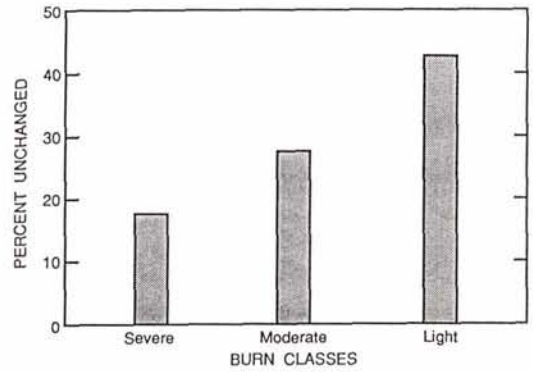


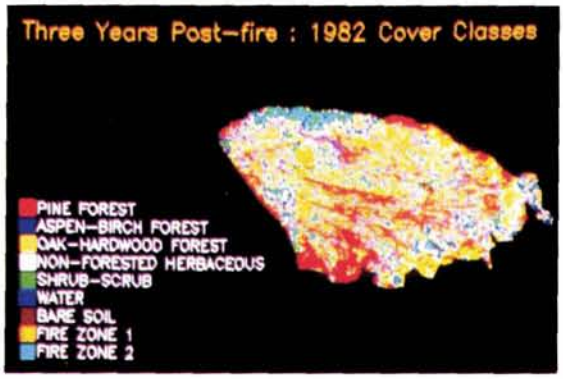
FIG. 5. Percent unchanged vegetation by burn severity. This includes both vegetation and non-vegetation classes.

CONCLUSIONS

Patterns of post-fire vegetation recovery and change were evident in the classified Landsat data, and the associated results agree with vegetation regrowth trends observed in ground based studies of fire damaged areas. The proportion of vegetation unchanged by the fire was lowest in the severely burned areas, and highest in the lightly burned areas. Both pine forest and deciduous forest showed decreases in the total percentage of each class which changed with decreasing severity of burn. Conversely, a severe burn within the shrub vegetation caused greater apparent change than a less severe burn, temporarily setting back the natural overgrowth and succession of shrub areas by coniferous and deciduous forest vegetation.

Using a geographic information system (GIS) to analyze the digital data by means of matrix operations identified not only

(a)



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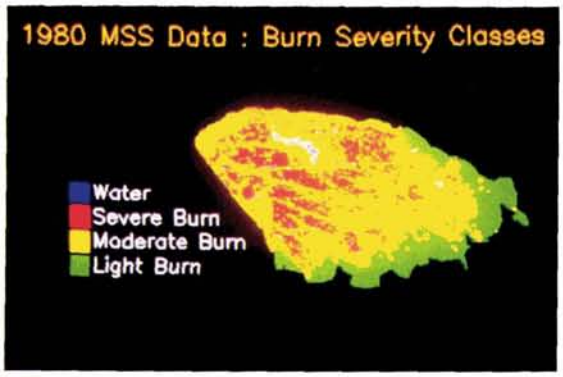
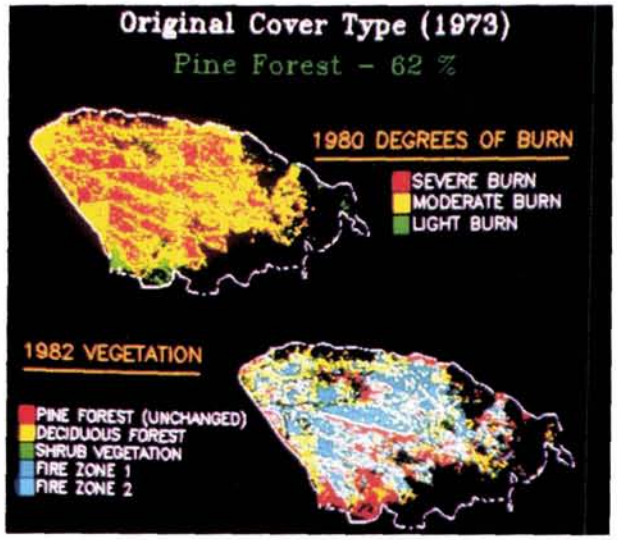


(c)

PLATE 1. (a) 1973 Landsat MSS classification. The predominance of the pine forest within the western and central portions can be clearly seen. (b) 1982 Landsat TM classification. Breakup to the burn is evident three growing seasons after the fire, with substantial recovery of the pine forest along the southern perimeter. (c) 1980 Landsat MSS classification. Diagonal lineations within the burn are moderately burned strips caused by fire winds during the peak of the blaze.



