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FOCIS was developed in Northern California's Klamath National Forest, where the high relief and diverse ecological conditions provided an excellent area for testing new timber inventory techniques. Comparison of samples from timber strata identified by FOCIS with strata identified by conventional procedures showed that both have about the same potential to reduce the variance of timber volume estimates over simple random sampling. A timber volume inventory of the western portion of the Forest (about 940,000 acres) using FOCIS technology yielded a softwood timber volume estimate with a coefficient of variation of 6.3 percent; the corresponding coefficient for conventional procedures was unavailable at the time of preparation of this report.

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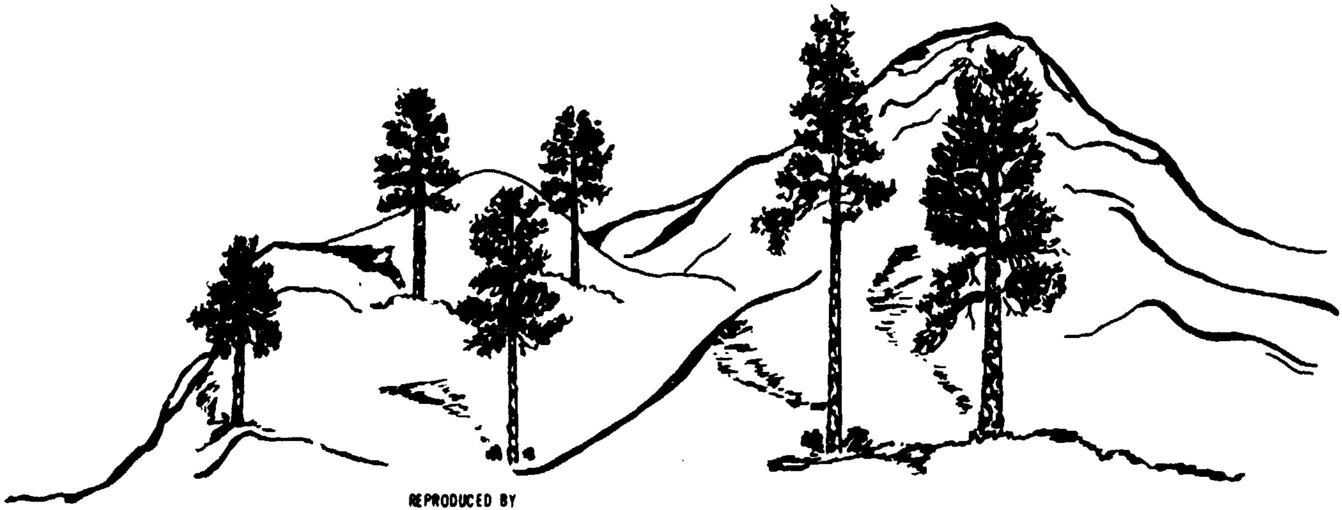

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FOCIS: A FOREST CLASSIFICATION AND INVENTORY SYSTEM USING LANDSAT AND DIGITAL TERRAIN DATA

Final Report of NASA Contract NAS 9-15509

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ABSTRACT

Accurate, cost-effective, automatic stratification of forest vegetation and timber inventory is the primary goal of a Forest Classification and Inventory System (FOCIS) developed at the University of California at Santa Barbara and the Jet Propulsion Laboratory of the California Institute of Technology at Pasadena. Conventional timber stratification using photointerpretation can be time consuming, costly, and inconsistent from analyst to analyst. FOCIS was designed to overcome these problems by using machine processing techniques to extract and process tonal, textural, and terrain information from registered Landsat multispectral and digital terrain data. The FOCIS stratification process:

1. segments a forest into natural regions with similar ecological properties;

2. derives a standard deviation texture channel synthetically from Landsat MSS Band 5;

3. performs an unsupervised clustering of Landsat multispectral and texture data followed by parallelepiped-maximum likelihood classification;

4. pools and spectrally edits classes under analyst supervision;

5. spatially edits classes with analyst supervision;

6. derives slope and aspect information from digital terrain data and registers it to Landsat data;

7. models regional forest types spatially using digital terrain and field reconnaissance data;

8. compensates for the effects of differential illumination (shadowing);

9. uses cluster plot sample data obtained in the field for timber volume calculation; and

10. generates Universal Transverse Mercator, 15-minute quadrangle, stratification maps; accompanying synthetic stereograms; and classification statistics.

FOCIS was developed in Northern California's Klamath National Forest, where the high relief and diverse ecological conditions provided an excellent area for testing new timber inventory techniques. Comparison of samples from

timber strata identified by FOCIS with strata identified by conventional procedures showed that both have about the same potential to reduce the variance of timber volume estimates over simple random sampling. A timber volume inventory of the western portion of the Forest (about 940,000 acres) using FOCIS technology yielded a softwood timber volume estimate with a coefficient of variation of 6.3 percent; the corresponding coefficient for conventional procedures was unavailable at the time of preparation of this report. This research was supported by NASA contract NAS-9-15509, USFS-UCSB joint agreement 37, USFS contract 53-91S8-0-6362, and the California Institute of Technology's President Fund Award, PF-123, under NASA contract NAS-7-100. This document constitutes the final report of NASA contract NAS-9-15509.

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INTRODUCTION AND OVERVIEW

In forestry and range science, the need often arises to sample and inventory natural vegetation. Conventional methods use manual interpretation of stereoscopic aerial photography to delineate areas of homogeneous vegetation (usually termed stands) using analysis of image tone, texture, and topography. Once delineated, stands exhibiting like characteristics are similarly labeled to form sample strata from which random samples are drawn to yield inventory data describing attributes of interest of the natural vegetation. Because this process is based on manual photointerpretation, it can be time consuming and costly, as well as inconsistent from analyst to analyst. For the past three years, research efforts have been underway at the University of California at Santa Barbara (UCSB) and the Jet Propulsion Laboratory (JPL) of the California Institute of Technology at Pasadena to develop an automated system for natural vegetation inventory utilizing digital image processing of multispectral Landsat data and registered digital terrain information. This technology, referred to as the Forest Classification and Inventory System (FOCIS), has shown the capability to classify and stratify forest vegetation for timber volume inventory as efficiently as conventional methods of manual photointerpretation.

1.1 CONVENTIONAL METHODOLOGY FOR TIMBER VOLUME INVENTORY

To provide a perspective for the description of FOCIS that we present in following sections, we briefly summarize the conventional methodology used to produce timber volume estimates by Region 5 (California) of the U.S. Forest Service. This methodology executes timber inventory in three steps: (1) stand mapping, (2) stratification, and (3) sample collection and data processing. The procedure begins with the delineation and mapping of timber stands. Foresters skilled in air photo interpretation techniques use conventional resource photography, typically normal color, 9" x 9" positive prints at a scale of 1:15,840 or 1:24,000, to delineate timber stands by drawing boundaries around homogeneous areas of uniform vegetation. Typically, a minimum size, e.g., five acres, will be required for delineation. Concurrent with the delineation process, the stand boundaries are transferred manually from the air photos to 7 1/2-minute topographic quadrangles, and labels are affixed to each stand indicating the species composition, height, crown density, and other features of interest for forest management purposes. The stand maps which are thus produced are a basic information resource, widely used at the Forest and Ranger District levels.

In Region 5, however, a further step is executed. The boundaries on the stand maps are scanned photomechanically and input to an automated, computerized database system which is manipulated through the RID*POLY software system developed by the Forest Service. Once scanned and edited, the polygons are displayed by map section on an interactive device and stand labels are assigned to the polygons using a light pen under the control of an operator. Unfortunately, the labeling process is, at the present time, relatively costly and labor intensive.

The second step is stratification of the stand maps. In this procedure, all unique stand labels are aggregated to form a dozen or so strata which are differentiated with respect to per-acre timber volume by such attributes as crown density, height, and species composition. By interrogating the RID*POLY database, the area of each stratum within the area to be inventoried can be obtained. Further pooling of strata is carried out in the event that some strata are characterized only by small areas. Once the final strata have been determined, sample locations are chosen for the collection of timber inventory data. The samples may be allocated in proportion to the size of the stratum, (referred to as PPS sampling, for probability-proportional-to-size), or may be allocated equally to all strata (referred to as RS, or random-stratified, sampling). The last phase of timber inventory is the collection and processing of the sample plot data to yield mean timber volumes for strata, the weighting of these means by the areas of their respective strata, and the calculation of total timber volume by species for the entire national forest.

This methodology has two distinct disadvantages. First, it is based on conventional photointerpretation, which is time consuming, costly, and can be inconsistent when more than one photoanalyst is involved. Second, the digitizing and labeling of stand maps, which is required to enter them into the RID*POLY database is, again, costly and time consuming, and prone to error. The Forest Classification and Inventory System described in this report bypasses manual photointerpretation by using automatic classification of Landsat and registered digital terrain data. Labeling of the automatically defined classes is still required; however, this labeling can be done much more rapidly and cost effectively than in the conventional procedure. And, because FOCIS utilizes the raster-based VICAR/IBIS software system, the classified images which are the analog of stand maps can be directly interfaced through software to the polygon-format files of the RID*POLY system.

1.2 TEST AREA: THE KLAMATH NATIONAL FOREST

The Klamath National Forest, located in Northern California, is the study area where FOCIS was developed and tested (Figure 1). The Forest includes 2,600 square miles of rugged terrain in the Siskiyou, Scott Bar and Salmon Mountains; it provides approximately 260 million board feet of timber per year, ranking sixth nationally in timber production. Past research in the Klamath has explored the topics of:

1. species-specific forest cover classification; and

2. modeling timber volume proportions of species and ecological relationships of species to terrain (Strahler et al., 1930).

The high relief and diverse ecological conditions throughout this Forest have made it an excellent location to test forest classification and stratification techniques.

1.3 STRATIFICATION OF FOREST VEGETATION

In conventional stratification of forest vegetation for large area inventory, three attributes characterize each stand: tree height, crown density, and regional type. Regional type refers to species composition, and is often defined by the dominant species in the stand; e.g., red fir, Douglas fir, ponderosa pine, or mixed conifer. It is important to distinguish between regional types because for a given size and density the timber volume will differ with regional type. This difference is related to the growth form of the species and the productivity of the site. Thus, the regional type of red fir, for example, will have a higher per-acre timber volume than will ponderosa pine type, given the same height and crown density classification.

Because forest composition varies systematically with terrain in the Klamath, regional type can be modeled using elevation and aspect data. To quantify the relationship between elevation, aspect, and regional type, field data are required. The simplest method of quantification involves systematically observing regional type at all aspects and elevations, and plotting regional type on a graph with elevation and aspect as axes. Lines fitted by eye then allocate the elevation-aspect space of the graph into fields associated with each regional type.

Classification of the Landsat and texture data into size-and-density-based strata using FOCIS is a six-step process;

1. unsupervised clustering;

2. statistical editing;

3. classification using a hybrid parallelepiped-maximum likelihood classifier;

4. differential illumination compensation;

5. spatial editing; and

6. field reconnaisance and final editing.

Combining these strata with modeled regional type produces a map of new strata based on characteristics of tone, texture, and terrain. These strata can then be sampled to determine the desired quantitative characteristics, such as timber volume by species (Figure 2).

The FOCIS automated stratification procedure uses the same three characteristics of tone, texture, and terrain that the photointerpreter uses in delineating timber stands. Landsat multispectral reflectance vectors provide tonal information and Defense Mapping Agency 1/250,000 digital terrain data provide the required terrain information. Texture data are derived from a spatial standard deviation filter passed over Landsat MSS Band 5. For a three-by-three moving window of pixels, the standard deviation of the nine reflectance values is computed, scaled, and placed in the location of the center pixel. In this way, an entire registered image is created containing information about local tonal variation.

The computer processing for FOCIS was carried out at JPL and UCSB using the Video Image Communication and Retrieval (VICAR) image processing system. Under continual development at JPL for the past ten years, the VICAR system was originally designed for enhancement of satellite pictures from the nation's unmanned space exploration programs such as Mariner, Viking and Voyager. Companion to VICAR is IBIS, the Image-Based Information System that manipulates polygon data in the form of strings of X,Y coordinates, overlays polygons on raster bases, and prepares such information as areal tabulations (Bryant and Zobrist, 1976).

2
MODELING ECOLOGICAL RELATIONSHIPS USING DIGITAL TERRAIN DATA

Observations in the Klamath National Forest and other western coniferous forest areas have shown that forest composition varies systematically with topography in many places. The distribution patterns of coniferous species have long been associated with particular elevation ranges; species are often referred to as "low elevation" or "high elevation" species (Boyko, 1947). Red fir, for example, is usually considered a high elevation species. Compass aspect (direction which a slope faces) has also been recognized as influencing tree growth and species distribution. North to northeast exposures are typically more favorable for tree growth than drier southwestern exposures (in the northern hemisphere). As a result, species that exhibit elevational zonation tend to occur at lower elevations on northeast-facing slopes. In an attempt to exploit the relationship between terrain variables and forest composition, we investigated three methods for employing digital terrain data in the Klamath National Forest to model species composition.

2.1 DIGITAL TERRAIN PROCESSING

The topographic data used in this research were derived from 1/250,000 Defense Mapping Agency (DMA) digital terrain models, now distributed by the U.S. Geological Survey through the National Cartographic Information Center at Reston, Virginia. For these data to be used as part of FOCIS, the terrain values were reformatted into an image and registered to the Landsat image. Registration of the terrain image to the Landsat image used a geometric resampling algorithm which employs a two-dimensional correction grid, derived from control points, to convert each pair of Landsat coordinates into digital terrain coordinates. These calculated coordinates are then used to select the terrain pixel (or an interpolated value of the pixel) to appear in the registered output image. Selection of control points which identify the spatial correspondence between digital and Landsat images can be quite difficult because terrain features are not necessarily recorded by the Landsat image. Similarly, linear cultural features such as roads, dams, bridges, etc., are not often resolved on the digital terrain image. Mountain peaks and river valley intersections provide the most reliable locations for control of registration.

After registration of the terrain data to the Landsat scene, separate images of slope angle and aspect were generated from elevation by the least squares fitting of a plane through each pixel and its four nearest neighbors. The output slope angle is scaled to reflect 0-90 degrees with the numeric range 0-255 (corresponding to the maximum numeric range of an eight-bit computer byte), and slope aspect is scaled so that the azimuth in degrees (0-359) also varies from 0 to 255. The aspect image is then transformed using a cosine transformation with a shifted axis, following the suggestion of Hartung and Lloyd (1969). The transformation is: cos(azimuth-45). When rescaled to one byte range, the value of 0 represents northeast, 128 represents southeast and northwest, and 255 represents southwest. This function is based on the ecological observation that sites on northeast facing slopes are most productive, those on southwest facing slopes are least productive, and those on southeast and northwest slopes are intermediate.

2.2 PREVIOUS USE OF TERRAIN DATA

Research in the Doggett Creek watershed showed that Landsat information combined with digital terrain data could recognize species-specific forest cover classes with high accuracy (Strahler et al., 1978). In that study, registered terrain data were used as pseudospectral channels in a conventional supervised classification framework. The study showed that the elevation channel proved the most valuable in differentiating species types -- a result confirming the importance of elevation in controlling species composition within the Klamath. This observation suggested that such terrain parameters as elevation, slope, and aspect could be used to predict species composition, expressed as proportions of total timber volume within species. Initial data analysis showed that slope angle does not predict composition well, so our modeling effort was confined to variables of elevation and aspect.

The model we devised used logistic regression to relate the proportion of each species to elevation and aspect. The model is of the form:

$$\ln\left(\frac{P_1}{P_0}\right)=a+b_1X_1+b_2X_2,$$

where P_1 is the proportion of timber volume drawn from a given species; P_0 is the proportion drawn from other species; a, b_1, and b_2 are empirically derived constants which differ for each species; X_1 is elevation; and X_2 is aspect transformed as cos(aspect-45). This model is discussed more fully in Strahler et al., 1980. For our application, the model was calibrated using timber inventory data from selected compartments in the Goosenest Ranger District (eastern Klamath), and species proportions were continuously modeled over a large portion of that District (Strahler et al., 1980). However, U.S.F.S. personnel suggested that simply predicting regional type (which indicates composition) would be more practical and useful for timber management. Accordingly, we turned our attention to modeling regional type, rather than species proportions, as described in the following two sections.

