CHAPTER 11

Forestry

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11.1 INTRODUCTION

Foresters and other resource managers have used aerial photographs to help manage resources since the late 1920s. As discussed in chapter 1, however, it was not until the mid-1940s that their use became common.

Obtaining photographic coverage was always a problem. For many areas of the world, reasonably complete coverage did not exist until after World War II. In addition, aerial photographs were generally not used stereoscopically for forest applications or as bases for sampling frames until the 1950s although field application of stereoscopic techniques often preceded formal documentation by ten to fifteen years.

After World War II, aerial photography was incorporated into the development of forest type maps, using the various plotters that had been used for military applications during the war. Initially, these type maps were often considered only as an ancillary management tool and were seldom used for broad-scale forest surveys.

One early use of aerial photographs in forestry was to classify forest stands by attributes such as land classification (Aldrich, 1953), forest types (Sandor, 1955), and stand volume (Aldrich and Norick, 1969). Timber stratification (Bickford, 1961; Moessner, 1963) and crown closure (Moessner, 1949) were important attributes used in estimating stand volumes.

Aerial photographic interpretation guides (e.g., Avery, 1957) and training kits (e.g., Moessner, 1960) emerged for teaching new forest photointerpreters skills in forest management and inventories. Some of the more sophisticated skills included parallax displacement applications, such as the measurement of gradient (Moessner and Choate, 1964) and tree heights linked to aerial stand volume tables which provided estimates of stand volumes (Moessner, 1957; Allison and Breadon, 1960; Pope, 1961; Haack, 1963). Special studies of the use of low-oblique aerial photographs for forest inventories were also conducted (Anderson, 1956).

This chapter reviews photographic interpretation in forestry, building on material presented in the background and basic chapters, especially chapter 5. After a brief look at the types of space and aerial photography that have been and are being employed in forestry, the discussion addresses forest classification, including type, species, size, and density; factors in stand delineation and mapping; and a variety of applications, including forest inventory, insect and disease damage assessment, recreation, roads and trails, regeneration surveys, ecosystem classification, and urban forestry.

11.2 FOREST RESOURCE PHOTOGRAPHY

Photography from both spacecraft and aircraft has been used in forestry applications.

11.2.1 Space Photography

Taking photographs from space is very much like taking photographs from aircraft. The photographs are acquired as a spacecraft travels along an orbit path, and cameras are operated with or without astronaut assistance. Cameras are basically the same as aerial cameras except they are specially designed for operation in the hostile environment of space. Other photographs of potential use to forest managers are taken more or less through the window of the spacecraft. Cameras used for hand-held photography are basically the same as professional cameras used on earth.

Panchromatic, color, black-and-white infrared (BWIR), and color-infrared (CIR) films have all been used. The optical characteristics of spacecraft windows limit the spectral sensitivity of films in hand-held cameras. Aerial cameras and cameras specially designed for use in space are equipped with optics that permit the recording of a wide range of spectral information with more types of film.

Space photography does have some unique qualities. The most often cited is that the extensive coverage gives users a broad regional view that is not available with large-scale photography. Both low and high oblique views and some stereoscopic views are available in current archives (app. B). Researchers have used space photographs to observe and evaluate broad patterns of vegetation, soils, and geologic features. Many regional patterns and vegetation associations that were once studied only through labor-intensive ground surveys are clearly visible. The synoptic view provided has also been used as a basis for planning extensive aerial projects for standard aerial photography flights.

Photographs of remote, undeveloped, and uninhabited areas of earth can be used to make initial studies of the extent of forest lands. The first photographs of some lands in South America, Asia, and Africa were taken from space. Photographs also have the unique quality of storing an extremely large volume of data in a relatively small space.

In spite of the limits of resolution and availability, some technical forestry work has been done with space photography. In 1971, Colwell used 70-mm photographs taken by Apollo 9 astronauts to study the utility of space photography in resource assessment. Langley (1969) addressed the need for frequent, broad area forest surveys and developed a multistage variable probability sampling design based on space photography. This was successfully applied to an inventory problem in the lower Mississippi valley.

Later, in 1978, Colwell et al. reported their efforts to classify forest lands with photographs from Skylab cameras. They used both transparencies and digitized photographs and found that successful classification depended upon the quality of the photography, time of exposure, and spectral sensitivity. Geometrically correct photographs, such as those acquired during the Skylab mission and the Shuttle Large Format Camera Experiment (app. B), can be used to accurately register data from other sensors.

Space photographs are as usable as aerial photographs in that they can be digitized and analyzed in an image processing system or a geographic information system (GIS). They may be examined monoscopically or stereoscopically or with zoom transfer scopes. It is difficult, however, to fit photographs from the Large Format Camera in stereoplotters. Another drawback is that users have no access to original negatives or transparencies. Because of their uniqueness, these products are normally stored in secure, limited access areas and only second or higher generation duplicates or prints are available to users.

11.2.2 Aerial Photography

Aerial photography remains the imagery of choice for forest management purposes because of its adaptability, stereoscopic view, and ground resolution. Present technology offers the forester a broad array of options in specifying coverage. The choice is often a compromise dictated by image quality requirements, format and scale needs, availability of photographic and interpretation equipment, and cost. When photographs of suitable date, scale, and film characteristics are available from stock, one should always consider purchasing existing coverage in lieu of obtaining new coverage. Refer to appendixes B and C.

11.2.2.1 Cameras, Formats, Films, and Filters

Although photography is discussed in chapter 2 and in many other sources, certain elements are highlighted here for their special significance to forest applications. Virtually any camera is potentially an aerial camera, and any film format can be adapted to aerial use. But most practical applications require that an aerial camera be reasonably portable and mountable, capable of taking a series of exposures in rapid succession, and compatible with a range of films. For most users, these factors narrow the choice of camera to three standard formats: 23 cm x 23 cm film; midformat of 70-mm, 120-mm, or 220-mm film; and small-format, 35-mm film. Choice of format for a given project affects more than the dimensions of first-generation products; it affects the entire design and conduct of aerial operations and their cost.

23 cm x 23 cm format: After 50 years, the term traditional can fairly be applied to the 23 cm x 23 cm format in forestry use. It offers the best resolution for a given ground coverage per frame, or alternatively, the broadest coverage per frame at a given scale. On the other hand, the forestry end-user rarely makes severe photogrammetric demands, and the geometric precision of the 23 cm x 23 cm cartographic quality camera may be wasted, particularly if the need is for contact prints.

Midformats: Midformat cameras include those that accept perforated 70-mm roll film and those that require unperforated 120-mm or 220-mm film. This includes a diverse assortment of cameras, ranging from the few metric models designed for high-precision photogrammetry to the far more numerous cameras intended for general photography. The three major format sizes for cameras in this class are 6 cm x 4.5 cm (actually 41 mm x 56 mm), 6 cm x 6 cm (56 mm x 56 mm) and 6 cm x 7 cm (56 mm x 69 mm). Most cameras are designed around a single format, but a few can switch formats by changing film magazines. Unlike 23 cm x 23 cm cameras, most in this class incorporate reflex viewfinders and are designed to accept an assortment of variable-focus lenses.

The 23 cm x 23 cm cameras are usually employed to acquire general multipurpose forestry coverage, while the midformat cameras might be used to obtain supplementary photographs of particular locations for special applications. Their suitability in this role is enhanced by their small size and light weight (under 2 kg in the lightest models), which translate into modest platform requirements. These factors have induced many foresters to acquire their own midformat equipment and adapt it to available light aircraft.

35-mm format: Even more than the midformats, the ubiquitous 35-mm camera has become the choice of foresters who wish to take their own supplementary aerial photographs at low cost and with rapid turnaround time. The 35-mm format redoubles both the advantages and disadvantages of the midformats. Cameras, lenses, filters, films, and processing are available virtually everywhere in profuse variety. Automatic exposure control and film handling have reduced the need for skill and experience in the photographer. The explosion of 35-mm technology in the consumer market has placed within easy reach an array of lenses, shutter and aperture mechanisms, and camera-control electronics equal in technical excellence to those found in the vastly more expensive 23 cm x 23 cm systems. On the other hand, the 36 mm x 24 mm image is even more limited than the midformats in its area of coverage at equivalent scale, having only 1/60 the image area of a 23 cm x 23 cm frame and only a third the area of the smallest midformat.

A significant operational difference between midformat and 35-mm photography is that the latter is not well adapted to direct interpretation in transparency form. Individual frames are too small for annotation, and the most practical camera orientation—long axis of the frame at right angles to aircraft track—puts them in the wrong relationship for direct stereoscopic viewing. Thus interpretation is rarely performed at contact scale. The fact that 35-mm transparencies can be projected for interpretation using standard slide projection equipment compensates for this to some extent; but where stereoscopic inspection is desired, enlargement is the rule, and the enlargement ratio assumes a major role in project planning. Another consideration is that enlargements increase any poor qualities of the transparencies such as lens distortion and graininess.

Film and filter selection for forest resource assessment: The principal kinds of film used in forestry aerial photography are (1) black-and-white panchromatic negative, (2) BWIR negative, (3) normal-color negative, (4) normal-color reversal, and (5) CIR reversal.

Panchromatic films are employed by foresters when high spatial resolution is needed and when no useful purpose is served by capturing color differences or recording extravisual light. These are the usual films chosen for stereoplotting and general mapping.