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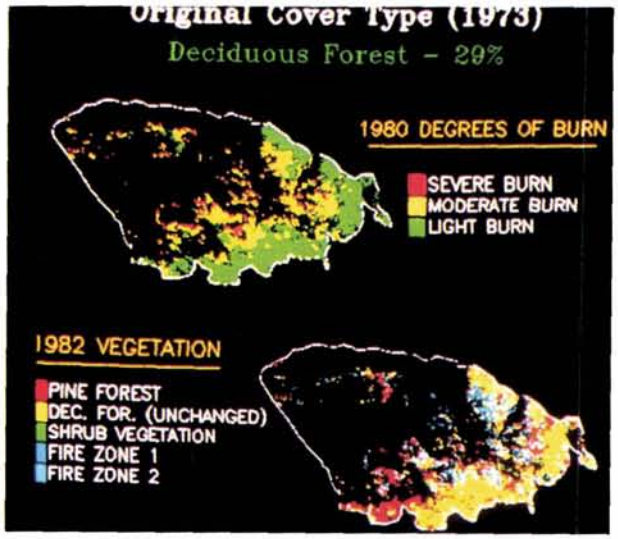

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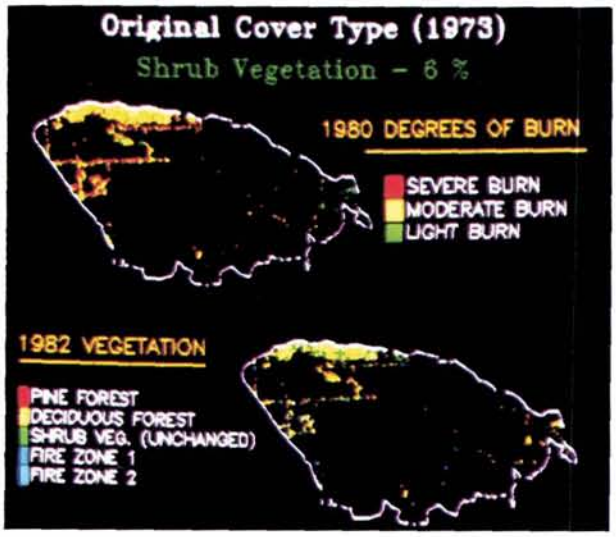

(c)

PLATE 2. Change from original (1973) vegetation to other vegetation as a result of the 1980 forest fire. (a) Change in pine forest vegetation. (b) Change in deciduous forest vegetation. (c) Change in shrub vegetation.

the type and amount of change, but also those classes which did not change. Additionally, the GIS restricted change analysis to the fire-affected area only by masking out unaffected vegetation through overlay operations. Potentially, the flexibility afforded by the GIS allows additional data sets from preceding or succeeding dates to be added, creating a database for the study of longterm change within the study site.

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Erratum

In the paper "The Mean and Variance of Area Estimates Computed in an Arc-Node Geographic Information System" by Prisley *et al.* (*PE&RS*, November, 1989, pp. 1601-1612), an erroneous statement was made regarding correlation of coordinate errors. When the assumptions were summarized in terms of expected values (p. 1602), it was noted that

$$E(\epsilon_i\epsilon_k) = 0 \text{ for } |k\text{-}i| > 1 \text{ and } E(\eta_i\eta_k) = 0 \text{ for } |k\text{-}i| > 1.$$

In fact, if errors at all points between i and k are pairwise correlated, then the errors at points i and k have a correlation of order ρ^{k-i}, and, consequently, $E(\epsilon_i\epsilon_k) \neq 0$ and $E(\eta_i\eta_k) \neq 0$. Thus, the derivations as written have omitted minor terms containing ρ^2, ρ^3, ρ^4, etc. The result of this omission is that the expressions for polygon area variance and covariance must be considered first-order approximations.

It is hypothesized that an exact solution of the variance expression, including low-order correlations of errors at non-adjacent points, would eliminate the dependence of the variance formula on the centroid location. For the purposes of variance approximation, and in light of the difficulty of obtaining reliable correlation estimates, the expressions given in the paper should prove adequate unless the correlation of X and Y errors is exceptionally high.