2.3 NATURAL REGION CONCEPT

The FOCIS stratification procedure is not applied to the entire Forest at once, but rather to a group of smaller geographical areas called natural regions (Figure 3). Because a large forest may exhibit extensive climatic, geologic, and ecological diversity, species-habitat relationships and spectral signatures which characterize particular timber types are not likely to be the same in all portions. Therefore, the Forest was divided into natural regions in which ecological relationships remain fairly constant and signature extension should be valid.

Natural regions were designated primarily on the basis of graphs which were developed during ground reconnaissance in order to model regional type (Figure 4). These graphs plot locations visited in the field according to their elevation and aspect; since each location is also identified by its regional type, the graphs identify combinations of elevation and aspect associated with each type. Natural regions are then defined as areas within which the elevation-aspect ranges of the various regional types remain constant. A natural region boundary has been crossed when the elevation-aspect range of a regional type shifts significantly or a new regional type appears. In the Klamath National Forest, which is particularly large and diverse, eight natural regions were defined for this study: two in the eastern Goosenest Ranger District and six in the larger western portion of the Forest.

2.4 MODELING REGIONAL TYPE

For timber management purposes, regional type is a loosely defined level of classification used to divide forests into broad categories based on species composition. The underlying reason for the differentiation of regional types is that timber stands of similar height and density characteristics but different regional types will have different timber volumes. Regional types are typically defined by the dominant species in the stand; e.g., red fir, Douglas fir, ponderosa pine, or simply mixed conifer.

The field graphs (Figure 4) used to define natural regions were also used in modeling regional type. For each natural region, lines fitted by eye partitioned the elevation-aspect measurement space into areas that represent each regional type present in the natural region. Functions defining those lines were input into a VICAR image processing program to determine for each pixel its most likely regional type, based on the elevation and aspect of the pixel. In this way, a new registered image for each natural region was created in which the value of each pixel specified a regional type (Figure 5).

3
LANDSAT- AND TEXTURE-BASED CLASSIFICATION

The second stage of the stratification process used Landsat and texture data to assign a label indicating tree height and density to each pixel within a natural region. Combining the modeled regional type with height and density class produces final strata based on the same attributes as conventional stratification -- regional type, height, and density (Figure 6).

3.1 TEXTURE

The use of texture in this stratification procedure has greatly increased the ability to discriminate timber volume strata. The use of texture by photointerpreters for forest stand discrimination is well established, but digital texture information has not been widely incorporated into Landsat-based classification systems.

In an attempt to quantify texture, or local tonal variation, a new channel was created from Landsat Band 5 by calculating the standard deviation of density values within a three-by-three moving window. Once calculated, the standard deviation value was scaled, assigned to the center pixel of the three-by-three window, and output in a spatially registered image format (Figure 7). In forested areas, low standard-deviation-texture values indicate continuous canopy cover and higher values are associated with areas of discontinuous canopy. The largest texture values occur at abrupt vegetation boundaries as a form of edge enhancement. For more background and detail concerning the standard-deviation-texture concept and its use in forest classification, see Strahler et al., (1979) and Logan et al. (1979).

3.2 CLUSTERING THE LANDSAT IMAGE

The classification of an area into height- and density-homogeneous classes was based on five channels of information: four Landsat MSS channels and the synthesized texture channel. The process involved unsupervised clustering using a modified version of an algorithm obtained from Pennsylvania State University. The algorithm is based on a method suggested by Tryon and Bailey (1972) for clustering large numbers of observations. Beginning with the first pixel in the first scan line, each pixel is selected in turn. The euclidean distance from the pixel to each existing cluster is calculated, and if the distance falls within a user-specified threshold, the pixel is merged into the cluster and the cluster centroid is recomputed. If the pixel does not fall within the distance threshold of an existing cluster, it becomes a new, single pixel cluster. When the process is completed, clusters are ranked from largest to smallest, and a user-specified number of centroids are output as classes for input to classification programs. The 200 largest classes were found to contain all the significant variation in the forested portion of the image, hence these 200 were retained for future processing. The output classes comprised a dataset which included:

1. the number of pixels used to define each class;

2. the centroid (mean values) for each class; and

3. the variances of individual channels for each class.

Because this clustering algorithm can compare each pixel to every existing cluster, the number of comparisons is a factorial function of the size of the image. Thus, it is often desirable to reduce computer time by clustering a sample of pixels from the image rather than the entire image. Typically, we have used a systematic sample of four percent of the pixels (every fifth pixel in every fifth line).

3.3 SPECTRAL EDITING PHASE

Because the clustering process produces an unwieldy number (200) of tightly-defined classes, these classes must be edited into a simpler, smaller set. This editing takes place in two phases in the stratification process. First is a spectral editing, based on the spectral similarity of classes. Second is a spatial-spectral editing, in which classes are combined depending on their spatial contiguity as well as spectral similarity.

During the spectral editing phase, a symmetric matrix of standardized distances between all class centroids is calculated. Standardized distance is simply the euclidean distance between classes calculated after standardizing each channel for the average within-class standard deviation. Through standardization, small differences in values for channels which vary less (e.g., Bands 4 and 5) are equated with larger differences in channels which vary somewhat more (e.g., Bands 6, 7, and texture).

This standard distance matrix is then input to the NTSYS (Numerical Taxonomy System) computer program package, which constructs a dendrogram of the classes using a complete linkage algorithm (Rohlf et al., 1974). The dendrogram is combined with a listing of class means (Figure 8) and is edited either by merging, pooling, or deleting classes. Editing is accomplished using the VICAR program EDSTATS which operates on the stored file of centroids and variance vectors according to a set of instructions prepared by the analyst. Because the editing is not automated, the analyst can compensate easily for variations in scaling and relative importance of the various layers of the database. In merging classes, a common centroid is formed and variances are recalculated with respect to the new centroid. All calculations are weighted by the number of pixels in the clusters merged. In pooling classes, a new centroid is formed, but variances are calculated based on dispersions around individual class centroids rather than around the new centroid. The new variances are thus within-class average variances. Deletion is often the most appropriate method for handling small classes which are not within the area of measurement space containing the phenomena of interest.

3.4 CLASSIFYING THE IMAGE

Usually, 70 to 100 spectral cluster classes will remain after the spectral editing phase. These classes are then input to a hybrid, parallelepiped-maximum likelihood classifier. The parallelepiped portion of the classifier operates by defining a "window" for each class centered around the mean of each class for each spectral channel. The size of the window is determined by a user-specified number of standard deviations. If a pixel falls through the window for only one class then that pixel will be assigned to that class. If a pixel falls within two or more class windows, then a maximum likelihood decision rule is invoked. In this step, a likelihood value is computed for each class that passed the parallelepiped step. The maximum likelihood value determines the class to which the pixel is most likely to belong and assigns the pixel to that class.

3.5 DIFFERENTIAL ILLUMINATION COMPENSATION

It was originally assumed that the spectral classes retained to classify the image would be sufficiently precise to contain only one height-density type. However, it became apparent upon viewing these spectral classes that variation within some classes was too great to be acceptable. Some of this variation was not the result of loose spectral definition, but was produced by differential illumination of slopes caused by high topographic variation combined with low sun angle at the time of the Landsat overpass. More densely-stocked areas with normal illumination had the same spectral reflectance as more sparsely stocked areas in poorly illuminated or shaded areas. This, problem, also noted by Sadowski and Malila (1977), ruled out the separation of forest strata based solely on spectral reflectances. Thus, it was imperative to develop a means of separating the image into categories based on illumination conditions at the time of the Landsat overpass.

The registered terrain data were used to model illumination conditions on a pixel-by-pixel basis. For each pixel, z, the angle between a normal to the land surface and the sun at the time of the Landsat overpass was calculated. For a diffuse (Lambertian) reflector, the apparent brightness of a surface under constant illumination at an angle z will be proportional to cos(z). Thus, a cos(z) image (Figure 9) displays the brightest values for pixels directly facing the sun and the darkest values for pixels in shade. From the cos z image a mask was created (Figure 10) to divide the image into two categories based on illumination: well illuminated, and poorly illuminated (shaded). The cutoff between these two categories was a zenith angle of 60 degrees; areas with angles greater than 60 degrees were considered poorly illuminated. This cutoff was based on interactive viewing on a CRT monitor of classes for which the problem had been originally recognized. Using the 60 degree cutoff, aproximately 10 percent of the image was considered shaded.

The mask of shaded and well-illuminated pixels was digitally added to the classifier image, serving to divide each spectral class into its shaded and unshaded components. Since only ten percent of the image was shaded, however, many classes remained undivided. The result of this action was to reduce the within-class variation effectively and remove a potentially adverse effect on the stratification process.

Although illumination correction was required for the application of the stratification procedure in the western portion of the Klamath National Forest, such correction may not be needed for less rugged areas. Only when low illumination of bright objects produces the same spectral response as higher illumination of dark objects is some form of illumination compensation required.

3.6 SPATIAL-SPECTRAL EDITING

The spatial-spectral editing phase is the most analyst-intensive of the stratification process and involves the aggregation of classes that are spatially continguous as well as spectrally similar. This phase constitutes the final editing in the classification process to reduce the number of classes to approximately the same number of height and density classes differentiated by the Forest Service. Depending on the diversity within the natural region in question, the final number of height-density types should range from five or six in an area of low diversity to nine or ten in an area of high density (J. Levitan, personal communication).

The first step in identifying classes to be aggregated is to cluster the classes remaining from the spectral editing phase, again using NTSYS. These clusters are based only on spectral similarity, but experience has shown that many spectrally similar classes are also spatially contiguous. The NTSYS dendogram is thus highly valuable as an editing guide.

Spatial contiguity of classes is established by interactive viewing of the classified image on a color TV monitor driven by a Grinnell Refresh Memory. This apparatus allows the viewing of six color-differentiated classes which can be overlain on a Landsat background image. While the classes are displayed, aerial photographs of selected test areas are inspected to verify that classes to be aggregated contain trees of similar size and spacing. Height-density labels are attached to the new classes as they are created. The labels follow U.S. Forest Service notation (U.S.F.S., 1979). For height, labels 2, 3, and 4 were used to indicate crown diameters of <12, 12-24, and 24-40 feet respectively; stand densities were noted as S (sparse), P (poor), N (adequate), and G (good), indicating crown closures of 10-19, 20-39, 40-69, and 70-100 percent respectively. In the western portion of the Klamath National Forest, ten height-density types remained after the spatial-spectral editing phase for all natural regions.

3.7 NATURAL REGIONS AND THE LANDSAT CLASSIFICATION

Because spectral signatures which characterize particular timber types are not constant over large areas, we intended to classify and stratify each natural region separately. However, to reduce time and cost, we carried out unsupervised clustering, spectral editing, classification, and differential illumination compensation for four of the six natural regions in the western Klamath taken together; the remaining two regions were treated separately as described above. Although the four regions were pooled to reduce processing, spatial-spectral editing was carried out in the manner most appropriate for each individual natural region.

The variation in spectral signatures which we anticipated for a given height-density class from region to region was confirmed by the spatial-spectral editing. Of the 200 spectral classes (100 classes after the editing phase), only 45 (or 22.5%) of those classes were assigned the same label in all four natural regions. Of these 45 classes, 40 were in the "not trees" type which contained classes not considered of interest for timber management. Ninety-seven percent of the spectral classes receiving a timber height-density label received a different label in at least two of the four natural regions.

3.8 MERGING REGIONAL TYPE AND HEIGHT-DENSITY CLASSES

To derive the final strata, the regional type map, modeled from digital terrain and field sample data, was merged with the Landsat- and texture-based height-density classes. In an image processing mode, this merging was accomplished by scaling and adding the images, pixel-by-pixel. There were four regional types (coded 1-4 with zero indicating a nontimber type) and ten height-density classes (coded 1-10); the regional type codes were scaled to values of 0, 25, 50, and 75, and the two images were simply added. Potentially, forty strata could have resulted from this addition, but all possible combinations did not occur and some strata contained very few pixels.

It was then necessary to decide which strata should be retained for final output. These decisions were made primarily on the basis of areal extent, with large strata always preserved. Height groups were generally the most easily handled, with small strata merged into larger strata of the same regional type, density, and similar height. The one major exception to the rule was the merging of regional types into the sparse (S) density classification. Sparse areas characteristically show high variance, which degrades final timber volume estimates. The final strata retained for sampling are listed in Table 1.

4
MAP PRODUCTS AND TABULATIONS

4.1 STRATUM MAPS

FOCIS stratification processing resulted in individual digital images for the eastern and western portions of the Klamath National Forest. Each pixel within each image possessed a unique value corresponding to one of the 23 final timber classes. Users of the data, however, expressed the preference for a map-like product that could be easily related to conventional U.S. Geological Survey (USGS) series maps. To this end, the classification image was geometrically rectified to a Universal Transverse Mercator (UTM) projection, and partitioned into twenty subareas approximately corresponding to standard USGS 15-Minute Quadrangles. Rectification proceeded by registering the classification image to the DMA 1/250,000 digital terrain data using a nearest-neighbor sampling technique. Throughout this process, the 1.5 acre, 80-by-80 meter Landsat-classification pixels were transformed into 1 acre, 63-by-63 meter pixels. The twenty quadrangles were extracted from the stratum map in UTM projection by generating a digital polygon image of 15-minute latitude-longitude lines. The resulting twenty quadrangle-polygons were assigned unique digital density values, and used as "masks" in a digital multiplication process that zeroed-out all pixels not belonging to the desired quadrangles. To further enhance the usefulness of the maps, the road net from the 1968 Klamath National Forest 1/250,000 map was digitized, registered and digitally overlain upon the stratification image.

The final filmwriter photographic products for the twenty quadrangles have unique symbol-grey tones (DN-symbols) assigned to each stratum class. This display method circumvents a basic cartographic problem; the human eye cannot readily differentiate more than 7 to 10 grey tones. The DN-symbols are created by expanding each pixel to a 10-by-10 matrix and placing one of ten geometric symbols in the matrix to identify size and density classes. Foreground and background DN-symbol tones are differentiated to highlight regional type categories. When the stratum map quadrangles are enlarged to their standard working scale of 1/62,500, the symbols are readily comprehensible (Figure 11).

4.2 STEREOGRAMS

Synthetic classification and Landsat MSS Band 5 stereograms of the 15-minute quadrangles were also generated to provide the user with a spatial context of pixel's topographic position. These stereograms were created by offsetting each pixel horizontally to the right in an amount proportional to the relative value of the corresponding registered elevation pixel value. The higher the elevation pixel, the greater the offset. Because parallax is artificially introduced, 100% stereo overlap viewing is possible (Figures 12 and 13).

4.3 STATISTICAL TABULATIONS

Timber inventory tabulations quantifying stratum map statistics were derived for each 15-minute quadrangle (Table 2). In Table 2, the column labeled "STRATUM" refers to an actual pixel count of stratum class acreages produced through FOCIS techniques. The column labeled "MAPPED AREA" gives the number of pixels in each stratum actually displayed on the maps. The discrepancy results because the map-displayed data were "simplified" using an algorithm that removes isolated pixels and smoothes boundaries based on user-supplied thresholds. This technique reduces the amount of "speckling" characteristic of Landsat-based classifications.

5

ASSESSING THE QUALITY OF THE STRATIFICATION

5.1 ASSESSMENT CRITERIA

Concurrent with the present Landsat-based stratification research, a forest-wide inventory was conducted by Forest Service personnel in the Klamath National Forest. This inventory provides a basis for comparison of conventional techniques based on photointerpretation with the Landsat-based FOCIS procedure.

One method of evaluating two stratifications is to assess the extent to which the strata contained within them are homogeneous. This homogeneity can be determined by comparing the variance within individual strata to the variance between strata in a classical analysis of variance (ANOVA) procedure; the better stratification will have the less likely F-ratio. This approach compares the potential of each stratification to reduce the standard error of the inventory estimate irrespective of the sizes of the geographical areas associated with the strata. Note that the F-ratios may not be compared directly because the degrees of freedom vary according to the number of samples and number of strata, and these numbers differ for FOCIS and Forest Service inventories.

A more relevant method is to compare the standard errors of the timber volume totals for the same region which are derived by the two different stratifications. The more precise inventory (that with the lower standard error) is the more desirable. Direct comparison of the totals for the two stratifications is not helpful, since there exists no third value of higher precision to serve as an absolute standard of comparison.