BWIR film is used in forestry to exploit the high infrared reflectance of foliage and the differences in infrared reflectance among tree species groups. When photographed with appropriate filters on BWIR film, coniferous trees appear in appreciably darker tones than deciduous trees. This contrast is the major benefit foresters derive from BWIR photography and explains why it is favored in areas, such as the Great Lakes region of the United States and Canada, where both conifers and hardwoods are commercially important in natural stands. BWIR film also tends to yield a wider range of contrasts than panchromatic within the two major species groups, though these are less pronounced and less reliably captured. Although the conifer/hardwood distinction is emphasized in BWIR photography, spatial resolution and the tonal gradations tend to be reduced, together with shadow penetration, because visible wavelengths are filtered out. Largely for this reason foresters have favored modified infrared photography, taken with a yellow (minus-blue) filter and thus recording green and red as well as infrared reflectance differences.

Normal-color negative film has obvious advantages over panchromatic and BWIR films in damage surveys and other applications where color differentiation is essential. It does not usually lend itself well to cover type discrimination, except at very large scales or in the brief seasons of distinctive leaf coloration.

The interpreter of a normal-color reversal transparency views the original image and so obtains better resolution than the interpreter viewing a contact print. Color fidelity and range of transparencies are also superior to those of prints. Hence for applications in which numerous reprints are not required (e.g., damage survey), reversal film is often preferable.

CIR reversal (positive transparency) film, because of its haze penetration at medium and high altitudes and because of its ability to detect stressed vegetation, has found a great deal of use in forest damage surveys. Against its advantages must be set its poor shadow penetration and the difficulty of obtaining proper exposure under any overcast conditions. While it is generally superior to normal-color film for cover type discrimination, in summer BWIR is its equal in this respect.

11.2.2.2 Time of Photography

Aerial photographs can be acquired under any daylight conditions on virtually any day of the year, but their value to foresters for a given project may depend strongly on choice of hour, date, and season.

Hour: In most vertical photography projects, the hour is chosen to keep shadowing at a serviceable minimum and the sun at a moderately high angle, usually greater than 30°. There are several reasons for this:

- Shadows directly impede interpretation. Illumination in shadow is heavily dependent on short-wavelength scattered light, which is effectively blocked by the filters used in most aerial photography. In steep terrain, shadows may obscure large areas at sun angles below 45°.

- Shadows create differential illumination effects. An interpreter viewing a wide-angle vertical photograph taken at low sun elevation sees only the shadowed side of the trees in the up-sun end of the photograph, and only the illuminated side in the down-sun end. Forest stands of the same type may differ radically in appearance merely because of their position in the frame (see chap. 5, sec. 5.8).

- Available light for photography varies with sun angle. Solar illumination is roughly proportional to the cosine of the sun's angle measured from the vertical. When the sun is low in the sky, too little light may be available for some kinds of photography, e.g., low-altitude color reversal photography, in which a comparatively slow film must be given very brief exposure to avoid image blur.

High sun angles can also cause problems, particularly when wide-angle lenses are used in vertical photography. If the angle of the sun from the vertical is less than half the angular field-of-view of the camera along the sun's azimuth, then the shadow of the aircraft lies within the field of view. At most scales the shadow itself is invisible, but surrounding it is a "hotspot" or shadowless area, noticeably brighter (on a positive product) than similar areas nearby (see chap. 5, sec. 5.5.3). The hotspot may compound any vignetting effect caused by the camera's internal geometry; the combination can be difficult to compensate for, even with automatic-dodging printing equipment, and can be a serious distraction.

Date: Within a desired season, choice of date for an aerial photography mission depends mainly on suitable weather. The limits imposed by weather vary with the kind of photography being attempted. Aerial photographers' clear-day maps, such as those published in the *Manual of Color Aerial Photography* (Smith, 1968), serve as guides to planners of large-area projects requiring clear weather. They show the average number of clear days to be expected each month across broad geographic regions.

Clear weather is required for infrared photography—except for plotwise projects in which clouded areas may be selectively avoided—largely because of the difficulty of gauging proper exposure in cloud shadow. Exposure for infrared-sensitive films is usually calculated in advance (with the Aerial Exposure Computer or similar device) on the assumption of full sunlight. Commonly available light meters are designed to filter out infrared light; they cannot be relied on to give correct exposure for infrared-sensitive films.

Normal-color and panchromatic films can be used under overcast conditions if enough light is available for proper exposure and a meter is on hand. Photographs taken under overcast are sometimes termed shadowless photographs. Viewed stereoscopically, they allow the interpreter to look through the overstory to ground level. Shadowless photography is particularly useful in assessment of blowdown.

Season: All seasons, except those of continuous rain, offer some aerial photographic opportunities to some foresters. In most parts of the world, summer is the most permissive season for general-purpose photography: foliage is fully developed and relatively stable during an extended period of clement weather. Where summer brings long periods of clear sky and low humidity, as in the western United States, seasonal constraints practically vanish for general-coverage photography. In less favored regions, such as New England, an entire summer may be too short a time for completion of extensive coverage. Summer affords a high degree of year-to-year comparability: one summer's photographs look very much like another summer's, and perturbations stand out clearly when two sets are compared.

In the temperate and boreal zones, winter photography has its uses. In snowless areas, leaf-off photography for photogrammetric work and survey line location can be carried on all winter, whereas in colder climates it is often confined to a few weeks in spring or fall. In snowy climates, winter is often ideal for determining the completion of projects such as road- and trail-building, regeneration harvests, and development of water impoundments. Area measurements of such forestry and wildlife projects is easy although the great contrast between forest cover and open snow may be difficult to accommodate. Light meters and automatic exposure cameras tend to underexpose snow scenes; exposure should usually be at least one stop slower than indicated. Low temperatures aloft increase the discrepancy between true and indicated altitude, which can easily amount to 165 m at 3300 m above mean sea level.

Spring and fall offer the chance to exploit major differences in phenology and coloration among species. Sayn-Wittgenstein (1978) discussed the question at length in a Canadian context, pointing out that leaf flush in spring and color change in fall are erratic in timing and sequence because of seasonal weather differences, within-species genetic variation, and site factors. Despite these complicating conditions, a great deal of useful work can be accomplished in these seasons.

In the temperate and boreal parts of the world, springtime photographs show many details that are hidden by leaves during summer. They allow the analyst to

- calibrate the photographs by using geographic features (boundaries and boundary marks, roads, extraction lines, water network)
- distinguish different forest types (full grown trees, scrub, brushwood)
- detect the presence of an undergrowth or an herbaceous stratum
- count the number of trees
- evaluate stem height with a parallactic micrometer
- distinguish among different species.

In the Great Lakes region, for example, the trembling aspen component of the northern hardwood forest normally flushes well ahead of other species in spring and retains active foliage in the fall well after other species have undergone color change. Photography done during a three-week period in May or September can take advantage of the differences, even though foliage conditions are in rapid change and the appearance of different species is hard to predict. Although species identification often demands considerable ground verification, spring or fall photography usually affords better species differentiation than comparable summer coverage. Normal-color film is often used in spring and fall, but CIR film provides superior color display and better haze penetration.

11.2.2.3 Photographic Scale Selection

Table 11.1 summarizes some attributes needed for forest management that may be interpreted from three scales of aerial photography. Nearly all scales have potential applications in forestry. Scale selection depends upon the project being considered. Some combinations of scale, film, and season serve a broader range of uses than others, though it is wise to remember that photographic projects may fail by trying to serve too many purposes or by being too narrowly specialized. Scale

Table 11.1. Recommended uses of three scales of aerial photography for interpreting various forest attributes (USDA Forest Service, 1992).

ATTRIBUTE	SCALE OF PHOTOGRAPHY (in thousands) 1:40	1:24	1:12
Natural Attributes			
Basal Area	2-3b	2-3b	1-2b
Canopy Cover	1-3b	1-3b	1-2b
dbh (Size Class)	1-3b	1-3b	1-2b
Species	2-3b	1-3b	1-2b
Existing Vegetation	1-3b	1-3b	1-2b
Vegetation Height	2-3	1-3	1-2
Vegetation Density	2-3	1-3	1-2
Snag Condition	2-3	2-3	1-2
Forest/Non Forest	1-3	1-3	1-2
Hardwood/Conifer	1-3	1-3	1-2
Structure (Forest)	2-3	2-3	1-2
Insect/Disease Occ.	2-3b	2-3b	1-2b
Fire Occurrence	1-3	1-3	1-2
Forage Production	2-3b	2-3b	1-2b
Range Condition	2-3b	2-3b	1-2b
Range Cover Type	1-3	2-3b	1-2b
Water Courses	1-3	1-3	1-2
Water Bodies	1-3	1-3	1-2
Turbidity	0	2-3b	1-2
Water Temperature	0	0	0
Snow	1-3	1-3b	1-2
Geologic Landforms	2-3abc	2-3b	1-2b
Soil Moisture	2-3b	1-3b	1-2b
Soil Map Units	2-3abc	2-3b	1-2b
Cultural Attributes			
Major Highways	1-3	1-3	1-2
Secondary Roads	1-3	1-3	1-2
Logging Roads	1-3	1-3	1-2
Jeep/Hiking Trails	2-3	2-3	1-2
Automobiles	1-3	1-3	1-2
Buildings/Houses	1-3	1-3	1-2

Where: 0 = Not recommended for this particular attribute.
1 = Recommended for small area project where great detail is required (e.g., riparian mapping)
2 = Recommended for medium area projects where broader classifications are useful (e.g., at district or forest level)
3 = Recommended for very large area mapping projects where little detail is needed (e.g., at state or country level)

and a = Used in conjunction with terrain data (slope, aspect, elevation).
b = Used in conjunction with field collected data.
c = Used in conjunction with larger scale photo-interpretation.

selection for a given project depends on the primary use for which the photographs are intended and is conditioned by questions of camera format and ground resolution.

Image requirements: The level of detail desired in the end product is one of the chief determinants of required scale. The detail available from an image of a given scale depends partly on the display medium—transparencies generally providing better resolution than prints—and partly upon the number of generations of reproduction separating the interpreted product from the original film. The greatest detail is required for such purposes as individual-tree species identification performed on the basis of gross morphology and branching habit, or damage diagnosis attempted without a priori knowledge of the damaging agents. The difficulty of such tasks obviously varies with the range of species present, size of individual trees, and complexity of stand composition; but in general, in complex forest types, individual-tree species identification accuracies of 80 percent or better can be expected only at scales of 1:2000 and larger even if interpretation is carried out on original transparencies.

Smaller scales may be satisfactory where the range of species is limited, where only a few distinctive species must be detected, or where high individual-tree accuracy is not essential, as in damage surveys aimed at ascertaining the extent and severity of some known outbreak. Original transparencies in the 1:7000 to 1:9000 range can provide adequate detail under these circumstances.

Most large-area forestry projects are taken at scales of 1:10,000 or smaller. At these scales, individual-tree interpretation is limited to fairly coarse measurements of height and crown diameter, and the interpreter interested in composition usually must focus more on stand properties than on individual-tree characteristics. However, the ability to distinguish one crown from another and estimate crown size is by no means unimportant. The point at which individual trees cease to be distinguishable from one another is difficult to specify, depending as it does on size, shape, and spacing of crowns as well as on photograph characteristics. With most kinds of photography, ability to resolve individual crowns is compromised at 1:20,000 and seriously limited at 1:40,000 although large isolated crowns can still be distinguished under magnification on 1:60,000 transparencies.

Coverage requirements: Resolution is important in scale selection. Equally important are coverage and utility. Scale must be set so as to produce a manageable number of exposures and to facilitate both the conduct of aerial work and subsequent use of the products. The great incentive for small scale in aerial photography is that every doubling of scale quadruples the number of photographs; however, economy in this direction has its limits. If photographs are to be used for organization and management of forestry activities, the product scale must be large enough to permit measurement and annotation of the smallest management units. In many forestry organizations, aerial photographs are used primarily as high-resolution map substitutes for fieldwork. A scale that is too small defeats this purpose by reducing detail to the vanishing point.

Too large a scale can create equally serious problems. Too little area may be depicted on one photograph for land navigation; type delineation becomes difficult when many polygons cross the photograph edges; and the quantity of photographs may overwhelm the printing budget and the filing system. As an extreme example, although 1:1000 scale stereoscopic coverage of an entire National Forest might contain an enormous quantity of useful information, it would require nearly 450,000 23 cm x 23 cm photographs to cover a 6500 sq km area.

The 1:15,840 scale, long used in the USDA Forest Service photography, was chosen largely for convenience in flight and interpretation on lands divided into square-mile sections by the Public Land Survey (see chap. 7, sec. 7.2.1.3). At this scale, correct sidelap and stereoscopic endlap for 23 cm x 23 cm photographs can be achieved by flying along alternate section and quarter-section lines and taking a photograph every mile. Because the four-inch square that equals one mile at 1:15,840 is evenly divisible into quarter-sections and quarter-quarter sections, mapping and measurement are simplified. For this region, the scale represents the kind of compromise that should be the objective of all aerial photographic planning.

11.3 VEGETATION CLASSIFICATION

Aerial photographs are used to prepare forest type maps, assess damage, determine areas, assign land use, and perform many other applications. Photographically derived classifications reduce, complement, or improve fieldwork; they do not to replace it (Avery and Berlin, 1992).

Classification requires a "sound knowledge of plant ecology and factors controlling the natural evolution of plant communities..." (Avery and Berlin, 1992). It also requires that the classes used be mutually exclusive and make allowance for transition zones. The interpreter needs to know how elevation, aspect, and position in the landscape relate to forest types. The interpreter also needs knowledge of what forest types to expect in an area.

The detail of a classification system depends upon the purpose of the classification and what information can be obtained from the photographs. Broad forest types may be sufficient for general information, yet more detailed information may be required for a forest plan or management survey.

The simplest classification scheme separates vegetated from nonvegetated areas. Each area may then be further subdivided as needed into detailed categories. The U.S. Geological Survey (USGS) has developed a widely used classification scheme that has two standard levels of detail. This scheme is designed to allow the user to subdivide the second level classifications into more detailed classes. Level I class for forest land is divided into three classes for level II—deciduous, evergreen, and mixed forest land. Depending on the required information, each level II class may be further divided by type, crown closure, size, or other criteria. See chapter 9 or Anderson et al. (1976) for complete information on the USGS system.

A different type of forest land classification uses various symbols to identify the forest type, size, and density. A classification of forest types might be coded as follows:

Forest Type	Total Height (m)	Crown Closure (%)
RP Red pine *(Pinus resinosa)*	(1) 1-6	(a) 70-100
A Aspen *(Populus tremuloides)*	(2) 6-12	(b) 40-70
JP Jack pine *(Pinus banksiana)*	(3) 12-18	(c) 0-40

In this classification, RP3a represents a red pine stand, 12 m to 18 m tall, with a 70-100 percent crown closure (fig. 11.1). Classes are determined by the final information needed.

11.3.1 Forest Type and Tree Species Identification

Forest type is a classification given to a stand or inventory plot determined by the tree species present in the area of interest. The ability to identify forest types, tree species, or vegetation types is often a basic requirement of many forestry applications of aerial photography. Identification of tree species can be done with a wide range of film types, formats, and scales. Large scales, up to 1:8000, are best for individual-tree species identification, however scales of up to 1:30,000 have been used for identification of certain vegetation types (Mielke et al., 1986). Panchromatic, color, and CIR films have been used with varying degrees of success. Color and CIR transparencies have higher resolution and greater contrast than prints of the same scale and are therefore better suited for tree species identification (Ciesla, 1990).

Aerial photography has been used extensively to identify tree species and forest types as well as to delineate boundaries between types or around disturbances such as a harvest, fire or disease. Qualitative characteristics such as texture, color, tone, shape, size, and pattern provide essential diagnostic clues. Occasionally a single characteristic is so distinct that it can become a primary identifying characteristic, such as the star-shaped crown of white pine *(Pinus strobus)* at large and medium scales. More often, however, all clues are used simultaneously as the interpreter considers the alternatives.

How does one recognize forest types and tree species on aerial photographs? Each photointerpreter is likely to develop his or her own mental keys with increasing experience. The interpreter must think of what the tree

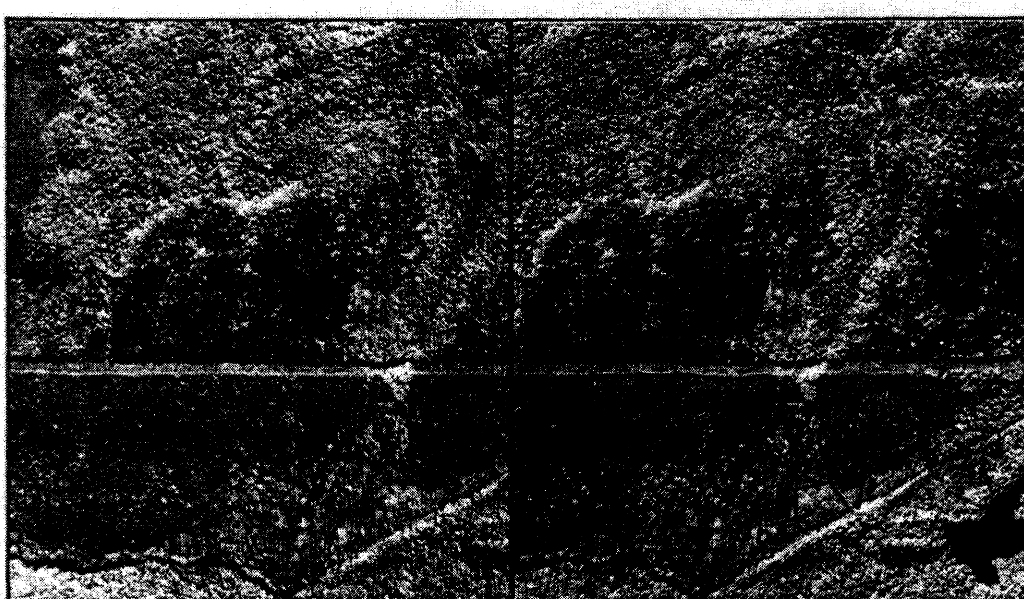


Figure 11.1. Classification of forest stands in Ontonagon County, Michigan. 1:15,840 scale stereoscopic photographs, June 1986. (Michigan Department of Natural Resources photographs)

will look like from above, know the climatic and physiographic requirements of the species, and know where it is likely to be found in the forest being studied. If the photographs are of sufficiently large scale, recognition is usually easy and direct, presuming the interpreter is familiar with the species. In essence, it looks like a ponderosa pine *(Pinus ponderosa)*, Douglas fir *(Pseudotsuga menziesii)*, or whatever it may be. On small-scale photographs this may not work so well. Even so, different species have their unique characteristics when viewed on a vertical aerial photograph.

Several characteristics of tree crowns are visible on aerial photographs and have proved to be useful in tree species identification. These include texture (including crown apex and margin), foliage color, and site (Heller et al., 1964).