At the time of preparation of this report, the first method was the only method available for direct comparison of the two inventories. Although the Klamath timber inventory data are complete for both stratifications in the western Klamath region, a final timber volume estimate with an associated standard error has been prepared only for the Landsat-based stratification. The Forest Service inventory includes the entire Klamath, consisting of both eastern and western portions. Since these portions are not separated, the volume totals are not directly comparable. The remaining sections in this portion of the report document the sample allocation, data collection, and calculation required for the inventory, and compare the Landsat-based stratification to the conventional stratification.

5.2 CLUSTER PLOT DATA

Following definition of the final strata, the actual per-acre timber volume associated with each stratum must be estimated. The estimates are obtained from ground samples, or "cluster plots," collected according to standardized procedures specified by Region 5 of the USFS (1979). These ground samples are termed cluster plots because each consists of five subplots arranged in the shape of an "L," with one subplot at the vertex and two along each arm. The arms of the cluster plot are oriented due north and due east with the subplots located two chains (132 feet) apart. Figure 14 presents the form used for tabulation of data collected at each sample site. This form includes a diagram of the subplot layout in the upper left corner. The use of such spatially clustered samples is a classic technique in sampling which is invoked when local variance is high and the travel cost to reach randomly located points is excessive (Cochran, 1977).

In the Region 5 method, variable radius plot measurements are made at each subplot through the use of a Bitterlich wedge, a hand-held precision optical prism. With this technique, the diameter of the tree, its distance to the center of the plot, and the basal area factor of the wedge determine if the tree is to be tallied or not (USFS, 1979). (The number of trees tallied times the basal area factor (10, 20, 30, or 40) directly estimates the basal area per acre.

The cluster plot data were processed by a standardized computer program at the Rocky Mountain Forest and Range Experiment Station at Fort Collins, Colorado. The program can produce many types of information used in stand or stratum characterization or in areal inventory, but for our analysis softwood timber volume by species for each plot was the only information extracted from the processed plot records.

5.3 SAMPLE ALLOCATION

Estimating the average timber volume for each Landsat-derived stratum requires allocating cluster plot samples to each stratum. A random stratified sample design with equal numbers of samples for each stratum is considered appropriate by the Forest Service for this purpose. A minimum of four cluster plots per stratum is the rule of thumb used for Region 5 Forests; this criterion implies 68 cluster plot samples for the Landsat-based strata. Unfortunately, it was not within the scope of this project to collect this large number of cluster plots independently, and it became necessary to rely in part on the cluster plots being collected by the Forest Service for the forest-wide inventory. To implement this procedure, the locations of the Forest Service cluster plots were manually transferred from 1:15,840 color air photos to a Landsat Band 5 image. By noting the line and sample coordinate and referencing the Landsat-based stratum image, each Forest Service plot was allocated to a Landsat-based stratum. The plots were then aggregated by stratum, and additional plots were randomly selected as needed to fill out each stratum to the desired sample size of four. Table 3 presents the final sample size for each stratum, and indicates the number of samples contributed by the Forest Service to each total.

This plot-sharing procedure unfortunately adds a bias to the timber volume total. The bias arises because the Forest Service strata are not sampled with equal probability, for the same number of plots is allocated to strata of varying areas. Because a Landsat-based stratum does not correspond exactly with a Forest Service stratum, it may be composed of several Forest Service strata. And because each Forest Service stratum is sampled with a different probability the Forest Service cluster plots are not allocated to Landsat-based strata with equal within-stratum probability, which is a requirement for unbiased estimation. Thus, the Landsat-based timber volume estimates will contain an unknown bias. Of course, this bias would not be introduced in a future application of the methodology, since samples would be allocated directly to the Landsat-based strata. And, this bias does not affect the standard error of the inventory estimate, which is a primary criterion for evaluating the effectiveness of the stratification, provided that the variances for the USFS strata contained within a Landsat-based stratum are not significantly different.

Another problem in sample allocation arose because Forest Service personnel chose to merge strata with similar stocking densities, thus creating a smaller number of strata than originally planned. In this merging, strata with G and N labels were combined, as were those with S and P labels. These merged strata were assigned labels of G and P, respectively. Table 4 presents a list of the final 12 strata recognized by Forest Service personnel in the timber inventory of the western Klamath region. In addition, since the new strata were expected to be somewhat more variable than the older ones, the intensity of sampling was increased, with at least six cluster samples obtained for each stratum.

Unfortunately, this merging was accomplished after UCSB personnel had collected the field data necessary to provide a minimum of four cluster plots for each Landsat-based stratum. In addition, some merging of Landsat-based strata had already taken place, in that a few of the areally smaller strata were merged into areally larger strata sharing the same density class but different height classes. Thus, there are twelve final Forest Service strata partially merged by density class, and seventeen Landsat-based strata partially merged by height class. Had Forest Service personnel been able to anticipate their merging, the Landsat-based strata could have been similarly merged to produce a system of strata corresponding more directly to that used by the Forest Service, and a target of six plots per stratum could have been used.

One final problem involving sample allocation concerns the red fir type. In the western portion of the Klamath National Forest, most of the red fir type exists in the Marble Mountain Wilderness Area, an area not managed for timber resources. Thus, this area was excluded from the forest-wide inventory conducted by the USFS and no cluster plot data were collected there. As a result, only six USFS red fir cluster plots were collected in the western portion of the Forest, the remainder of the plots being located in the Goosenest Ranger District. Only one of the six Forest Service cluster plots fell in a Landsat-based stratum with a red fir label. Since there were five FOCIS red fir strata, each requiring four cluster plots to adequately estimate their timber volume, nineteen additional cluster plots would have been required in the red fir type. Due to the limited extent of the red fir type outside the wilderness area and the costs associated with collecting nineteen cluster plots, we used the USFS estimates of timber volume for FOCIS red fir strata in our preparation of the total volume and standard error values.

5.4 COMPARISON OF STRATIFICATIONS

Table 5 presents a cross tabulation of Forest Service labels for cluster plots with those derived using FOCIS. At first glance, few labels appear similar. However, recall from earlier discussion that the Forest Service merged strata with labels of N and G as well as P and S; this action indicates that N and G, and P and S, overlap considerably as labeled. Note also that many of the labels are quite similar, although they may not be exactly the same. If N and G, and P and S are merged together, and we consider strata that are within one size class of one another to be similar, and if we consider the UCSB strata P equivalent to the USFS strata M (since the Forest Service did not recognize a unique pine type in the western Klamath region), then about 40 percent of the labels are similar.

Many of the remaining differences arise from the greater spatial precision of the labeling of the UCSB strata. Recall that each one-acre pixel is classified independently of all others by the FOCIS procedure. On the other hand, Forest Service labels are derived from photointerpretation and delineation of polygons with a five-acre minimum size. Many of these polygons will actually contain a mixture of strata, although the label is awarded to the preponderant type. Thus, the spatial aggregation constraint used in manual photointerpretation accentuates the dissimilarities between the two sets of labels.

Before the capability of USFS and UCSB stratifications to increase the precision of timber volume estimates can be compared using analysis of variance, the within-stratum variances must be tested to assure homogeneity, a basic assumption of the analysis of variance procedure. Tables 6 and 7 present summary statistics for Forest Service and UCSB strata respectively. A visual inspection shows that the within-stratum variances are reasonably homogeneous. A statistical test, using the distribution of the statistic F_{max} confirms this conclusion. The test is carried out by forming the ratio of the largest variance to the smallest variance within the set, and comparing that value with a tabled valued for F_{max} given a confidence level and a sample size used to estimate the variances. However, strict application of this test requires that all variances be estimated using the same, fixed sample size; unfortunately, fixed sample size is not a characteristic of the USFS and UCSB data, since the number of samples collected varies from stratum to stratum. Still, a rough comparison is possible. For the Forest Service data, F_{max} observed is 21.8, a value considerably lower than the critical F_{max} value of 29.9 for a 5 percent confidence interval, a sample size of six, and twelve variances to compare (Rohlf and Sokal, 1969). Thus, it seems safe to conclude that the USFS within-stratum variances are sufficiently homogeneous for a meaningful analysis of variance.

A scan of the variances of the UCSB strata, shown in Table 7, shows that many of the values are similar in magnitude to those of the Forest Service. Note, however, that one variance is very low--that of M4P. This value is based on two samples which have similar values, and appears to be an accident of sampling. In the sampling procedure, four USFS plots were allocated to sample this stratum. However, data for only two of these plots were received, and the two values were coincidentally very close, On this basis, it seems reasonable to treat this variance as an outlier. If this value is removed, the largest to smallest variance ratio is 50.1 (M3N to P3P). This value compares with a conservative critical F_{max} of 124 for a 5 percent significance level, sample size of four and twelve within group variances (Rohlf and Sokal, 1969). Thus, we can also consider the within-stratum variances for UCSB data to be homogeneous.

Figures 15 and 16 present the results of analyses of variance for Forest Service and UCSB inventory data respectively. The F values used for both analyses are highly significant -- probabilities associated with the observed values are .0001. Although the F values cannot be compared directly since each is based on different degrees of freedom, the fact that the probabilities associated with them both round to the same value suggest that they are similar. Thus, the results indicate that both stratification through conventional photointerpretation with accompanying preparation of stand maps and stratification through FOCIS procedures are about equal in their potential to reduce standard error in a well-designed random stratified sample plan.

5.5 LANDSAT-BASED TIMBER VOLUME INVENTORY

To assess the magnitude of the standard error of a timber volume total using FOCIS technology for stratification, we used the image processing capabilities of VICAR to measure the areas of strata within the western Klamath region. Since the stratum maps from which the cluster plot samples were drawn were resampled to one-acre pixels for the preparation of final map products, it was a simple matter to invoke VICAR routines to automatically count the number of pixels, and therefore the number of acres, of each stratum. These areas are shown in Table 8. To estimate the timber volume of a particular stratum, the mean timber volume for the samples collected is simply multiplied by the area; the standard error of the estimate is also simply scaled up through multiplication. The timber volume total for the entire area is estimated as the sum of the individual volume estimates of the strata. The standard error of the total, however, is not obtained by simply adding the standard errors of the strata. Because these errors are considered orthogonal, the standard error of the total is reduced by a significant amount since uncorrelated errors will tend to cancel.

Table 8 also presents the inventory total and its standard error for the western region of the Klamath National Forest. For the mapped area of 944,883 acres, the value is 4.456×10^9 cu ft. with a standard error of 0.2801×10^9 cu ft. This standard error represents 6.3 percent of the total timber volume. A 90 percent confidence interval on the timber volume estimate includes the range of 3.900×10^9 to 5.012×10^9 cu ft.

As noted on earlier pages, the variance for UCSB timber stratum M4P was accidently very low. Because this stratum also had the largest area, the estimated standard error observed, 0.2801×10^9 cu ft., is probably too low. Accordingly, we substituted a value of 15.0 for the standard error of M4P and recalculated the total standard error. The more realistic value is 0.3358×10^9 cu ft., representing about 7.5 percent of the timber volume total.

Because of sampling biases and the inclusion of data for the red fir strata which were derived from the eastern portion of the forest, the total volume estimate cannot be taken as unbiased. However, preparing a total timber volume with standard error validates the use of FOCIS technology for large area timber volume inventory. It seems clear that with a consistent, well-designed plan to sample the timber volume of FOCIS-derived strata that large area timber volume inventory can be carried out on a basis that is fully competitive with conventional technologies.

6
THE GOOSENEST RANGER DISTRICT

The Forest Classification and Inventory System described in this report was developed over a two-year period. During that time, many changes and improvements were implemented, particularly in the stratification phase. Thus far in this report, the final stratification and inventory techniques have been presented -- work accomplished primarily during the second year. In this section, a brief description of the stratification procedures used in the first year of research will be presented.

The Goosenest Ranger District was the area targeted for the initial research effort. The Goosenest is geographically separate from the larger western portion of the Klamath National Forest, and has different geological and ecological conditions (Figure 1). Its climate is more continential, with less precipitation, hotter summers, and colder winters; geologically, the District includes extensive areas of basaltic lava flows of Quaternary age.

6.1 NATURAL REGIONS

The Goosenest Ranger District was divided into two natural regions prior to stratification. These natural regions were intended to have constant spectral and ecological relations, as in the natural regions of the western portion of the Klamath National Forest. The natural regions were separated on the basis of the distribution of Douglas fir. In Natural Region 1, Douglas fir was a common, though clearly not dominant, species, whereas in Natural Region 2 Douglas fir was absent. The boundary dividing the natural regions has ecological significance beyond the distribution of Douglas fir.

A conspicuous feature of Natural Region 2 is extensive areas of flat-lying basalt flows vegetated with stands of "east-side pine." This type is dominated by sparse stands of ponderosa and Jeffrey pines, commonly with a grass or shrub understory. It is abundant in the transition between high desert and montane coniferous forest on the drier eastern slopes of California, and is characterized by low site quality, highly variable densities, and an understory of high desert shrubs. The east-side pine type grades into lodgepole pine at higher elevations on the lava flows, and into a mixed coniferous forest of white fir, incense cedar, and Jeffrey pine on slopes of surrounding mountains.

Natural Region 1 does not exhibit a well developed east-side pine or lodgepole pine type. This Natural Region is characterized by high relief and a more diverse mixed coniferous forest, with Douglas fir, white fir, incense cedar, ponderosa pine, and red fir occurring in a wide range of combinations. One common characteristic of the two Natural Regions is that they both have significant amounts of red fir type at higher elevations.

6.2 GOOSENEST STRATIFICATION PROCEDURES

The primary difference between the stratification procedures used in the first year in the Goosenest and in the second year in the western portion of the Forest lies in the method of assigning the regional type component to the stratum label. As previously explained in section 2.4, the regional type labels for the western Klamath were obtained through the use of ecological models that were derived from field graphs which predicted regional type using the terrain variables of elevation and aspect. In the Goosenest, regional type labels were assigned manually during the Landsat spatial-spectral editing phase through interpretation of 1:15,840 resource photography.

Except for this departure, the procedures used in the Goosenest for processing the Landsat spectral and texture data were not significantly different from those presented in sections 3.1-3.7. Illumination masking (section 3.5), however, was not used in the Goosenest; the terrain is not as rugged in the eastern Klamath an the problems of differential illumination were not as apparent as in the western portion.

Manual assignment of regional type labels was only moderately successful, for mixed conifer and red fir regional types were not distinguished well. Apparently, the spectral characteristics of these two types are quite similar, probably due to the similarity in growth form of red fir to that of such mixed conifer species as white fir and Douglas fir. This failing, along with the observation that regional type was strongly controlled by elevation and slope aspect, led to the formulation of the ecological model concept discussed in section 2.4.

It is worth noting that the east-side pine type was easily differentiated in the clustering and labeling procedure. This differentation is probably due to the unique spectral characteristics of the ponderosa and Jeffrey pines that characterize the type, with their longer leaves and more globular canopy shapes. A distinctive understory may also contribute to this effect.

A list of the final strata for the two Natural Regions in the Goosenest is presented in Table 9. There are no red fir strata in these two natural regions due to the inability to differentiate the type from mixed conifer using only spectral and texture data. Goosenest strata were not sampled to assess accuracy of timber volume estimates because (1) they were not created using the final stratification procedures, which are superior; and (2) the additional field sampling would have been too costly to carry out.

7

CURRENT AND FUTURE RESEARCH

Throughout the course of this project several topics were identified for continuing and future research. One area of immediate importance identified through correspondence with Jack Levitan and Harry Bowlin from Region 5 concerns the resolution of the resulting stratum map. As previously noted, the Forest Service stratum maps have a minimum map unit size of ten acres, while the FOCIS procedures produce a pixel-by-pixel stratification. Levitan and Bowlin pointed out that the stratum maps produced as part of conventional forest-wide inventories also serve to identify stands upon which timber management practices can be executed. The stratum map produced by FOCIS procedures does not fill this need of providing management units because in a forest environment individual pixels are too small to be managed individually.

In response to this problem, a project was funded by Region 5 to test the feasibility of labeling previously delineated timber stands using the FOCIS stratum map (Woodcock et al., 1980). This approach draws on the strengths of both conventional air photo interpretation and the automated FOCIS stratification. Manual interpretation provides the best delineation of timber stands, while FOCIS provides a more consistent, cost-effective stratification that can be more easily updated.