11.3.1.1 Texture

The perceived texture of a forest stand and/or tree crown on aerial photographs can provide considerable information about the species' or type's physical characteristics and consequently its identity. The texture of a single tree on a photograph is determined primarily by its crown shape, branch structure, crown size, and at very large scales, foliage type and orientation. Typical descriptions of texture are needle-like, feathery, well-defined, indistinct, billowy, upright tufts, rounded, fine, lacy, clumped, and solid (e.g., Sayn-Wittgenstein, 1960; Ciesla and Hoppus, 1990). Similarly, the texture of a stand is determined by the size of trees in the stand, crown diameter, crown closure, and to a certain extent, texture of the individual crowns. Some example descriptors of stand texture are fine-textured, carpet-like, fuzzy, honey-comb, pincushion, smooth, even, uniform, popcorn ball, pock-marked, lumpy, and rough. For example, oaks (*Quercus* spp.) have foliage with a coarse, granular texture, while larch (*Larix* spp.) have foliage which is lacy or transparent in appearance.

Descriptions of crown characteristics of the tree species which occur in a given geographic area can be summarized either in tabular form (table 11.2) or as pictorial keys (figs. 11.2 and 11.3).

Texture can indicate several different things to the photointerpreter. As

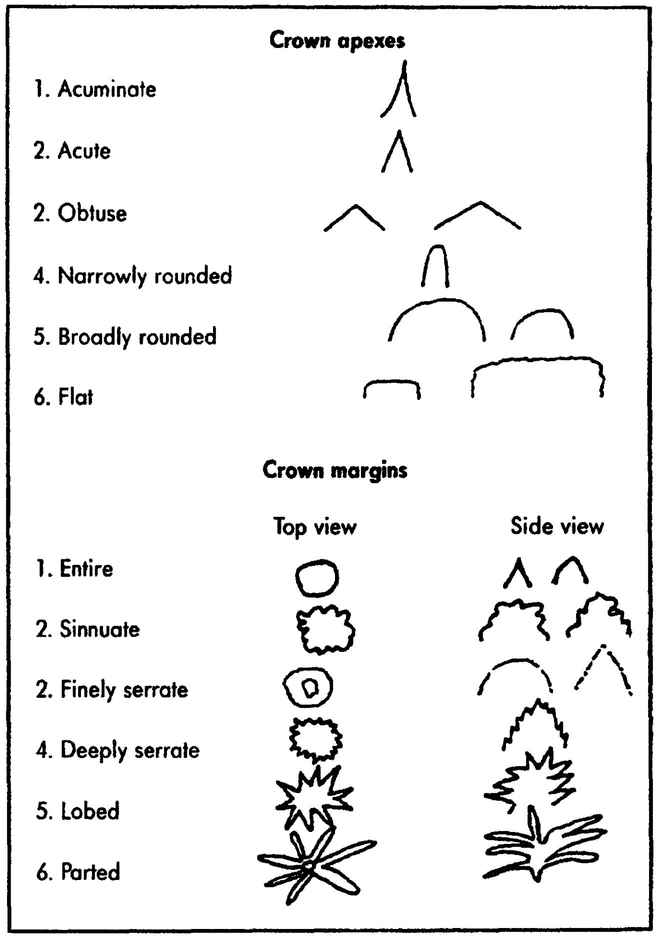


Figure 11.2. Apexes and margins of tree crowns as seen on aerial photographs (Heller et al., 1964).

Table 11.2. Aerial photographic crown characteristics of major conifers occurring in New Hampshire, New York, and Vermont (Ciesla, 1984).

SPECIES	CROWN TYPE	CROWN APEX	CROWN MARGIN	FOLIAGE TEXTURE
Red or black spruce	Broadly conical	Obtuse	Lobed	Medium
Balsam fir	Narrowly conical	Acute/acuminate	Finely serrate	Fine
Eastern hemlock	Broadly conical	Obtuse	Sinnuate	Fine
Eastern white pine	Irregular, horizontal branching	Broadly rounded	Lobed/parted	Medium
Red pine	Open, rounded	Broadly rounded	Finely serrate	Fine
Eastern larch	Narrowly conical	Acute	Finely serrate	Fine
Northern white cedar	Oval	Broadly rounded	Entire/sinnuate	Medium

discussed, texture can provide an indication of forest species or type. For example, a stand of conical trees with very narrow crowns, such as black spruce *(Picea mariana)*, will create a much finer texture on a photograph than a stand of larger-crowned white pine or red oak *(Quercus rubra)* (fig. 11.4 — see color section). Texture can also provide an indication of stand age. A seedling-sapling stand will have a much finer texture, because of the small crowns, than a mature stand of the same species (fig. 11.5 — see color section). Similarly, the texture of an overmature stand may be very rough and coarse because of the uneven canopy, the large emergent crowns, and the large number of different tree species of many ages and crown characteristics that are often visible from the air (fig. 11.6 — see color section). Texture can provide an indication of crown closure class or stocking. A densely stocked stand will have a smoother, more even texture than a poorly stocked or open stand (fig. 11.7 — see color section). Texture can also be a valuable indicator of crown diameter and stand size (fig. 11.8). Fox and Lee (1989), for example, found it faster and equally accurate to estimate crown diameter of old growth redwood from their texture on 1:130,000 CIR photographs than to measure the crown diameter of individual trees.

The shape and size of tree crowns are good indicators of species at large scales (e.g., used extensively by Heller et al., 1964, and Croft et al., 1982). Where the crown of a species is large and very distinctive, as with white pine, it can even be used at smaller scales. For example, ponderosa pine appear to have rounded, more ball-like crowns; Douglas fir may look like an asterisk; and subalpine fir *(Abies lasiocarpa)* has a very narrow crown for its width. Also, with the true firs, one may see the cones clustered at the top of the tree. Shadows may give the interpreter a good side view of a tree's crown.

Crown size and shape are also very important in the way they affect stand texture, and knowledge of them can be useful. Crown texture may be defined by crown apex, margin, and branch pattern. The shape of the apex or tip of the tree crown is often helpful in tree species identification. Crown apexes can vary from acuminate or acute, as is the case in species of fir (*Abies* spp.) and spruce (*Picea* spp.), to the broadly rounded crowns char-

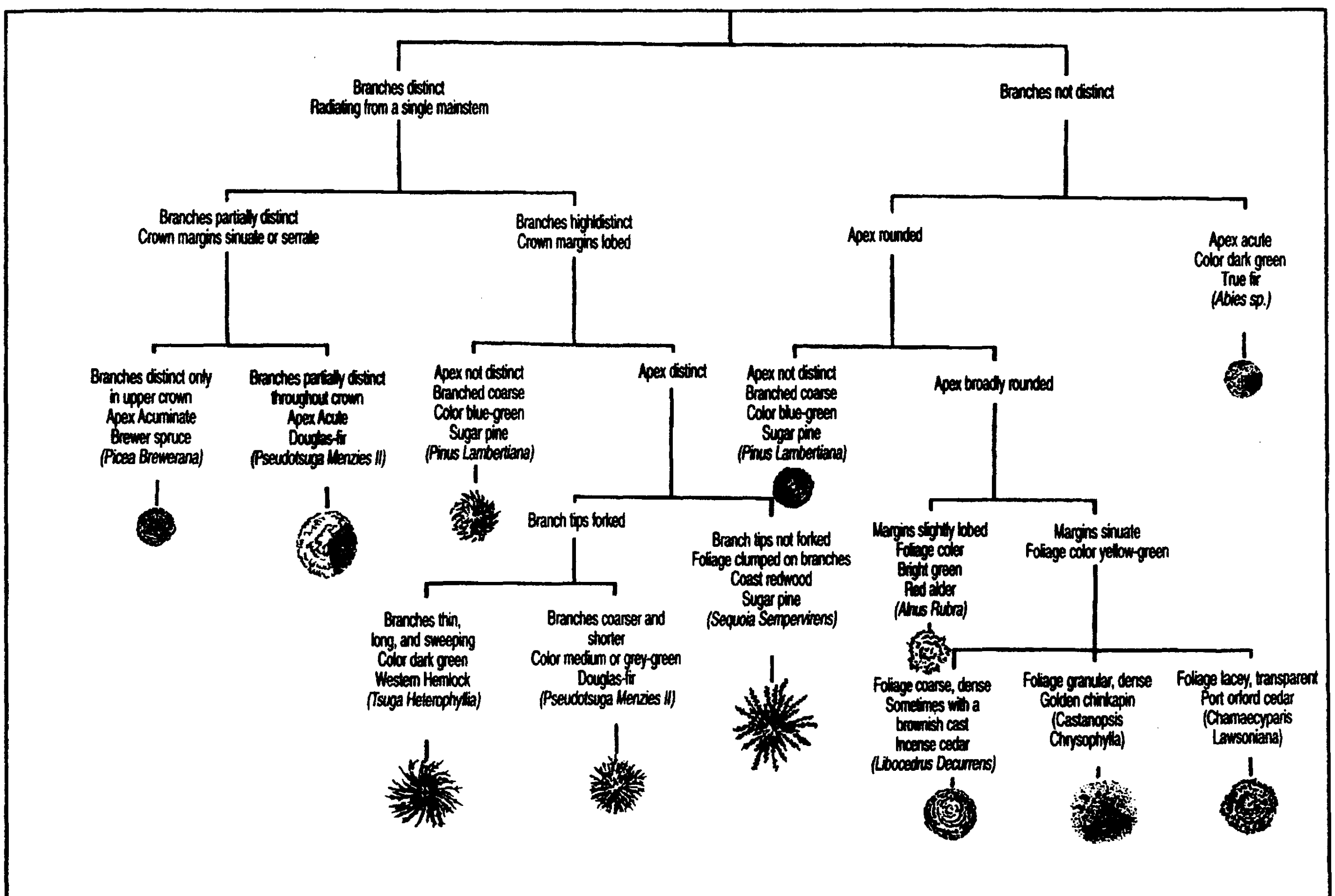


Figure 11.3. Partial key to identification of tree species in southern Oregon and northern California on large-scale, color aerial photographs (Ciesla and Hoppus, 1990).

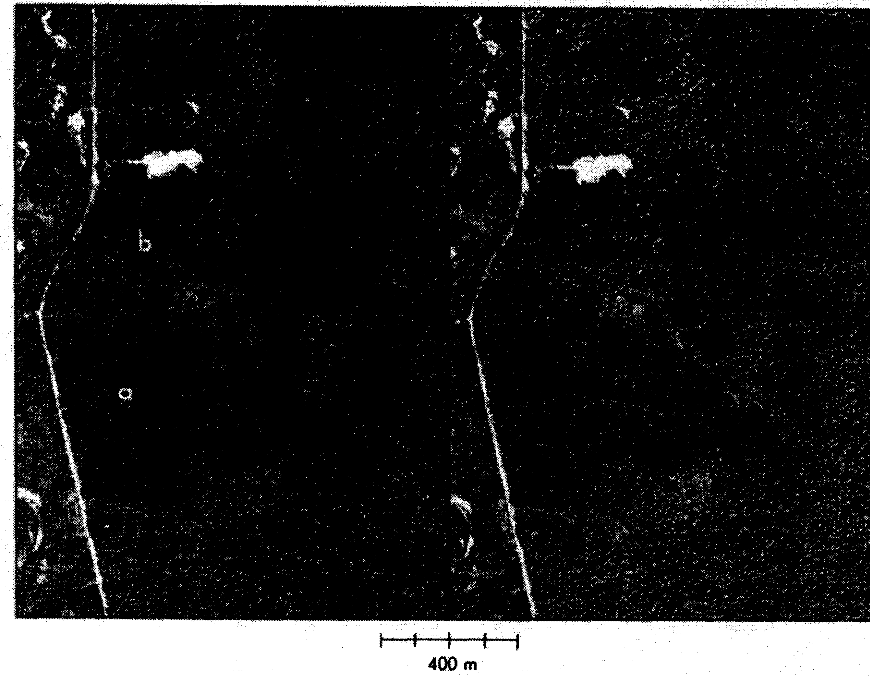


Figure 11.8. Texture can provide an indication of crown diameter and stand size. The coarseness of the texture in this panchromatic stereopair of black spruce *(Picea mariana)* stands is directly related to their crown diameter and stand size. The finer stands are composed of much smaller individuals than the more coarsely textured stands. Scale 1:20,000. Albany, New Hampshire, 12 September 1970. (USDA photograph)

acteristic of many hardwoods (fig. 11.2). The outer margin of the crown can vary from smooth or entire in the case of species of *Chamaecyparis, Thuja,* or *Libocedrus,* to sinuate in species of *Abies,* to deeply lobed, a characteristic typical of the soft pines. Crown margins are most clearly visible in open forests. In dense, closed forests they are obscured by neighboring trees (fig. 11.2). Some species, such as the spruces and hemlocks (*Tsuga* spp.), have distinct branches when viewed on aerial photographs. Others, such as the true firs (*Abies* spp.), have their branches obscured by thick foliage and are less distinct.

Texture remains relatively consistent across different film types and film batches, though it does change with scale. In general, forest stands look smoother and more finely textured at smaller scales. For example, the description of a red oak stand may be "very pock-marked and rough" at large scales, but the same stand would look much softer, smoother, and more even at smaller scales.

11.3.1.2 Tone and Color

Conifers are characteristically darker in tone and color than are hardwoods. The contrast between conifers and hardwoods is generally visible on all film emulsions but is most pronounced on infrared films. Subtle differences in the hue and chroma of foliage are helpful for characterizing individual species. For example, foliage of the soft pines—eastern white pine, western white pine *(Pinus monticola),* and sugar pine *(Pinus lambertiana)*—tends to have a blue-green color (Heller et al., 1964; Croft et al., 1982; Ciesla and Hoppus, 1990). These differences are most visible on color film but can also be seen on CIR film.

Heller et al. (1964) used Munsell color charts to describe tree foliage color on color aerial photographs taken in northern Minnesota. Other workers have used more generic terms such as blue-green, dark green, or olive green to describe foliage (Croft et al., 1982; Ciesla and Hoppus, 1990).

Color (or tone in black-and-white films) is also useful in interpretation. Shades vary from the bright, light green of larch, without needlecast, to the brownish green of lodgepole *(Pinus contorta* var. *latifolia)* and the dark green of ponderosa pine. The various foliage colors lead to different shades of gray on black-and-white (BW) photographs, but the distinctions are harder to see. Some differences can be seen on CIR photographs that are not easily visible in true color or in BW.

Reflectance differences create distinctions in color and tone on aerial photographs (chaps. 2 and 5). These differences allow discrimination of plant species and vegetation types on aerial photographs. The characteristic surface, thickness, internal structure, and pigment content of leaves, and the characteristic structure and geometry of the canopy—as determined by the orientation of the plants and their leaves—all affect the amount of radiation reflected. Infrared reflectance in particular offers broad potential for type discrimination. Vegetation reflects much more near-infrared than visible light, and subtle differences between species (in their crown characteristics) can show up as large differences in infrared reflectance (color/tone) (see fig. 5.11, chap. 5). For example, the needle foliage of conifers creates internal shadows. This, in combination with the fact that the needles themselves reflect less infrared radiation, gives them a darker appearance than hardwoods in the infrared.

Color (and tone) can indicate several different things to the interpreter. Color (tone) can provide an indication of species or type (fig. 11.9 — see color section). In CIR, for example, forest species display a range of color saturations and hues. In the photographs for the figures in this section, this range is from gray-brown to green for most conifers and from pink to orange for hardwoods. The extent and location of this color range can vary considerably. Another commonly printed expression of CIR color is where almost all vegetation is some version of red, with conifers a darker red and hardwoods a lighter red. Color can provide an indication of stand age. A seedling-sapling stand, for example, is often lighter in color and tone (and more pink in CIR) than an older stand of the same species. Color can provide an indication of the type of understory. Particularly in the more open stands or species with small crowns and less dense canopies, the understory can have a profound effect on the general impression of stand color. For example, a white birch *(Betula papyrifera)* stand with an understory of red spruce *(Picea rubens)* will appear much darker than a similar stand with a hardwood understory (fig. 11.10 — see color section). The presence of standing ground water, where visible from the air, can also have a significant effect on stand color because of its high absorption and therefore darker appearance, particularly on infrared photographs. Color can also indicate the proportion of dead stems in a stand (fig. 11.11 — see color section). Dead leafless stems appear strikingly turquoise (light greenish-blue) in CIR (and very light and pale in normal color, panchromatic and BWIR) and are typically very distinctive, particularly when they represent a high proportion of the stand's stocking.

Color does not vary as much as texture does with the scale of the photography. Color and tone do vary considerably with film type, however, and descriptions of forest color will thus be specific to a particular film type. Hardwoods in summer in CIR, for example, are typically shades of orange, red, and pink, whereas the same hardwoods in normal-color photographs are shades of green. Similarly, in BWIR, hardwoods in summer are very light in tone, whereas they appear darker and closer to the tone of conifers in panchromatic photography.

Color must be dealt with in relative terms, for even within a single emulsion/film type, color can vary. CIR photography in particular has not proved consistent enough to allow a species to be described in precise hue, chroma and value. Factors such as shadow, season, printing process, film batch, and exposure can all have an effect on the appearance of color photography, and CIR is extremely sensitive to some of these. Intensity of tones and shades can vary considerably between missions, film batches, and formats (and somewhat even within a frame as well as between frames) as a result of changes in sun angle, light intensity, exposure, and/or variations in film and processing (Nielson and Wightman, 1971; Enslin and Sulivan, 1974). While a great deal of information can be gathered from color, the interpreter of CIR must assess image color carefully.

Although absolute color may change, relative colors generally remain consistent and can be relied upon. Tables 11.3 and 11.4 were developed for New England species from study of many large- to medium-scale photographs. Species were observed to differ independently in both color and color intensity. In the tables, the species are ranked as to where they fall relative to each other within the range observed in CIR photography: with respect to color, conifers (excluding hemlock) may range from a gray-brown to a green in CIR, and hardwoods (including hemlock) range from a pink to an orange. Color intensity is an attempt to capture the depth, strength, concentration, and saturation of the color and is expressed simply as ranging from soft to intense color.

The pattern of colors, tree crowns and shadows on aerial photography merges to become part of the texture as the scale gets smaller. Here, however, pattern refers to the spatial relationship of those features where they are still distinguishable as discrete objects. For example, where individual crowns are distinguishable (e.g., at 1:6000 and larger), the pattern of species distribution within a stand may give information about the forest type. Whether the stand is made up of scattered widely spaced individuals, an even distribution of the type's component species, or clusters of one of the species com-

Table 11.3. The relative colors of species on CIR photographs. Softwoods (excluding hemlock are marked from grey/brown to green; hardwoods (including hemlock) are ranked from pink to orange.

grey/brown	White pine	pink	Hemlock
↑	Red pine	↑	Beech
	Pitch pine		White oak
	Balsam fir		Sugar maple
	Red spruce		Red maple
	Black spruce		Aspen
↓	Tamarack	↓	White birch
green	dead stem	orange	Red oak

Table 11.4. The relative color intensity of species on CIR photographs. Both softwoods and hardwoods are ranked from soft to intensely colored.

Hemlock	soft color	White birch
White pine	↑	Yellow birch
Balsam fir		Beech
Pitch pine		Aspen
Tamarack		Sugar maple
Black spruce		Red maple
Red Pine		White oak
Red spruce	↓	Red oak
Atlantic white cedar	intense color	

ponents, can be a clue to the forest type or provide additional information about the type at that particular site.