In this project, the boundaries of manually delineated timber stands in a RID*POLY computer file were converted to an IBIS graphics file. These boundaries were registered to the FOCIS stratification and overlain to determine which pixels fell inside the stands. A label was then generated for each stand using a "plurality wins" voting rule on the labels of the individual pixels within the stand boundary. The results of the study indicated that this approach would be a feasible interim solution in locations where stand boundaries previously exist and the labels are either of poor quality or outdated.

As part of this project it was necessary to develop an interface between the Forest Service's vector-based (graphics) RID*POLY information system and the VICAR/IBIS image processing system used at JPL and UCSB. This interface will expedite future research projects involving interchange of data from one system to another.

The long-term solution to the problem of concurrently providing a forest inventory and a map of management units for timber management planning is another area of interest for future research. The eventual solution to this problem is to develop image segmentation techniques to separate clusters of adjoining picture elements which are more homogeneous within their borders than between them. These clusters will resemble timber stands and provide an automated method for delineation of management units. The clusters, instead of pixels, will then be stratified into forest types by a method similar to the FOCIS procedure, producing a label for each cluster according to the spectral values and terrain elements which characterize it. Unfortunately, the development of such segmentation techniques is a lengthy research task that involves a fundamental issue in the use of remotely sensed data and may require several years to be developed.

Another area of research identified during the FOCIS project involves reducing the influence of local topography on the classification of remotely sensed data. In FOCIS, an illumination mask was used to reduce the impact of differential illumination on classification accuracy. Although this procedure is useful, it is not a final solution to this problem. One solution that is currently being explored is the use of illumination/reflection variables as pseudospectral channels in an unsupervised classification scheme similar to the one currently used in FOCIS. The inclusion of illumination/reflection variables will constrain individual classes created in the unsupervised classification to be similar spectrally while at the same time having similar illumination/reflection geometry. The advantage of this approach is that it does not require the assumption of isotropic reflectance by surface cover types.

A different direction of research has evolved from the ecological modeling used in FOCIS. Through this modeling process it became apparent that changes in regional type were associated with variation in site quality for timber growth. Research to model timber suitability, or site index, in a spatially continuous manner, directly from environmental variables, has begun under the support of the California Space Institute. The output of such a model could be potentially useful for timber management purposes when compared to a stratum map like those produced by FOCIS. In essence, present and potential tree growth could be compared -- locations of large discrepancies may prove to be the locations of highest return from forest management practices.

In July, 1981, we began a project funded by Region 5 to provide an inventory of the Eldorado National Forest using the techniques developed in FOCIS. This project will allow completion of an inventory with knowledge of the techniques to be used from the outset of the project. During the course of the FOCIS project many changes occurred in the techniques employed, as would be expected in a research environment. As these changes were made and our understanding of the issues improved, we realized that previously executed steps should have been done differently. As a result, the stratification of Klamath National Forest probably does not exhibit the full capacity of presently-implemented FOCIS techniques. The Eldorado inventory should prove FOCIS technology in a truly operational mode, and we welcome the opportunity to extend it to this area.

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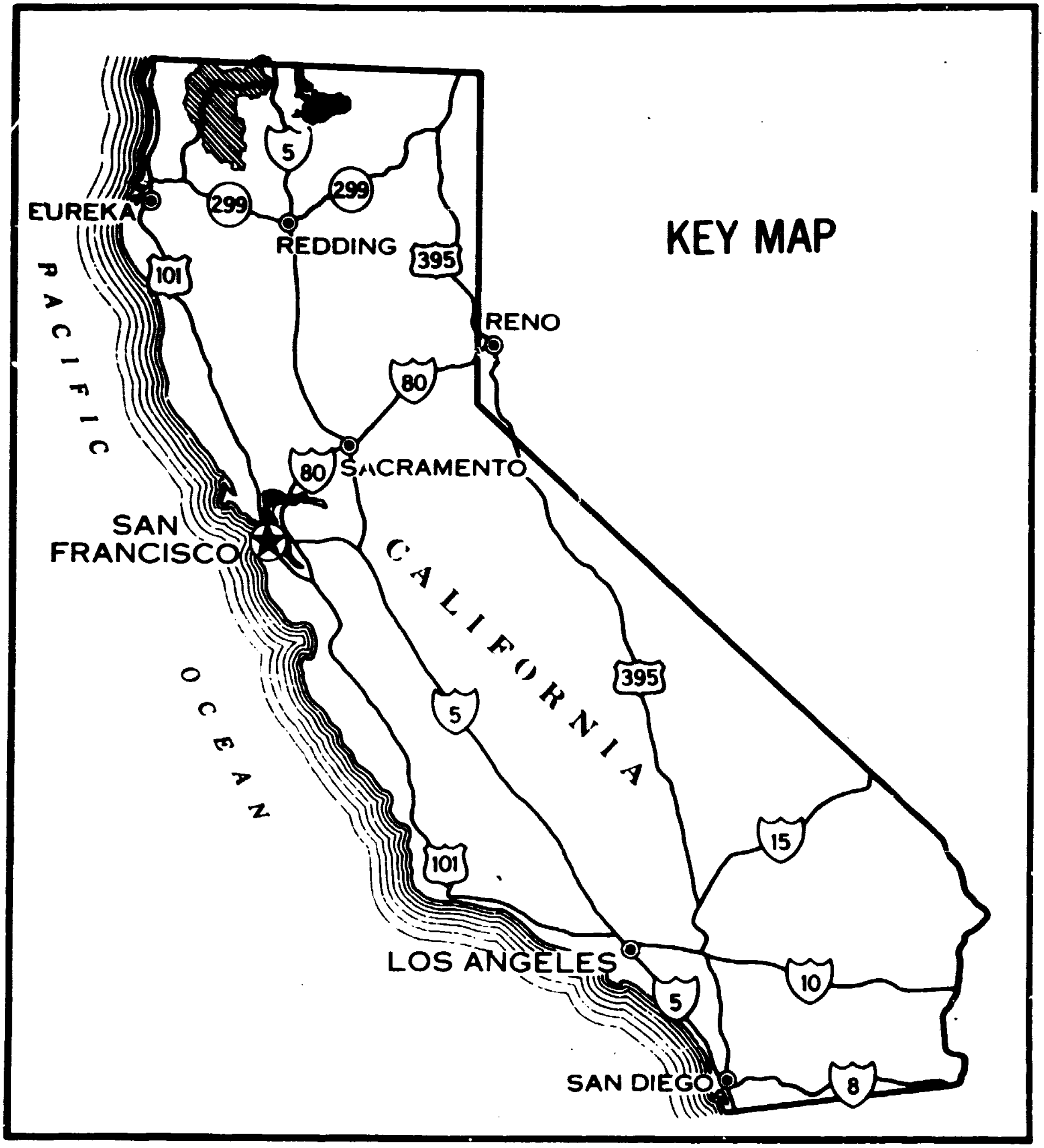


Figure 1. KEY MAP. Index map showing location of Klamath National Forest within the state of California, U.S.A. Hatched area: western portion; shaded area: eastern portion. From U.S. Forest Service.

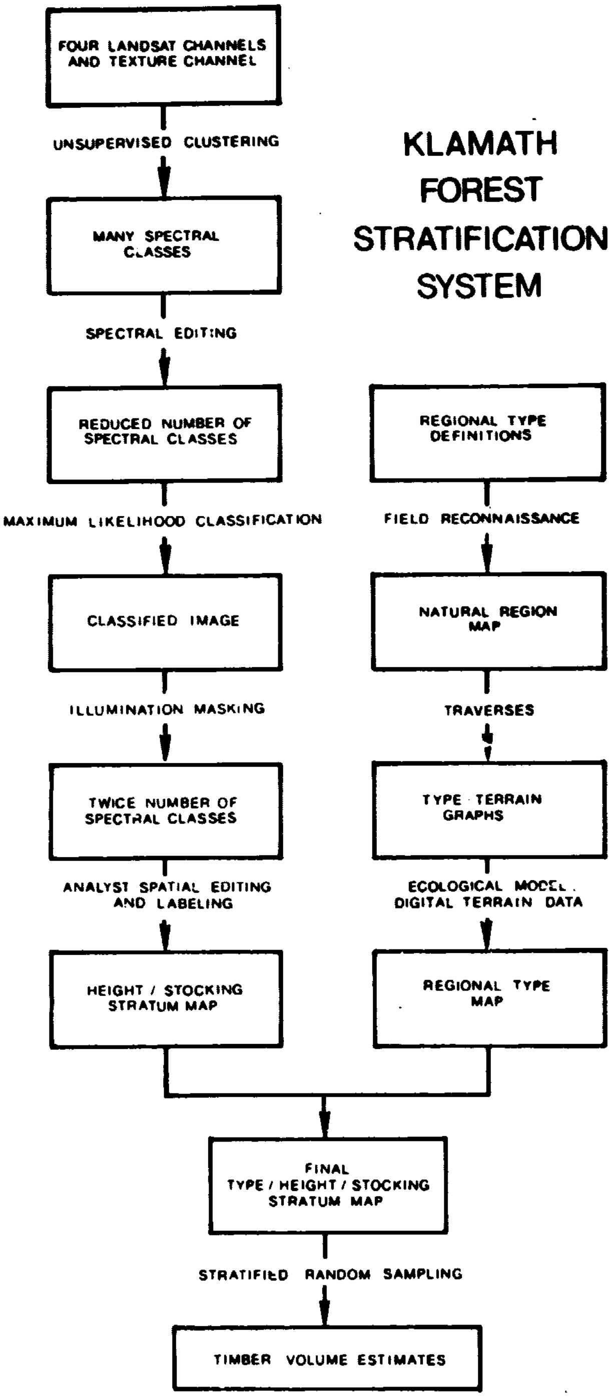


Figure 2. STRATIFICATION SYSTEM. Flow diagram illustrating stratification procedure as devised and implemented for the western portion of Klamath National Forest.

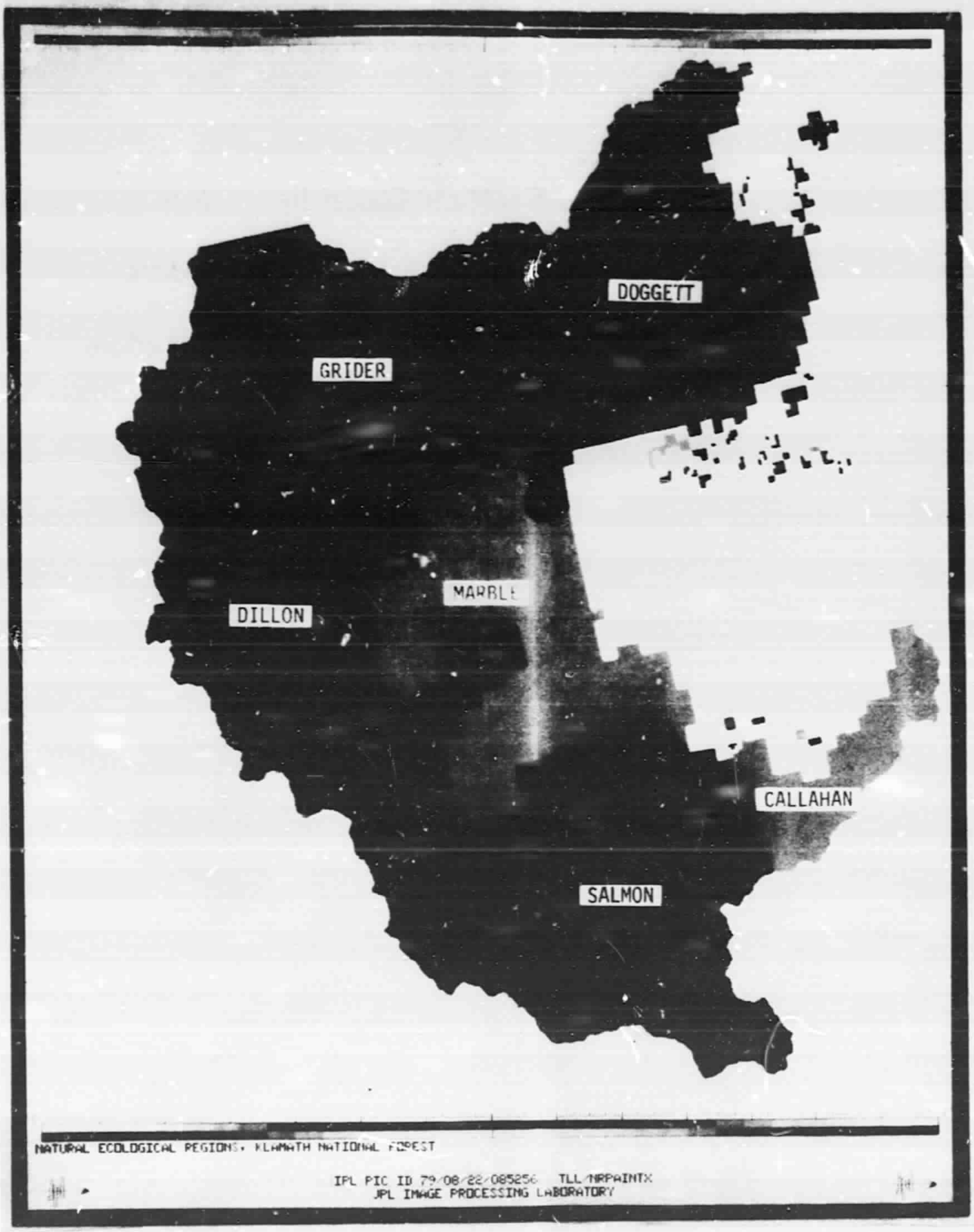


Figure 3. NATURAL REGIONS. Image showing the six natural regions in the western portion of the Klamath National Forest. Stratification procedures are not applied to the entire forest, but to each natural region separately. Natural regions were designated on the basis of field graphs (Figure 4).