11.3.1.3 Site

The interpreter often identifies a species based on the ecological requirements of the species as much as on the appearance of the trees themselves. Site factors such as latitude, longitude, elevation, aspect, and topographic position often dictate where certain species can be found. For example, in the southern Appalachian Mountains, pure stands of red spruce and Fraser fir *(Abies fraseri)* occur at elevations above 1550 m. Trees such as eastern larch *(Larix laricina)*, black spruce, and bald cypress *(Taxodium distichum)*, are associated with poorly drained sites or bogs. In the Rocky Mountains, blue spruce *(Picea rubens pungens)* is often restricted to riparian zones, while ponderosa pine occupies drier south-facing slopes, and Douglas fir occupies cooler north-facing slopes.

In some areas there may be strong associations, such as the occurrence of black spruce with tamarack in New England, of Atlantic white cedar *(Chamaecyparis thyoides)* with low wet areas, or of red spruce with high elevations in Vermont and New Hampshire. In other areas, the associations will be weak and less reliable, either naturally or as a result of subsequent disturbance. For example, in New England, the long and complicated land use history has weakened the association of topography with most hardwood species (Spurr, 1948).

Sometimes site information may be better used in the negative sense. For example, in the Pacific Northwest, if the site is a steep southwest slope, one may presume there is no red cedar *(Thuja plicata)*, hemlock *(Tsuga heterophylla)*, or grand fir *(Abies grandis)* present.

Texture, color, pattern, shape, size, and association are extremely important aids in the interpretation of aerial photographs. Although each can vary considerably across scale, season, film batch and emulsion, the information each contains can provide essential diagnostic clues. Effective use of this qualitative information is enhanced by an understanding of the local area, familiarity with the photographs being used (the season, scale, and emulsion), familiarity with the appearance of species and types from the air, and an understanding of species/type ecology.

11.3.1.4 Sources of Interpretation Error

Within-species variation in crown characteristics can be a source of interpretation error leading to misclassification. Among the factors that can cause significant variation are tree age and stress.

Young trees tend to have a higher reflectance in the near-infrared region of the spectrum than do mature trees of the same species. Therefore they may appear in brighter hues of red on CIR film (Grundman, 1984; Ciesla et al., 1986). Older trees often have more distinct branches than their younger counterparts. In northern California and southwestern Oregon, Douglas fir stands tend to have a partially distinct, layered branch pattern up to about age 100 when viewed on large- and medium-scale aerial photographs. Large old growth Douglas fir tend to have more distinct branches. A similar pattern has been noted for several species of *Abies* which occur in this area (Ciesla and Hoppus, 1990).

Stress caused by site-related factors, insects, and disease can affect foliage color and density, crown form, and branch patterns. Trees growing on deep, fertile soils at low elevations tend to have different crown forms than their counterparts on shallow, rocky soils at high elevations. In the northeastern United States, balsam fir *(Abies balsamea)* growing on low elevation sites has a narrow, spire-shaped crown. Under these conditions, it can be easily separated from red spruce, a closely associated species which tends to have a more obtuse crown with distinct branches when viewed on vertical aerial photographs. At high elevations, both species are affected by high winds, which alter the crown appearance, making them difficult to distinguish on aerial photographs.

Position of a tree crown on an aerial photograph can also change its appearance. Trees on shaded slopes will appear darker and have less contrast with their neighbors than trees in full sunlight. Vignetting, which is common with wide-angle lenses, can cause similar problems at the edge of photographs. Tree species identification is best done on optimally exposed portions of aerial photographs.

11.3.1.5 Photointerpretation Guides and Keys

Photointerpretation guides and keys are most often developed and used as reference and training material (chap. 1). Through the use of guides and keys, consistency can be maintained over time while interpreting larger areas with more interpreters. Expanded guides and keys can also be used to document the process and products of particular photointerpretation projects. In the interpretation process, the photointerpreter has an easier time interpreting vegetation types given graphic and/or textual reference material. Similarly, data users can better understand what the photointerpreter has interpreted if the user has access to a key or guide which explains the classification scheme and its limitations. Guides provide general description of forest types or species. Keys provide a step-by-step elimination process for identifying types or species.

Guides: The following is an example of a guide to applying large-scale, spring-time, panchromatic photographs, for recognizing forests types in Europe (Schram, 1993):

In general, coniferous trees appear dark gray or black, while deciduous trees are light gray.

A. Coniferous stands: Generally interpreters can distinguish among Norway spruce and Douglas fir, pine and black pine, Japanese larch and European larch.

- Norway spruce and Douglas fir. Single trees are recognized by their typical triangular silhouette. Stands have a dark gray color. When magnified and viewed stereoscopically, the canopy looks like a carpet of maidenhair *(Polytrichum commune)* and individual trees look like asterisks. Generally Douglas fir has a larger crown than spruce.

- Pines. The canopy has a granular structure. The tone is lighter than fir or spruce. The color of black pine is darker than that of other European pines. Young stands may be confused with young spruce or fir although knowledge of the site helps.

- Larches. In early spring, larches lack needles. The straightness of the stems and the presence of verticil separate larches from broadleaved trees. In early spring, the stands look like dead stands of spruce. As the season advances the larches appear white. Toward the end of spring, Japanese larch appears dark gray and European larch, light gray.

B. Deciduous stands: Beech, oak, hornbeam, birch, and fruit trees may be separated by the tone of the stems and the appearance of the litter beneath the canopy.

- Beech (*Fagus* spp.). The gray stems stand out against a light forest floor. Beech leaves decompose slowly, and the litter appears light for a long time. The tops are composed of straight and upright standing branches and are covered with many thin twigs. On aerial photographs, the tops appear fuzzy due to tiny and mamauvish fusiform buds. The stems are moss-free and highly reflective.

- Oak. The litter, which decomposes rapidly, is very dark. The ruffled stems are mostly covered with moss and lichen and reflect little incoming light. Branches are winding. The big twigs and globular buds are visible.

- Hornbeam (*Carpinus* spp.). Hornbeam is similar to beech in appearance, but the litter is darker. Hornbeam sprouts earlier than beech.

- Birch (*Betula* spp.). The top is very fine. The white bark of the stems is very apparent.

- Fruit trees. Fruit trees have light-colored flowers before they sprout leaves. The trees appear as white balls in the stands.

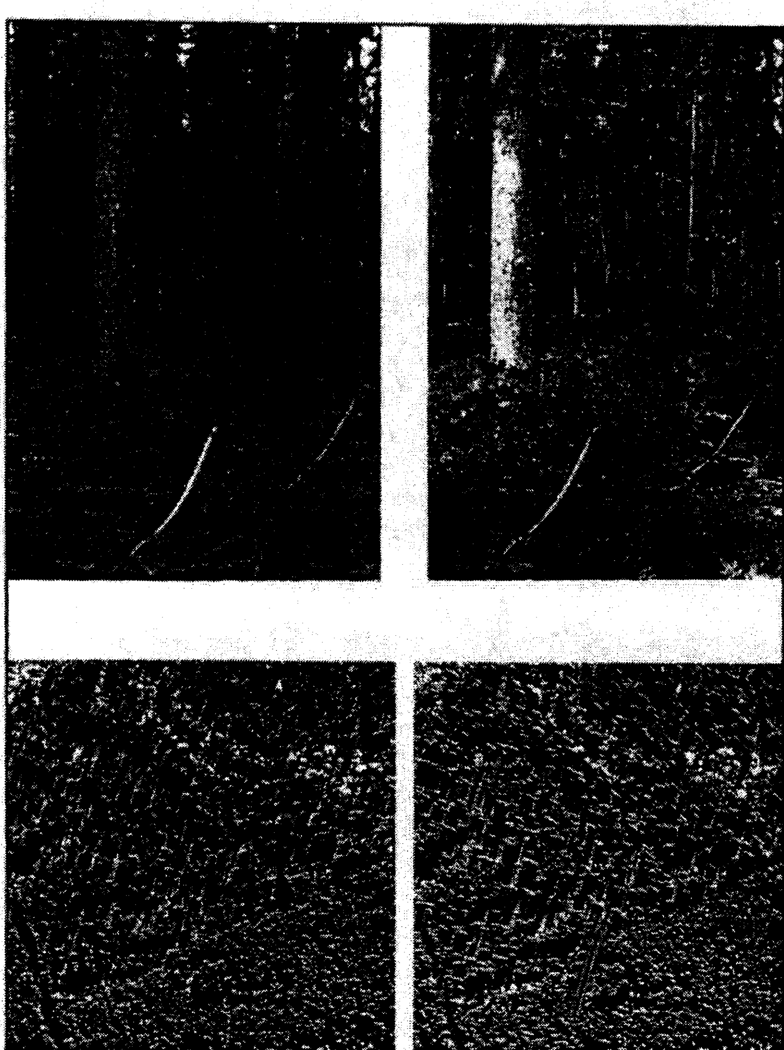
Photointerpretation guides are available for several forest regions of the United States, including the Great Lakes region (Heller et al., 1964), the northern Rocky Mountains (Croft et al., 1982), the northeastern states (Ciesla, 1984b), and northern California and southern Oregon (Ciesla and Hoppus, 1990).

Keys: There are essentially two types of photointerpretation keys: the dichotomous or elimination key and the selection key. A dichotomous key, if designed properly, is less subjective than a selection key. The selection key is more useful where the types being identified are highly variable in species and spatial composition (Hershey and Befort, 1993). Dichotomous keys are useful where types are homogeneous or where individual species are being identified on large-scale photographs.

Dichotomous keys are best supplemented by photographic or diagrammatic examples. Keeping the adage "a picture is worth a thousand words" in mind, the textual dichotomous key can be thought of as an organizational tool or a method of accessing a selection key. The descriptive words used in the dichotomous key must be well defined and thought out. Figure 11.12 illustrates a portion of a dichotomous (elimination) key to the land and forest types of interior Alaska (Hegg, 1966). In the example, only three of 37 photointerpretation classes are ultimately keyed out. Figure 11.12 illustrates one of the three classes. Note that text describing tone, texture, and shape is used only at the level of the key where specific types are identified. Above this level, environmental characteristics rather than photograph characteristics are most useful.

Selection keys are generally organized by the classes they are designed to aid in identifying. For example, if forest types are the classes being used, selection key examples will be organized by type, with needle-leaf types grouped apart from broad-leaf types, which are in turn grouped apart from mixed types and nonforest types. Selection keys can use textual dichotomous keys as a method of entry into the selection key. Once the selection key or guide has been entered, it is usually a matter of examining diagrammatic and/or photographic examples (along with accompanying text) and comparing those examples with the types being interpreted. Figure 11.13 illustrates part of a selection key used to aid in the identification of tree species on large-scale photographs in Canada (Sayn-Wittgenstein, 1978). Interpretive keys to aid in the identification of tree species on aerial photographs have also been developed for European forests (Grundman, 1984).

There are several considerations in developing a photointerpretation key. Keys are generally designed to meet the requirements of a particular project, in a given area, using a specific type of photography. A key to tim-



ber types using 1:15,840 scale color photographs might not be especially useful to a photointerpreter trying to identify vegetation types in marginal or nonforest areas using 1:60,000 scale CIR photographs.

The primary issue is the objective. What is to be classified? If a textual dichotomous key is to be used, descriptive differences between specific classes need to be written in a key form. This can be the most difficult part of the process, and time should be spent to make sure terms are well-defined and understood. Stereograms depicting the specific classes need to be collected and annotated. It is best to select aerial photographic examples that can be accompanied by ground reference information such as ground sample data and/or terrestrial stereograms. Aerial reconnaissance information such as low oblique stereograms and organized notes taken during the reconnaissance may also be used (fig. 11.14 — see color section).

Photographic keys have a number of limitations that need to be considered in their development. For the most part, keys are specific to a type of photography. When large areas are being interpreted, classes tend to become more generalized. Variation within classes increases, and variation between classes decreases. Finding good examples of each class to use as illustrations becomes difficult. It may be that several examples will be needed to illustrate the range of variation found in certain classes.

Figure 11.12. Portion of a dichotomous key to the land and forest types of interior Alaska (summer photography, modified infrared, scale 1:5000) and example photograph of spruce (*Picea rubens* spp.) sawtimber on the Chena River drainage southeast of Fairbanks, Alaska. Diameters of the sawtimber trees range from 23 cm to 33 cm. Gross volume on a plot taken here was about 82 cubic meters per ha. The coarse texture and low stocking are typical of old-growth spruce.

1. Tree cover sparse, less than 10% or completely absent, no evidence of tree remnants . . . See 2
1. Tree stocking over 10% or evidence of previous stocking from tree remnants . . . See 12

12. Trees or remnants of poor form, less than 14 m (45 ft) tall; (a) north aspect and/or poorly drained, (b) south aspect with over 60% slope, the slope appearing dry and unstable . . . See 13
12. Trees or remnants of good form, a commercial species with moderate slope and drainage, usually under 762 m (2500 ft) elevation . . . See 21

21. Physiographic or stand disturbance evident . . . See 22

21. Physiographic or stand disturbances not evident . . . See 27

27. Foliage gray to black; crowns or shadows triangular, conical or cigar shaped and dense. Occurs in river valley bottoms, drainage ways, and toes of north slopes . . . See 28

27. Foliage white to medium; crowns or shadows not sharply tapering . . . See 30

28. Stand height under 12 m (40 ft); texture fine to medium; often with brush or hardwood nurse crop. High reflectance of new growth may often give light tone to canopy. *CFL—spruce, seedlings and saplings*

28. Stand height over 12 m (40 ft). Tone generally quite dark . . . See 29

29. Stand height 12 m to 20 m (40 ft to 65 ft), well stocked to all trees; texture medium course. *CFL—spruce, pole timber*

29. Stand medium to lightly stocked with trees over 15 m (50 ft); texture medium to course with ragged crowns. *CFL—spruce, sawtimber* (see photograph).

11.3.1.6 Identification of Tropical Tree Species

Forests of the tropical zones, which constitute about half of the world's forests and in which most developing countries are situated, are overexploited in some regions, under harvested in others, and unmanaged in nearly all. Although trees are the dominant vegetation on more than half of the tropical land area, forest products contribute little to the social and economic welfare of the people. Scientific management of tropical forests needs a large amount of reliable information that can only be obtained in a time- and cost-effective way with the help of aerial photographs and other forms of remote sensing. In spite of the importance and urgency, relatively less progress has been made in recent years in the use of aerial photographs of tropical forest vegetation than that of temperate and boreal vegetation.

The role of aerial photographs in tropical forest resources surveys and mapping has been well-established for designing ground sampling, forest type mapping, height and crown diameter measurements, estimation of height and crown density, volume stratification, direct volume estimation, and selection and assessment of wood resources outside the forestland. As with other parts of the world, the outstanding value of aerial photographs in tropical forests is the ease and accuracy by which area determination can be made. Under certain conditions, the areas of different forest cover and land use types can be obtained directly from the photographs, though this is normally obtained from maps.

Primary tropical rain forests, generally comprised of irregular crowns of various heights and close canopy, appear in medium dark tone and have coarse to mottled texture. In many parts of the world, only a few of the large number of tree species present are identifiable on the basis of tonal and other variations. The secondary tropical rainforests are smaller in height, lighter in tone, and less irregular in appearance. More or less pure types consisting of one or a few characteristic species are comparatively easy to identify and delineate. Although species identification is difficult, the interpreter may be able to delineate homogeneous areas bearing characteristic composition dominated by specific groups of species, on the basis of topography and general image appearance.

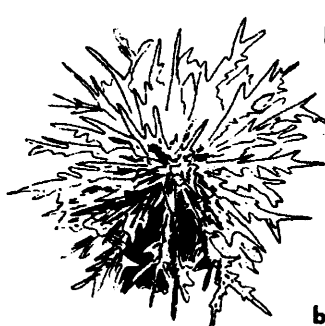


Figure 11.13. Western hemlock *(Tsuga heterophylla* [Raf.] Sarg.). Western hemlock is a large tree (45 m to 60 m) which is often dominant, and favors mixtures of western red cedar *(Thuja plicata)*, Douglas-fir *(Pseudotsuga menziesii)*, grand fir *(Abies grandis)*, black cottonwood *(Populus trichocarpa)* or red alder *(Alnus rubra)*. The tone of western hemlock and Douglas-fir is similar. At large- and medium-scales, western hemlock is generally darker than western red cedar and lighter than amabilis fir. Its crown is conical, but becomes very broad with age. The foliage of older trees is denser than in Douglas fir; and branching extends closer to the ground; crown surface texture is fine and feathery. Branch ends tend to be forked. In very large-scale aerial photography (e.g., 1:600), the characteristically drooping top may be seen. Photographic illustrations are not included here (modified from Sayn-Wittgenstein, 1978).

In Guyana, Swellengrebel (1959) used 1:10,000 scale photographs to identify a number of species occurring in groups in mixed and Mora forests, including *Mora excelsa, Mora gonggrijpii,* and *Ocotea rodiaei.* In India, Shedha (1979) delineated dry deciduous forest, bearing teak in different proportions (20 percent classes), on 1:10,000 scale aerial photographs. In Dutch Guyana, baboah trees have been successfully identified and counted because they have a light-toned image and formed the dominant crown canopy (Howard, 1970). In Brazil, associations of *Mora excelsa* and pure upper stories of *Gonpia glabra* were identified on 1:40,000 scale photographs (Heinsdijk, 1957). In Sumatra, pure stands of camphor have been identified on 1:40,000 scale photographs (Hannibal, 1952). In British Honduras, mahogany was recognized on 1:15,000 scale photographs, taken during a brief period in February or March, when the species has a distinct reddish flush. A number of dry species that characteristically occurred in pure or nearly pure stands in Surinam could be recognized.

Sometimes a commercially valuable species can be associated with other species which can be identified. In Ghana, areas containing silk cotton *(Ceiba pentandra)* were recognizable on photographs by their association with the umbrella tree *(Musanga smithii).* Associations containing *Raphaea* spp. can usually be readily delineated and excluded from tropical forests since they occur in a swamp land system (Howard, 1970).

Dipterocarpus as a genus is often recognizable by its large crown and characteristic light photographic tone (Loetsch, 1957; Merritt and Ranatunga, 1958; Wheeler, 1959). In New Guinea, at high elevations, Boon (1956) was able to identify the conifers *Agathis* and *Aurocaria* on 1:40,000 scale photographs by their distinctive crown shapes; and in New Zealand, *Agathis* has been similarly identified. In Western Australia, pure stands and groups of *Eucalyptus marginata, E. diversicolor,* and sometimes *E. calopylla, E. patens, E. jacksoni,* and *E. redunca* are identified and delineated on photographs of a scale of 1:15,840 and larger (Howard, 1970).

In the tropical dry deciduous forests, certain species can be identified when they grow in pure or nearly pure stands and have characteristic form. Coniferous forests, which are composed of one or few species, grow to fairly tall heights. Conifers have smaller regular crowns than other trees and are easily identified on the aerial photographs because of their conical crowns and fine texture. Savannah forests which have scattered groups of trees separated by grassy areas are also clearly visible on the photographs.