○ **Red Fir**
⊗ **Red Fir/Mixed Conifer Intermediate**
× **Mixed Conifer**
✖ **Mixed Conifer/Douglas Fir Intermediate**
● **Douglas Fir**
◬ **Mixed Conifer/Ponderosa Pine Intermediate**
△ **Ponderosa Pine**

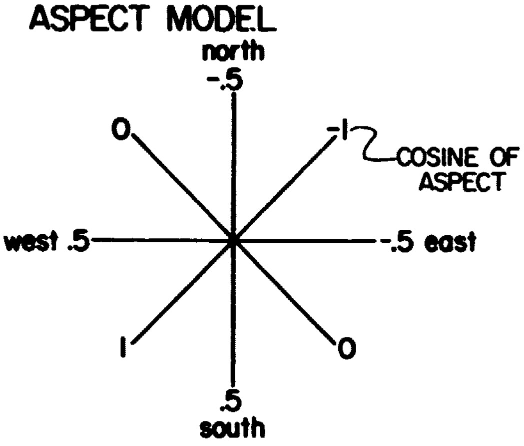
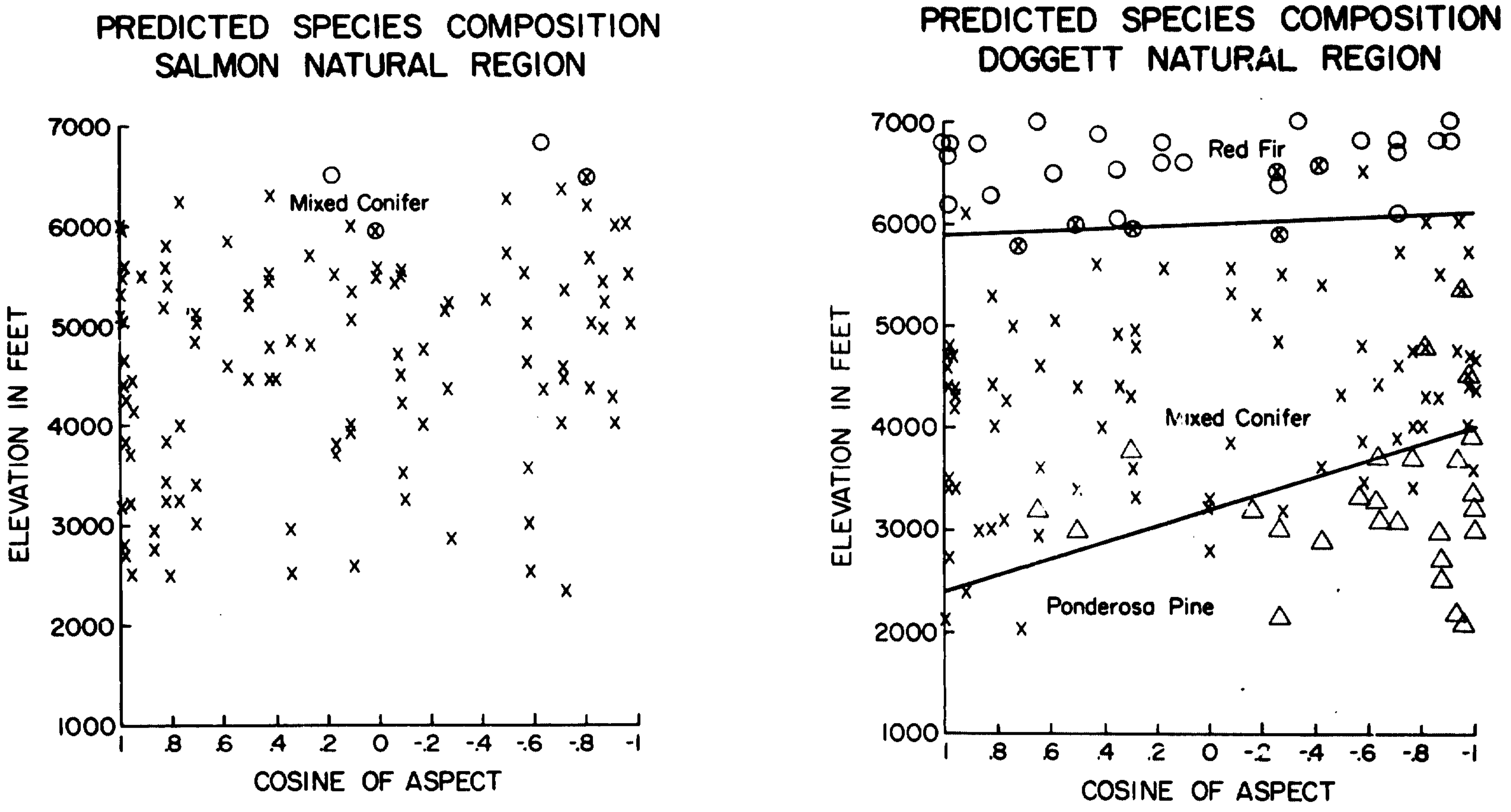


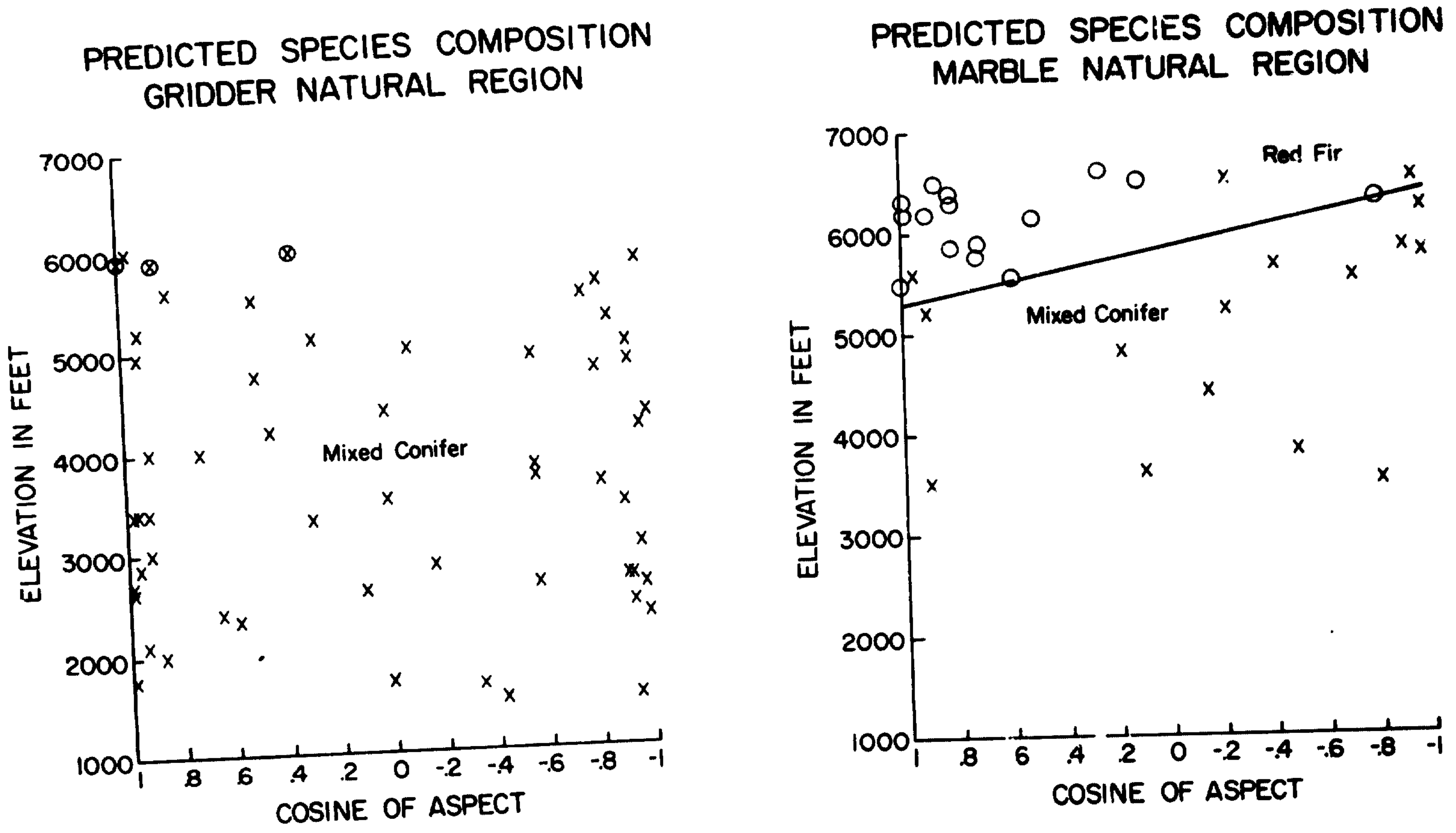
Figure 4. PREDICTED SPECIES COMPOSITION. These six graphs, derived from ground reconnaissance data, were used to designate natural regions and model regional forest types. Points on the graph represent locations visited on the ground, and corresponding symbols represent the regional type best characterizing the location. Lines partition terrain measurement space into elevation-aspect ranges for prediction of the regional type of each pixel. Figure 4(a) is a key to the regional type symbols and the aspect model.



PREDICTED SPECIES COMPOSITION
SALMON NATURAL REGION

PREDICTED SPECIES COMPOSITION
DOGGETT NATURAL REGION

Figure 4(b) and (c). PREDICTED SPECIES COMPOSITION. Salmon and Doggett natural regions.



PREDICTED SPECIES COMPOSITION GRIDDER NATURAL REGION

PREDICTED SPECIES COMPOSITION MARBLE NATURAL REGION

Figure 4(d) and (e). PREDICTED SPECIES COMPOSITION. Gridder and Marble natural regions.

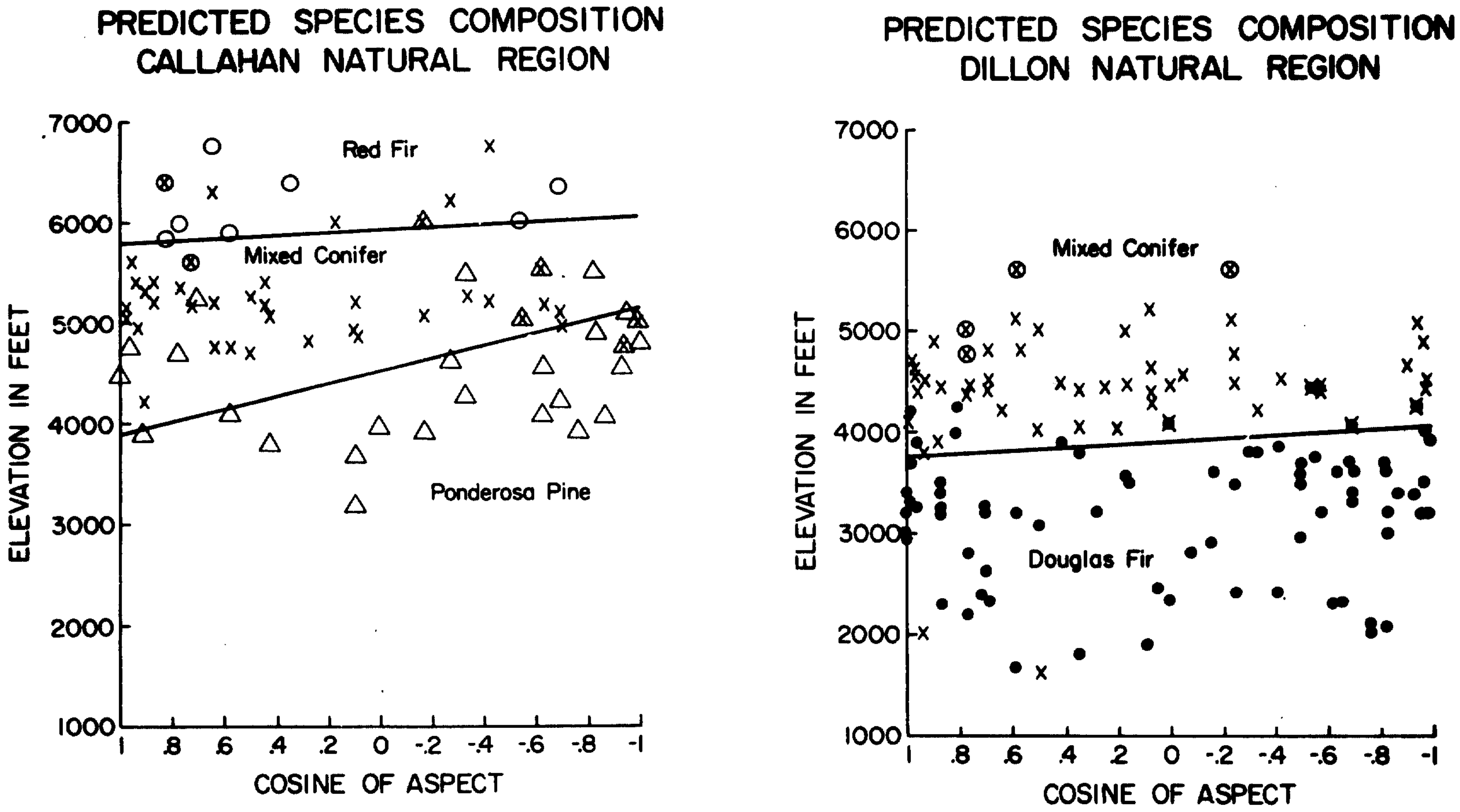


Figure 4(f) and (g). PREDICTED SPECIES COMPOSITION. Callahan and Dillon natural regions.

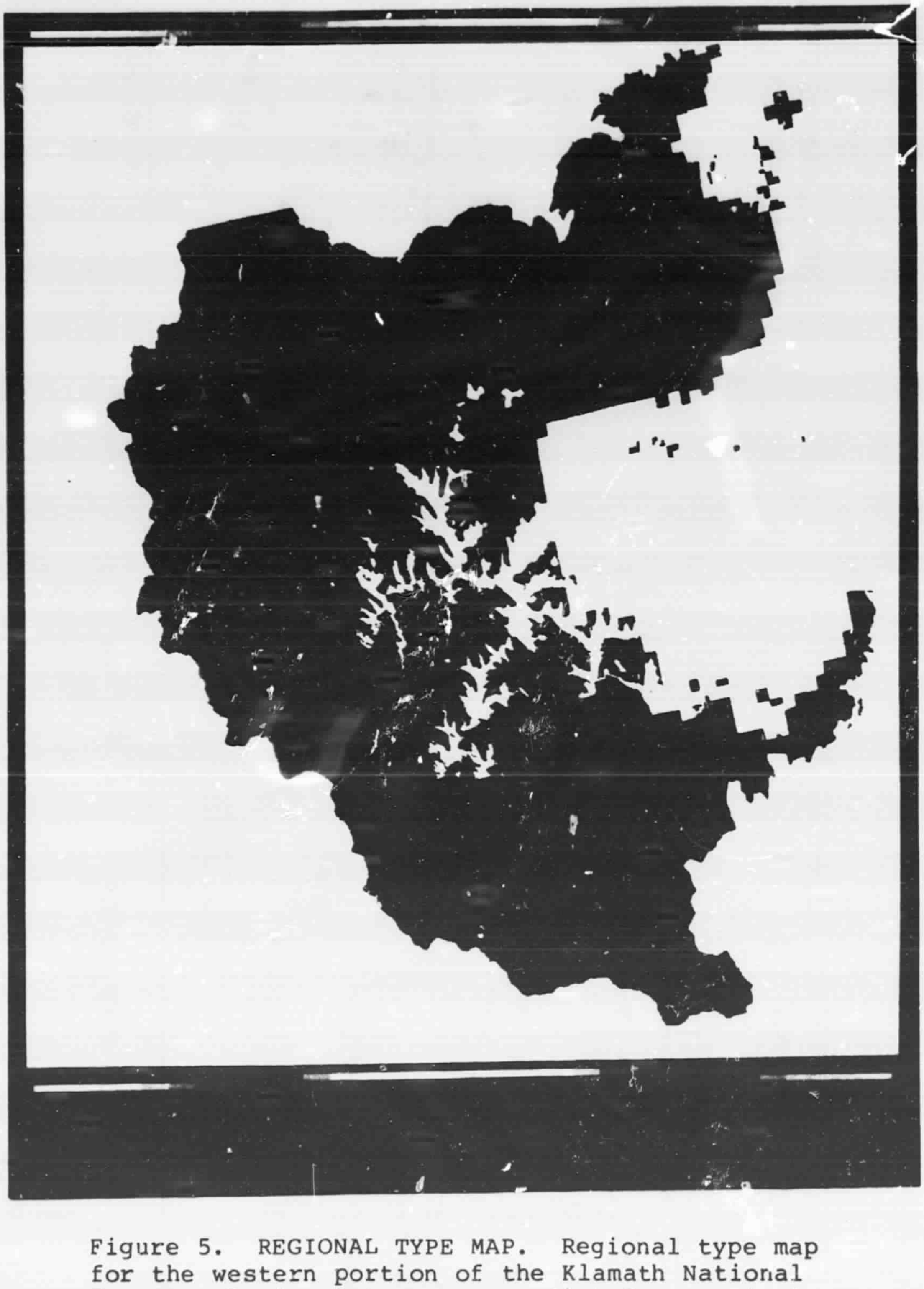


Figure 5. REGIONAL TYPE MAP. Regional type map for the western portion of the Klamath National Forest. Regional type was predicted on a pixel-by-pixel basis according to elevation-aspect ranges derived from field graphs (Figure 4).

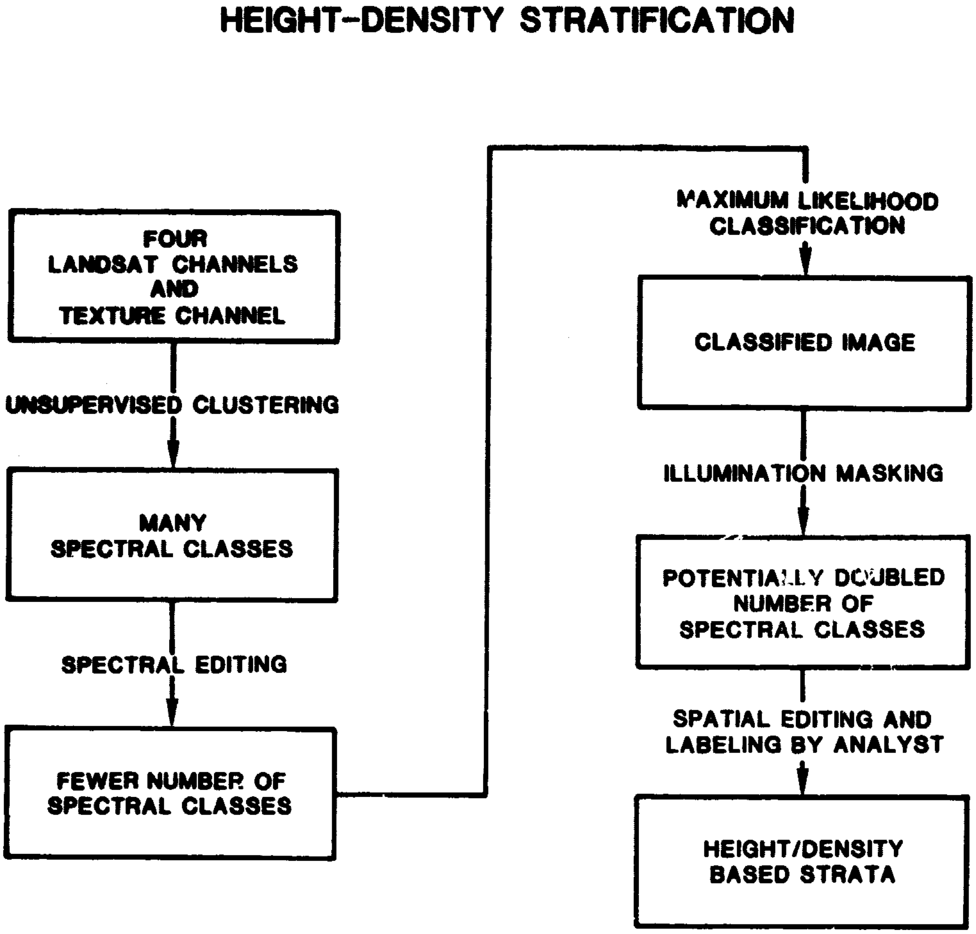


Figure 6. HEIGHT/DENSITY CLASSIFICATION. Schematic representation of individual steps in Landsat and texture classification phase of FOCIS. This phase is designed to produce tree height and density homogeneous classes.

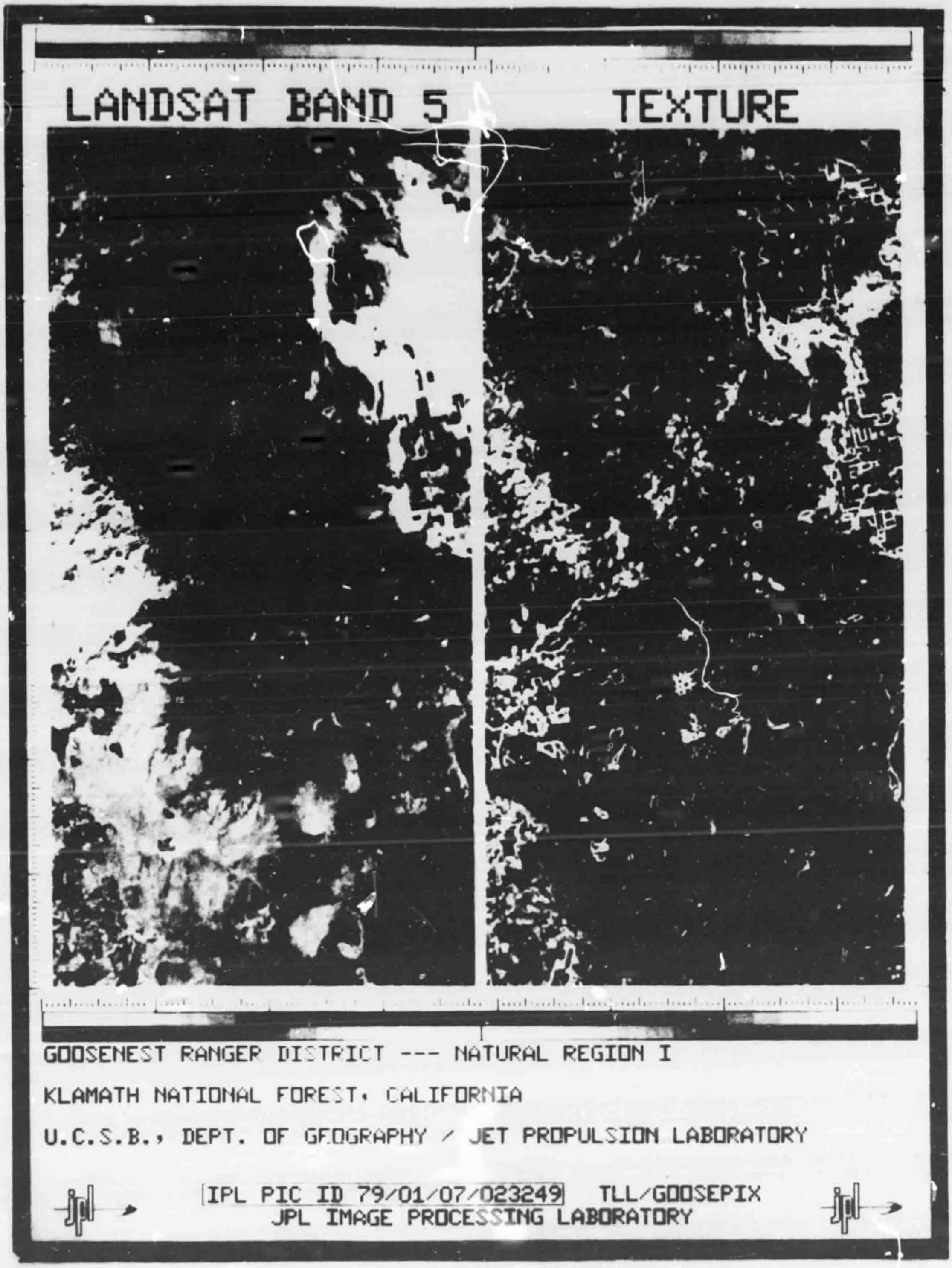


Figure 7. LANDSAT BAND 5 AND TEXTURE CHANNEL. Goosenest Ranger District Natural Region 1 showing Landsat Band 5 and the texture channel synthesized from it. Texture channel was derived by calculating the standard deviation of brightness values within a three-by-three box window passed over the Landsat data.

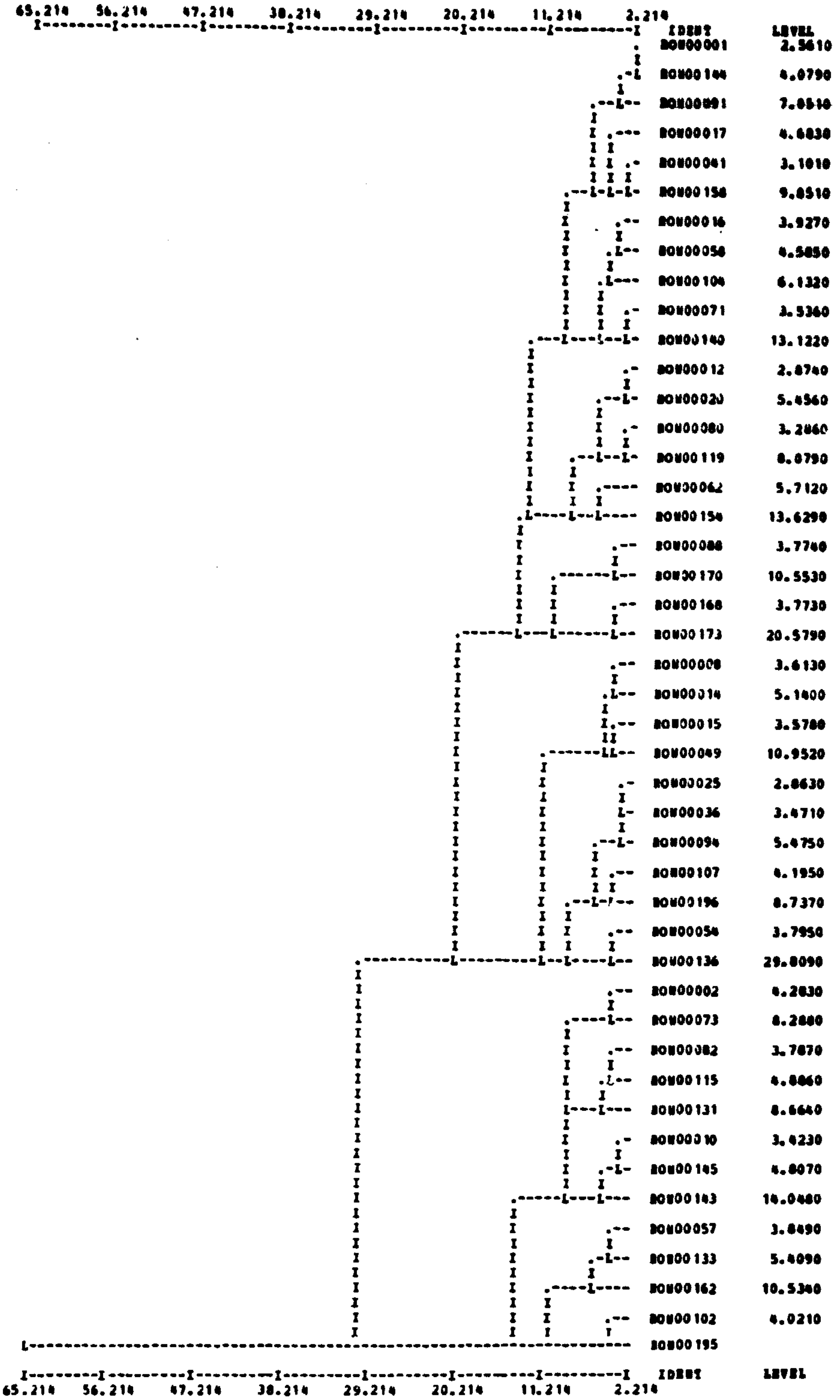


Figure 8. DENDROGRAM AND CLASS MEANS. Portion of the dendrogram produced by complete linkage clustering of 200 classes obtained by unsupervised clustering of four spectral channels and a texture channel taken from Band 5. The clustering and dendrogram were produced by the NT-SYS computer program package (Rohlf et al., 1974).

Figure 9. COSINE OF THE ZENITH ANGLE. This image displays the cosine of the angle between a normal to the slope and the sun at the time of the Landsat overpass. Bright areas correspond to slopes oriented directly toward the sun, and the darkest areas represent shadowed terrain. The image gives a strong visual impression of a landscape model illuminated from the southeast.

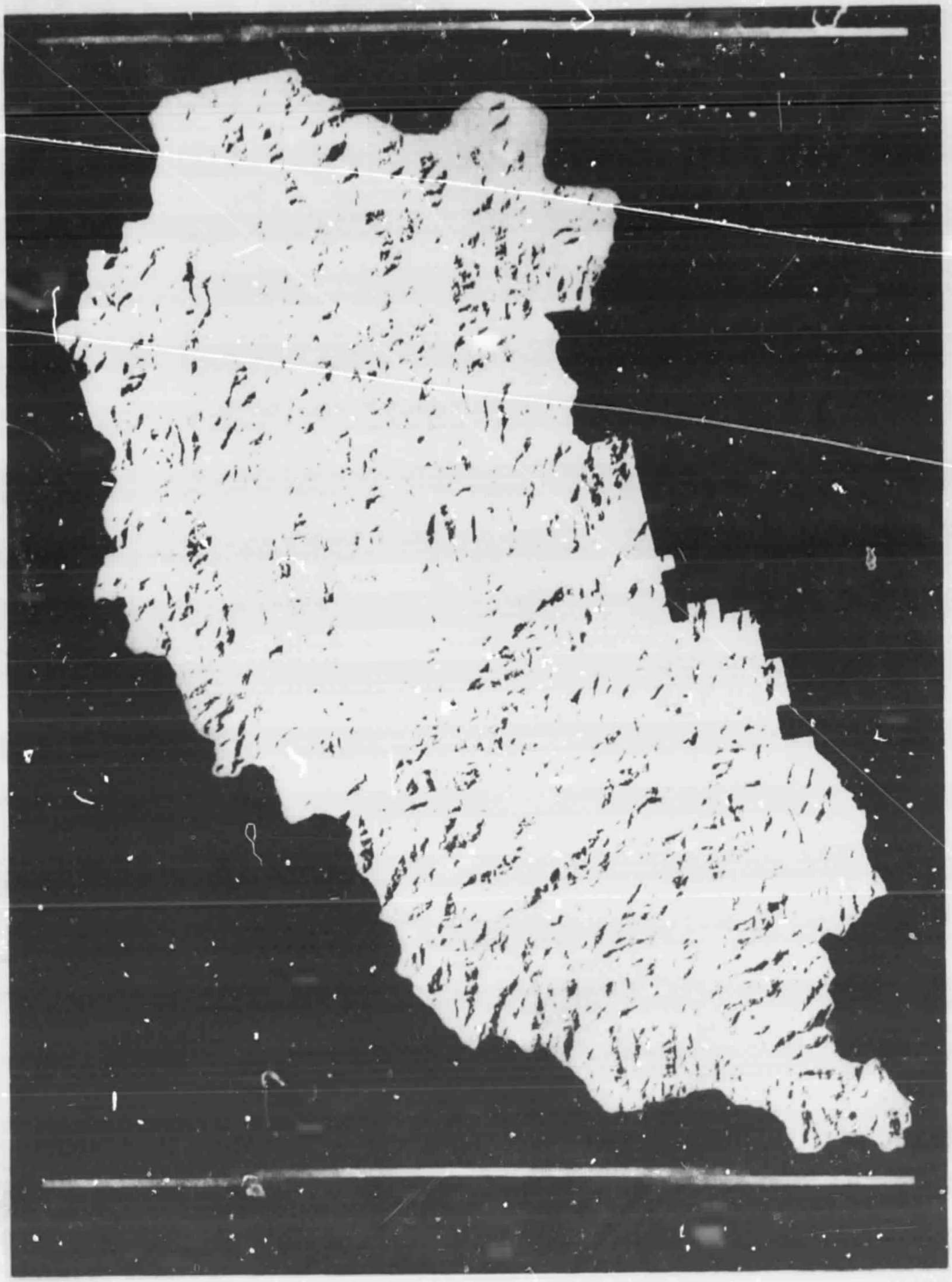


Figure 10. MASK OF THE COSINE OF THE ZENITH ANGLE. This image was used to divide the forest area into normally illuminated and poorly illuminated categories. The mask was digitally added to the classification image. Dark areas correspond to zenith angles of less than 60 degrees.

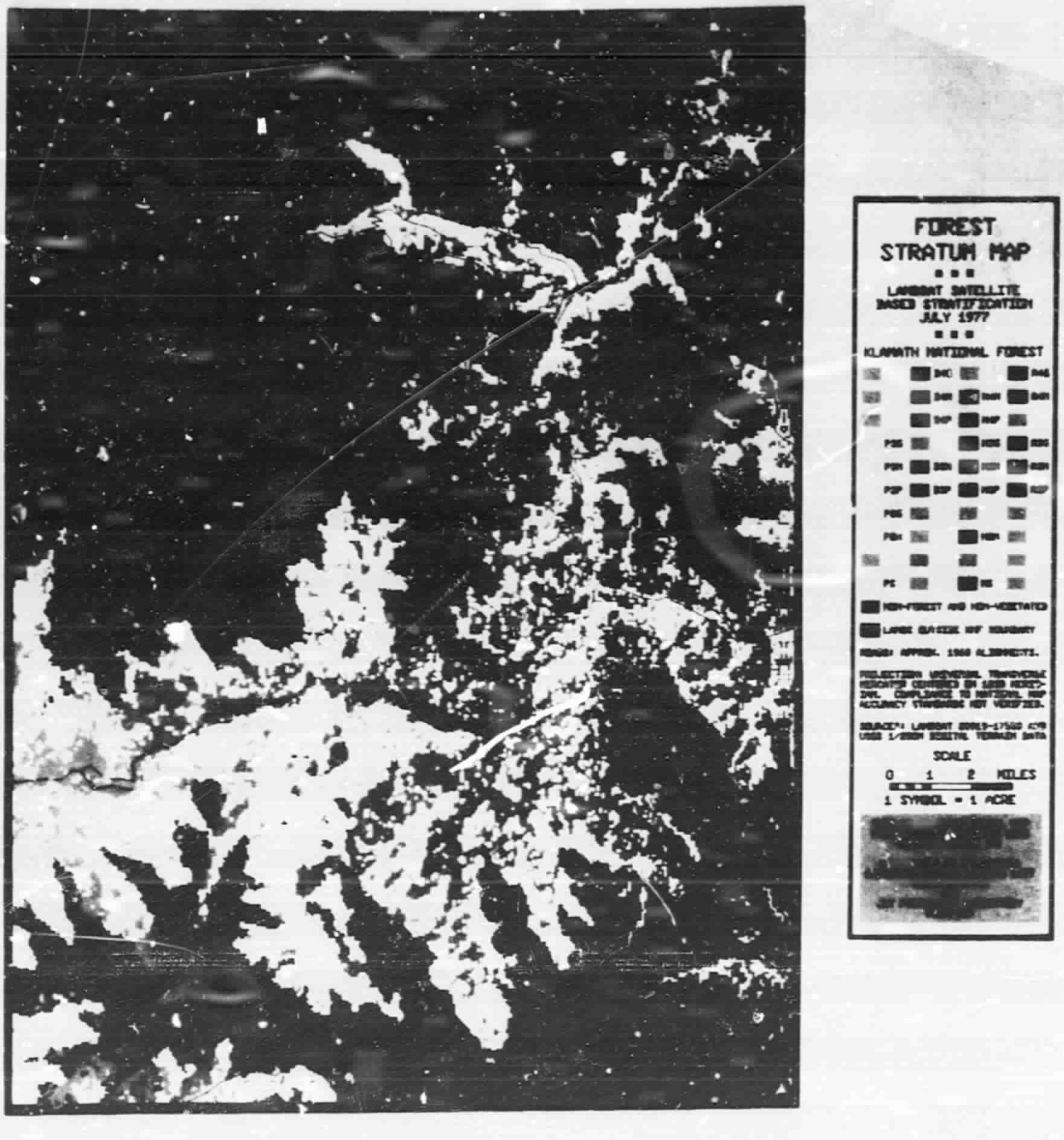


Figure 11. 15 MINUTE QUADRANGLE STRATUM MAP. One of twenty generated stratum-classification maps approximately corresponding to USGS 15 minute quadrangles. UTM projection was obtained by registering Landsat-based classification image to 1/250,000 DMA digital terrain data. Individual one-acre pixels are displayed as DN symbols, where symbol shape identifies the stratum size and density class, and foreground-background tones differentiate regional type categories. At a user working scale of 1:62,500, the symbols are easily comprehensible.

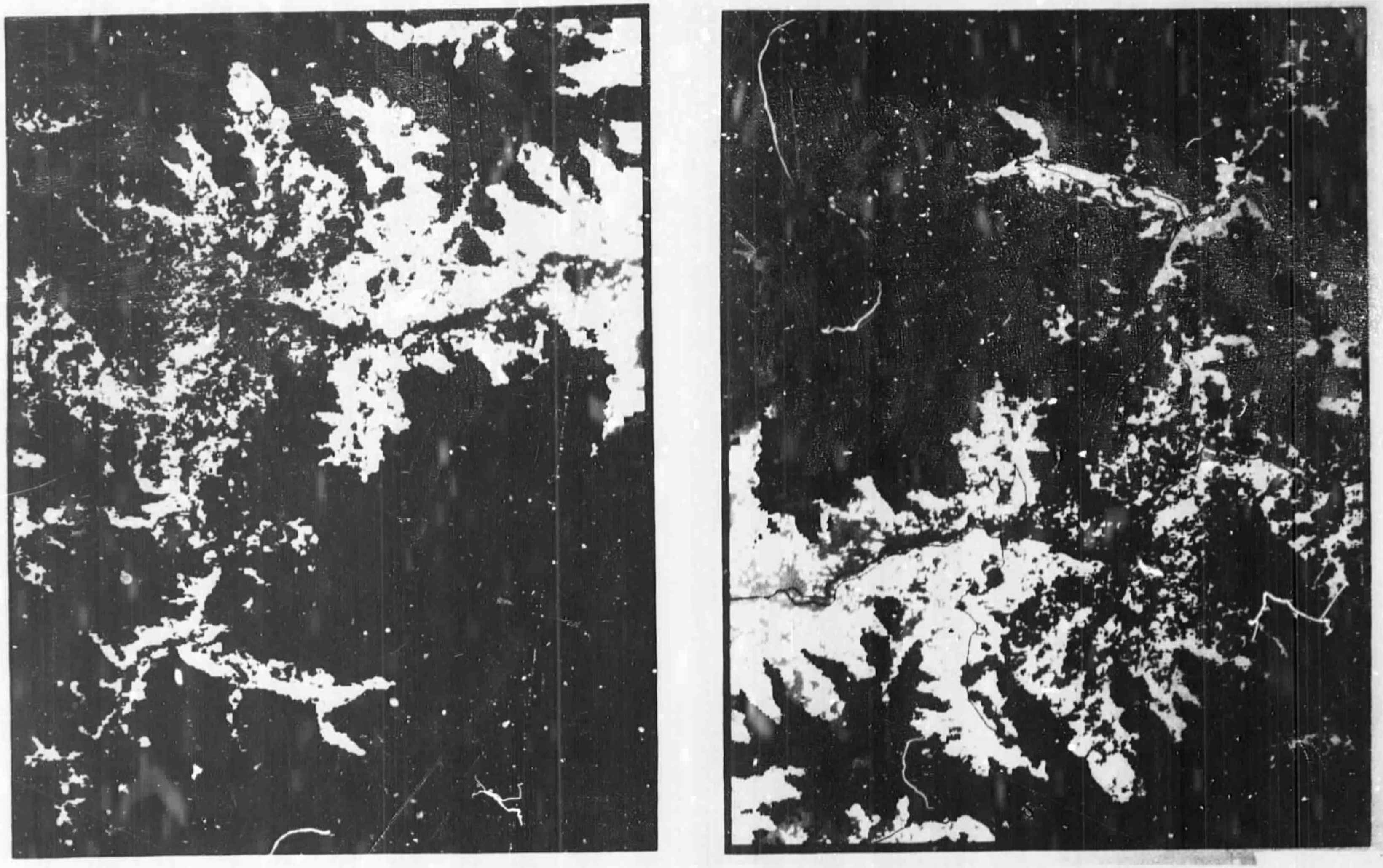


Figure 12. SYNTHETIC CLASSIFICATION STEREO PAIR. Twenty synthetic classification stereo pairs of Klamath National Forest 15 minute quadrangles were generated to provide user with spatial context of each pixel's topographic position. Artificial parallax permits 100% stereo viewing, but because of this, image cannot be viewed in stereo as they are fixed on the page.

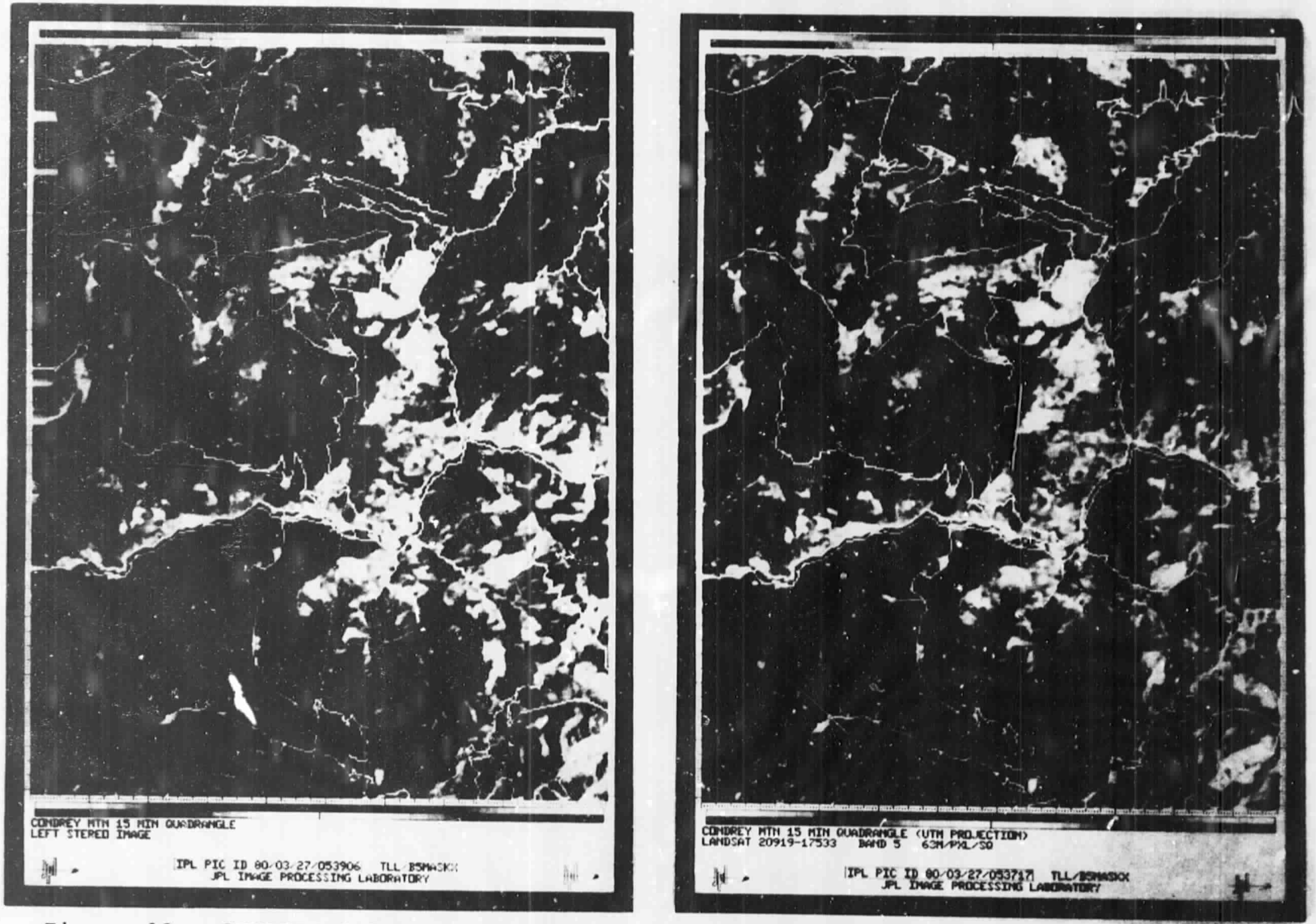
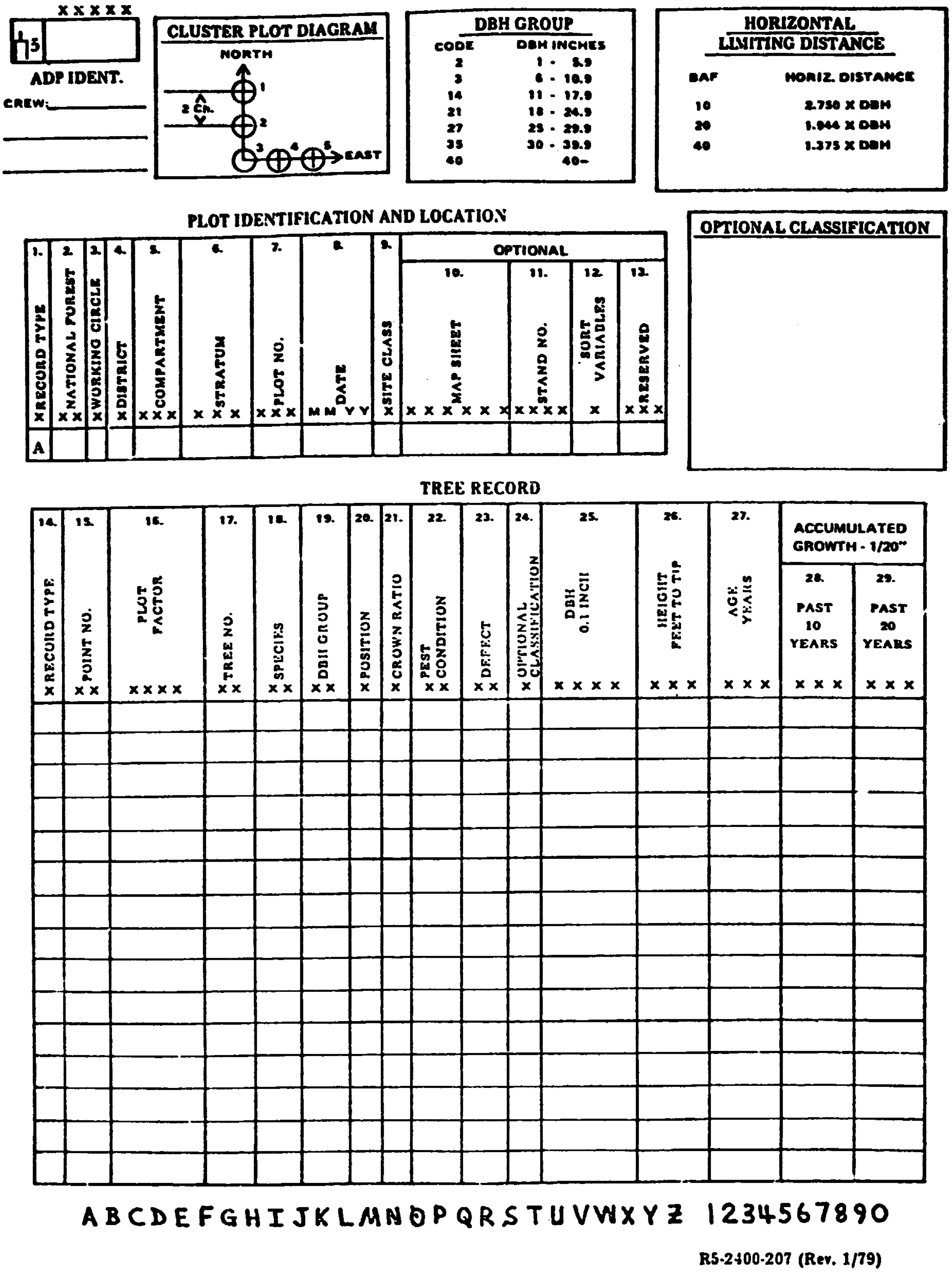


Figure 13. SYNTHETIC BAND 5 STEREO PAIR. Twenty Landsat MSS Band 5 stereo pairs were also generated for the 15 minute quadrangles of the Klamath National Forest. Artificial parallax permits 100% stereo viewing, but because of this, images cannot be viewed in stereo as they are fixed on the page.



USDA-FOREST SERVICE

CLUSTER PLOT RECORD

X X X X X

5

ADP IDENT.

CREW:

CLUSTER PLOT DIAGRAM

DBH GROUP

CODE	DBH INCHES
2	1 - 5.9
3	6 - 10.9
14	11 - 17.9
21	18 - 24.9
27	25 - 29.9
35	30 - 39.9
40	40-

HORIZONTAL LIMITING DISTANCE

BAF	HORIZ. DISTANCE
10	2.750 X DBH
20	1.944 X DBH
40	1.375 X DBH

PLOT IDENTIFICATION AND LOCATION

1.	2.	3.	4.	5.	6.	7.	8.	9.	OPTIONAL			
									10.	11.	12.	13.
RECORD TYPE	NATIONAL FOREST	WORKING CIRCLE	DISTRICT	COMPARTMENT	STRATUM	PLOT NO.	DATE	SITE CLASS	MAP SHEET	STAND NO.	SORT VARIABLES	RESERVED
X	X X	X	X	X X X	X X X	X X X	M M Y Y	X	X X X X X X	X X X X	X	X X X
A												

OPTIONAL CLASSIFICATION

TREE RECORD

14.	15.	16.	17.	18.	19.	20.	21.	22.	23.	24.	25.	26.	27.	ACCUMULATED GROWTH - 1/20"	
														28.	29.
RECORD TYPE	POINT NO.	PLOT FACTOR	TREE NO.	SPECIES	DBH GROUP	POSITION	CROWN RATIO	PEST CONDITION	DEFECT	OPTIONAL CLASSIFICATION	DBH 0.1 INCH	HEIGHT FEET TO TIP	AGE YEARS	PAST 10 YEARS	PAST 20 YEARS
X	X X	X X X X	X X	X X	X X	X	X	X X	X X	X	X X X X	X X X	X X X	X X X	X X X

ABCDEFGHIJKLMNOPQRSTUVWXYZ 1234567890

R5-2400-207 (Rev. 1/79)

Figure 14. CLUSTER PLOT RECORD. U.S. Forest Service cluster plot records were used for collecting ground samples to estimate per-acre timber volume associated with each timber stratum. A diagram of the subplot layout is shown in the upper left corner.

```
CLUSTER PLOT DATA ANALYSIS                                              1
ONE-WAY ANALYSIS OF VARIANCE

GENERAL LINEAR MODELS PROCEDURE

CLASS LEVEL INFORMATION

CLASS      LEVELS     VALUES

USFS         12       D3G D3P D4G D4P M3G M3P M4G M4P R3G R3P R4G R4P

NUMBER OF OBSERVATIONS IN DATA SET = 114

NOTE: ALL DEPENDENT VARIABLES ARE CONSISTENT WITH RESPECT TO THE
      PRESENCE OR ABSENCE OF MISSING VALUES. HOWEVER, ONLY    88
      OBSERVATIONS IN DATA SET CAN BE USED IN THIS ANALYSIS.
```

```
CLUSTER PLOT DATA ANALYSIS                                              2
ONE-WAY ANALYSIS OF VARIANCE

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: SVOL

SOURCE                   DF        SUM OF SQUARES            MEAN SQUARE

MODEL                    11        20509.17419499         1864.47038136

ERROR                    76        32343.02113609          425.56606758

CORRECTED TOTAL          87        52852.19533108

MODEL F =              4.38                            PR > F = 0.0001

R-SQUARE              C.V.                STD DEV              SVOL MEAN

0.388048           52.0824            20.62925272            39.60895227

SOURCE                   DF           TYPE I SS     F VALUE     PR > F

USFS                     11      20509.17419499        4.38     0.0001

SOURCE                   DF          TYPE IV SS     F VALUE     PR > F

USFS                     11      20509.17419499        4.38     0.0001
```

Figure 15. USFS ANOVA. Results of analysis of variance for Forest Service inventory data.

```
CLUSTER PLOT DATA ANALYSIS                                                4
ONE-WAY ANALYSIS OF VARIANCE

GENERAL LINEAR MODELS PROCEDURE

CLASS LEVEL INFORMATION

CLASS      LEVELS    VALUES

UCSB         17      D3G D3N D3P D4N D4P MS M2P M3G M3N M4G M4P PS P2G
                     P2N P3G P3N P3P


NUMBER OF OBSERVATIONS IN DATA SET = 114


NOTE: ALL DEPENDENT VARIABLES ARE CONSISTENT WITH RESPECT TO THE
      PRESENCE OR ABSENCE OF MISSING VALUES. HOWEVER, ONLY    71
      OBSERVATIONS IN DATA SET CAN BE USED IN THIS ANALYSIS.
```

```
CLUSTER PLOT DATA ANALYSIS                                                5
ONE-WAY ANALYSIS OF VARIANCE

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: SVOL

SOURCE                     DF          SUM OF SQUARES           MEAN SQUARE

MODEL                      16          21957.88954292         1372.36809643

ERROR                      54          18483.13363181          342.28025244

CORRECTED TOTAL            70          40441.02317473


MODEL F =                4.01                               PR > F = 0.0001


R-SQUARE                 C.V.                 STD DEV             SVOL MEAN

0.542961              48.2064             18.50081762           38.37838028


SOURCE                     DF             TYPE I SS     F VALUE    PR > F

UCSB                       16        21957.88954292        4.01    0.0001


SOURCE                     DF            TYPE IV SS     F VALUE    PR > F

UCSB                       16        21957.88954292        4.01    0.0001
```

Figure 16. UCSB ANOVA. Results of analysis of variance for UCSB inventory data.

Table 1 - UCSB FINAL STRATA--WESTERN PORTION. List of UCSB Final Strata, Western Portion, Klamath National Forest.

Red Fir Type

R4G
R4N
R3G
R3N
R3P

Mixed Conifer Type

M4N
M3G
M3N
M4P
M3P
M2N
MS

Douglas Fir Type

D4G
D4N
D3N
D4P
D3P

Ponderosa Pine Type

P3G
P3N
P2G
P3P
P2N
PS

```
CLUSTER PLOT DATA ANALYSIS                                                4
ONE-WAY ANALYSIS OF VARIANCE

GENERAL LINEAR MODELS PROCEDURE

CLASS LEVEL INFORMATION

CLASS     LEVELS    VALUES

UCSB        17      D3G D3N D3P D4N D4P MS M2P M3G M3N M4G M4P PS P2G
                    P2N P3G P3N P3P


NUMBER OF OBSERVATIONS IN DATA SET = 114


NOTE: ALL DEPENDENT VARIABLES ARE CONSISTENT WITH RESPECT TO THE
      PRESENCE OR ABSENCE OF MISSING VALUES. HOWEVER, ONLY    71
      OBSERVATIONS IN DATA SET CAN BE USED IN THIS ANALYSIS.
```

```
CLUSTER PLOT DATA ANALYSIS                                                5
ONE-WAY ANALYSIS OF VARIANCE

GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: SVOL

SOURCE                  DF       SUM OF SQUARES            MEAN SQUARE

MODEL                   16       21957.88954292          1372.36809643

ERROR                   54       18483.13363181           342.28025244

CORRECTED TOTAL         70       40441.02317473


MODEL F =             4.01                              PR > F = 0.0001


R-SQUARE              C.V.              STD DEV              SVOL MEAN

0.542961           48.2064          18.50081762            38.37838028


SOURCE                  DF          TYPE I SS       F VALUE     PR > F

UCSB                    16       21957.88954292        4.01     0.0001


SOURCE                  DF         TYPE IV SS       F VALUE     PR > F

UCSB                    16       21957.88954292        4.01     0.0001
```

Figure 16. UCSB ANOVA. Results of analysis of variance for UCSB inventory data.

Table 1 - UCSB FINAL STRATA--WESTERN PORTION. List of UCSB Final Strata, Western Portion, Klamath National Forest.

Red Fir Type

R4G
R4N
R3G
R3N
R3P

Mixed Conifer Type

M4N
M3G
M3N
M4P
M3P
M2N
MS

Douglas Fir Type

D4G
D4N
D3N
D4P
D3P

Ponderosa Pine Type

P3G
P3N
P2G
P3P
P2N
PS

Table 2 - TIMBER INVENTORY TABULATIONS. Timber inventory tabulations quantifying stratum map statistics were derived for each 15-minute quadrangle. "MAPPED AREA" differs from "STRATUM" category in that it presents/ pixel counts after smoothing of map to reduce "speckling." "OUTS BDY" = Outside Klamath National Forest Boundary. "NONFORST" = Non-vegetated or non-forest areas within forest boundary.

Condrey Mtn 15 Minute Quadrangle
Klamath National Forest Stratum Tabulation Acreages

	Stratum		Mapped	Elevation Zones							Slope Zones (Degrees)				Aspect Quadrants				
	Area	Prcnt	Area	500-2000	2000-3000	3000-4000	4000-5000	5000-6000	6000-7000	7000-9000	0-6	6-19	19-35	35+	Flat	NE	SE	SW	NW
OUTS BDY	9284	6.53	9284	0	0	982	2698	3872	1732	0	893	3648	4494	249	927	2244	988	1613	3512
NONFORST	55433	39.00	53180	3685	15780	17046	10711	5004	3207	0	9759	27063	17553	1058	7503	13336	18977	11036	4851
R4G	0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R4N	29	0.02	27	0	0	0	0	9	20	0	0	23	6	0	3	2	0	21	3
R3G	6	0.00	5	0	0	0	0	2	4	0	3	2	1	0	2	0	0	4	0
R3N	251	0.18	237	0	0	0	0	37	214	0	36	153	55	7	16	14	36	167	18
R3P	852	0.60	959	0	0	0	0	71	781	0	115	577	166	14	84	120	268	307	73
M4N	1773	1.25	1666	0	46	544	522	660	1	0	128	1040	576	29	102	198	357	726	390
M3G	6010	4.23	6095	0	256	2287	1978	1364	125	0	470	2769	2614	157	377	755	1741	1961	1176
M3N	6730	4.74	6465	0	359	2808	2315	1243	13	0	545	2775	3165	253	466	809	1367	2573	1523
M4P	1397	0.98	1138	0	79	603	472	239	4	0	132	682	553	30	101	163	442	527	164
M3P	13510	9.50	15105	0	942	5434	4772	2331	31	0	1251	6488	5411	360	997	1558	3756	5199	2180
M2N	9760	6.87	9500	0	704	3999	3186	1435	436	0	898	4856	3789	217	673	1186	2962	3474	1465
MS	9842	6.92	10389	0	555	3562	3714	1434	577	0	842	5063	3724	213	631	1860	3910	2498	943
D4G	0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D4N	0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D3N	0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D4P	0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D3P	0	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P3G	1495	1.05	1621	25	879	590	1	0	0	0	229	493	722	51	288	293	22	124	768
P3N	2894	2.04	2633	125	1616	1152	1	0	0	0	517	1009	1280	88	510	1009	322	282	771
P2G	2506	1.76	2287	86	1487	933	0	0	0	0	425	1045	977	59	478	804	311	232	683
P3P	8013	5.64	9019	578	4900	2533	2	0	0	0	1751	3389	2701	172	1818	2504	799	1100	1792
P2M	5543	3.97	5537	369	3472	1801	1	0	0	0	1097	2589	1857	100	984	1868	1322	670	799
PS	6700	4.71	6989	609	3850	2240	1	0	0	0	1178	3040	2326	156	1004	2420	1892	754	630
	142136		142136	5477	34925	46514	30374	17701	7145	0	20269	66684	51970	3213	16962	31143	39292	33268	21471

Table 3 - STRATA SAMPLE SIZE. Total sample size for each UCSB stratum is shown, indicating the number of samples collected by both UCSB and USFS.

	Sample Size		
STRATUM	UCSB	USFS	TOTAL
D3G	1	3	4
D3N	0	4	4
D3P	0	4	4
D4N	0	11	11
D4P	0	3	3
MS	0	4	4
M2P	3	1	4
M3G	2	2	4
M3N	1	3	4
M4G	2	2	4
M4P	0	2	2
PS	1	3	4
P2G	3	0	3
P2N	2	2	4
P3G	3	1	4
P3N	4	0	4
P3P	4	0	4
TOTAL	26	45	71

Table 4 - USFS FINAL STRATA--WESTERN PORTION. List of final strata used by the Forest Service, western portion, Klamath National Forest.

Red Fir Type	Mixed Conifer Type
R46	M4G
R4P	M4P
R3G	M3G
R3P	M3P

Douglas Fir Type
D4G
D4P
D3G
D3P

Table 5 - CROSS TABULATIONS. Cross tabulations of Forest Service and Landsat-based stratum labels.

FOREST SERVICE STRATA	UCSB STRATA														
	D3G	D3N	D3P	D4N	D4P	MS	M2P	M3G	M3N	M4G	M4P	PS	P2N	P3G	TOTAL
D3G	0	0	0	3	0	0	0	0	0	0	0	0	0	0	3
D3P	1	0	3	3	0	0	0	0	0	0	0	0	0	0	7
D4G	0	2	1	3	1	0	0	0	0	0	0	0	0	0	7
D4P	0	2	0	1	1	1	0	0	0	0	0	0	0	0	5
M3G	0	0	0	0	0	0	0	1	0	1	1	1	0	0	3
M3P	0	0	0	0	0	0	0	0	1	0	0	1	0	0	4
M4G	2	0	0	1	0	1	1	1	0	1	1	0	2	0	9
M4P	0	0	0	0	1	1	0	0	1	0	0	1	0	1	4
R3G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R3P	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2
R4G	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R4P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
TOTALS	3	4	4	11	3	4	1	2	1	2	2	3	2	1	45

Table 6 - WEST KLAMATH USFS STRATUM STATISTICS.
Listing of Forest Service stratum statistics, showing mean timber volume and variance for each stratum. Units are in hundreds of cubic feet per acre.

STRATUM	MEAN	VARIANCE	NUMBER OF PLOTS
D3G	60.9505	562.127	8
D3P	19.8846	60.244	8
D4G	53.1217	593.308	12
D4P	26.1846	118.207	9
M3G	26.4898	435.473	6
M3P	13.1358	58.190	6
M4G	52.0731	568.643	10
M4P	33.4496	253.936	7
R3G	47.7531	252.713	7
R3P	24.9327	657.775	4
R4G	54.5239	662.701	7
R4P	39.3685	1312.953	4

Table 7 - WEST KLAMATH UCSB STRATUM STATISTICS.
Listing of UCSB stratum statistics, showing mean timber volume and variance for each stratum. Units are hundreds of cubic feet per acre. Areas for each stratum in acres are also shown.

STRATUM	MEAN	VARIANCE	NUMBER OF PLOTS	AREA
D3G	56.8805	664.489	4	25771
D3N	38.7392	517.942	4	25127
D3P	20.9490	121.511	4	26663
D4N	40.4195	325.578	11	81797
D4P	33.3743	778.072	3	48451
MS	27.7532	479.792	4	127403
M2P	19.8062	117.354	4	22679
M3G	40.2462	657.136	4	87005
M3N	41.9012	703.558	4	100800
M4G	39.0922	477.769	4	121200
M4P	62.5805	0.324	2	174685
PS	21.9700	338.396	4	14862
P2G	44.1053	87.030	3	5629
P2N	18.8155	78.462	4	10768
P3G	54.1432	190.126	4	4068
P3N	35.2130	138.379	4	8548
P3P	15.1530	14.028	4	20277
R3G *	47.7500	252.610	7	18060
R3P *	24.9300	657.922	4	14155
R4G *	54.5200	662.548	7	6915

* Red for values taken from USFS data, as explained in text Section 5.3.

Table 8 - WEST KLAMATH UCSB INVENTORY.
Timber volumes by strata for western portion,
Klamath National Forest Units.

STRATUM	MEAN VOLUME	STANDARD ERROR	NUMBER OF PLOTS	AREA	STRATUM VOLUME	STANDARD ERROR
D3G	56.88[1]	25.778[1]	4	25,771[2]	1,465,855[3]	332,162[3]
D3N	38.74	22.758	4	25,127	973,420	285,920
D3P	20.95	11.023	4	26,663	558,590	146,953
D4N	40.42	18.044	11	81,797	3,306,235	445,015
D4P	33.37	27.894	3	48,451	1,616,810	780,284
MS	27.75	21.904	4	127,403	3,535,433	1,395,317
M2P	19.81	10.833	4	22,679	449,271	122,841
M3G	40.25	25.635	4	87,005	3,501,951	1,115,187
M3N	41.90	26.525	4	100,800	4,223,520	1,366,860
M4G	89.09	21.858	4	121,220	10,799,430	1,324,813
M4P	62.58	0.569	2	174,685	10,931,787	70,283
PS	21.97	18.396	4	14,862	326,518	136,701
P2G	44.11	9.329	3	5,629	248,295	30,318
P2N	18.82	8.858	4	10,768	202,654	47,691
P3G	54.14	13.789	4	4,068	220,242	28,047
P3N	35.21	11.763	4	8,548	300,975	50,275
P3P	15.15	3.745	4	20,277	307,197	37,969
R3G	47.75	15.900	7	18,060	862,365	108,534
R3P	24.93	25.650	4	14,155	352,844	181,538
R4G	54.52	25.740	7	6,915	377,006	67,275
TOTALS			89	944,883	44,561,143	2,801,326

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[1] Units are hundreds of cubic feet per acre.

[2] Units are acres.

[3] Units are hundreds of cubic feet.

Table 9 - UCSB FINAL STRATA--GOOSENEST PORTION. A list of the final strata for the Goosenest Ranger District. Strata were created using the first year's stratification techniques. Ponderosa Pine strata occurred only in Natural Region 2; Mixed Conifer strata occurred in both Natural Regions.

Mixed Conifer Type	Ponderosa Pine Type
M4G	P4P
M4N	P3G
M3G	P3P
M3N	P2G
M3P	P2N
M2G	P2P
M6	PS
MS	