Several tidal and swamp forest types appear quite distinct. *Rhizophora* and *Avicennia*, the most common of about a dozen genera of mangroves, are commonly associated with tidal channels and register in dark tone and very fine texture. Palms have characteristic feathery appearance and light tone. Nipa palm, which generally occurs upstream and adjacent to mangroves, has light tone and uniform height. Nipa palms are shorter than mangroves but are taller than grasses. Sago palm has somewhat darker tone, irregular height, and a star-shaped pattern. *Casuarina equisetifolia* and coconut palm, which grow in strips along the beaches, are distinct because of their pine-like thin and light-tone crown and star-shaped crown, respectively.

In Indonesia, it was possible to recognize seven vegetation classes on 1:20,000 scale aerial photographs (Kools, 1949): (1) cultivated area, (2) young secondary forest, (3) old secondary forest, (4) devastated primeval forest, (5) mangrove forest, (6) swamp vegetation, and (7) dry-land high forest in five density grades. In north Borneo, Francis and Wood (1955) were able to segregate sixteen vegetation types on 1:25,000 to 1:30,000 scale photographs.

In Pakistan, the principal dipterocarp *(Gurjan)* could be easily distinguished on 1:20,000 scale photographs because of its characteristic crown (Zahir-ud-Din, 1954). Similarly in Thailand, one dipterocarp *(Yang)* could be distinguished because of its large crown and bright shining leaves. In Malaya, seraya *(Shorea curtisii)* is characterized by a white crown along ridges (Brown, 1959).

In Sudan, it was possible to distinguish *Isoberlinia doka* forest with reasonable accuracy, and some progress has been made in recognizing *Khaya senegalensis* in the savannah forest at a scale of 1:16,000. Many variations of savannah woodland could be distinguished on 1:30,000 scale photographs in the open forests of central and eastern Africa (Spurr, 1960).

In Central and South America, broad associations characterized by photographic appearance, soil uniformity, moisture conditions, and topographic position could be recognized, but the individual species could not be identified (Spurr, 1960). In the Peten region of Guatemala, Mason (1952) differentiated several principal vegetation types including (1) broken ridge high forest association, (2) lowland high forest consisting of two stories of which the upper contains isolated trees of great height and crown diameter (the lighter toned ones in March and April frequently being mahogany—*Sweitenia mahogany)*, (3) wet lowland forest characterized by palms, (4) hillcap forest on the upper slopes and ridge tops of limestone hills, (5) pine forest *(Pinus caribaea)* on high granite soils, and (6) savannahs. In the Araucaria *(Araucaria angustifolia* (Bert.) O. Ktze) forests in the plateaus of southern Brazil, only two native species are easily mapped on panchromatic aerial photographs: Parana pine and bracatinga (*Mimosa scabrella* Benth.). The first species, when in adult and mature stage, has a circular, dominant, and dark green crown. Bracatinga, in its initial stage, appears as a dense and homogeneous stand.

On 1:50,000 scale aerial photographs covering moist tropical forest of Kerala and Tamilnadu, India, the following forest cover and land use types were delineated: tropical evergreen, tropical semievergreen, moist deciduous, dry deciduous, teak plantation, eucalyptus plantation, reeds, bamboos, rubber plantations and tea estates (Tomar, 1968). In tropical moist deciduous and tropical dry deciduous forests of Bastar region, India, the following forest cover types could be interpreted on 1:15,000 scale aerial photographs: sal, teak, young plantation and regeneration areas, scattered bamboos, medium and dense bamboos, regrowth on abandoned shifting cultivation areas, scrub lands and degraded forest, shifting cultivation and grass lands. These types were further stratified in 5 m height class and 20 percent crown density classes (Tomar, 1970b).

11.3.2 Tree Size

Instead of measuring tree diameter at breast height (dbh) or basal area, the forest photointerpreter measures crown closure and crown diameter and counts the number of trees (Colwell, 1960). Where relationships have been established, dbh may be estimated from the crown diameter. These parameters are most often used for stratifying the forest in advance of a ground inventory rather than for directly calculating the volume of merchantable timber (Howard, 1970).

To estimate tree size, one usually looks at the crowns. Crown diameter is associated with stem diameter and tree size. A large crown diameter usually means a large tree and vice versa. Photointerpretation aids such as the wedge micrometer can be used to measure crown diameters (chap. 2). This is just a wedge, or two lines intersecting at an acute angle, printed on transparent plastic. The user lays it on the photograph and slides it along until the tree crown (or any other object) just fits within the wedge. Both sides of the wedge are tangent to the tree crown. The diameter of the crown's image can be read from the scale on the side of the wedge. The scale of the photograph is then used to calculate crown diameter.

The dot micrometer is used for comparison instead of actual measurement. A series of dots are printed on transparent plastic. The user lays this on the photograph and selects the dot which appears most nearly the same size as the object being measured. The interpreter soon becomes accustomed to the crown sizes associated with the different tree size classes so measurements will seldom be necessary for size classification alone.

Crown or tree counts can be made fairly accurately on photographs of open grown stands, but they are of limited value when examining closed forest. In tropical rain forest, the crowns of trees other than those of emergents are often so interlaced that it is impossible to measure crown diameter; however, the crowns of the dominant trees can be measured at a scale of 1:10,000 (Paelinck, 1959) and possibly at scales down to 1:20,000.

Stratification of forests on the basis of crown density can be done quite rapidly and accurately. On 1:10,000 scale photographs, 10 percent crown density classes are easily delineated, as are 20 percent crown density classes on 1:20,000 scale photographs.

In the tropics, the stratification of forests into crown closure classes has been used for woodland (Paelinck, 1958; Howard, 1959) and montane forest (Merritt and Ranatunga, 1958; De Rosayro, 1959), but not as far as is known for rain forest emergents. In Sri Lanka, the virgin forests were divided into eight classes using 1:15,840 scale photographs (De Rosayro, 1959). In Brazil, crown density has been used successfully to stratify parana pine (Heinsdijk, 1960). In *Eucalyptus camalduesis* forest, five crown density classes (20-percent increments) were recognized and related to basal area by crown ratio and the establishment of plots in the field.

Crown characteristics and tree height can sometimes be used to stratify the forest into two or three utilization classes. Heinsdijk (1958) stated that three volume classes were readily assessed by an experienced interpreter: less than 150 cu m per ha, 150 cu m to 250 cu m per ha, and more than 250 cu m per ha. He was also able to develop a linear relationship between the timber volume of the upper story trees and total timber volume of the stand. Three volume strata were recognized on 1:60,000 scale aerial photographs of East Godavari, India: low volume, 15-50 cu m per ha; medium volume, 50-100 cu m per ha; and high volume, over 100 cu m per ha. When alloting volume class to stand, not only crown density but also stand height and canopy texture were considered (Tomar, 1970a).

Size, in terms of sawtimber, poles, etc., can also be estimated from tree height. Some interpreters become very good at estimating tree heights from the stereoscopic image. Shadows sometimes help. At scales of 1:20,000 and larger, forest stands can be easily classified into 5 m or even narrower height classes. Heights can be measured with a parallax wedge or similar instrument, but to do so requires time and skill beyond the ordinary.

11.3.3 Density

Density is characterized by the percentage of crown closure. This is usually a visual estimate, often assisted by a comparative photographic template. If the overstory is quite sparse, separate estimates of density can be made for the overstory and understory.

11.4 TIMBER STAND DELINEATION AND MAPPING

Timber stands are the smallest unit of land that a forester usually manages. Maps of stands are one of the most important tools that the forester uses. This section discusses how to map forest stands using aerial photographs.

11.4.1 What To Map

Stands are areas of existing vegetation that are distinguishable from adjacent vegetation (usually in species, size, or density) and which are useful to management for physical, biological, or organizational reasons. On the whole, the stand is the largest piece of land having boundaries related (except coincidentally) to a resource. In all cases stand boundaries will (1) reflect actual vegetation differences or other differences which may affect administration or management, and (2) be locatable on the ground and on aerial photographs.

Other attributes that may affect administration or management can include excessive slopes or topographic breaks along a watershed boundary where management activities would affect two different streams. Nonvegetative criteria used to delineate stands must be things that can be located on the ground at any time, not be subject to rapid or capricious change, carry some rational implications for management, and be accepted across the whole region.

In addition, stand boundaries should be wholly contained within one management unit such as a subcompartment. All subcompartments should be within one compartment, all compartments within one district, etc. This hierarchy is imposed for practical reasons of information organization and management. Certainly it can sometimes result in stand boundaries that do not indicate any difference in vegetation. However, subcompartment boundaries (and thus higher land units) are nearly always located on topographic breaks. When the breaks are sharp, real vegetative differences are congruent with stand boundaries. The one exception is that no subcompartment is allowed to lie in more than one administrative unit (county, state, country) so that subcompartment boundaries are sometimes placed along administrative lines which are not related to topographic features. This may result in adjacent stands which are so vegetatively similar as to have been one stand had it not been for the administrative line which forms their common boundary. This is done for aggregating data by larger political units.

Administrative lines and subcompartment boundaries, though not necessarily related to differences in vegetation, are not subject to arbitrary and capricious changes because they are management neutral. The subcompartment and compartment boundaries will remain the same regardless of the uses imposed upon the land.

If soil and land type boundaries are congruent with actual vegetation boundaries, then they automatically contribute to stand boundaries. If they are not congruent, any union or intersection of actual vegetation with soil or land type that may be desired in a particular case can be obtained by manipulation of the map layers with a GIS. This avoids contaminating the vegetation layer—based mostly on what can actually be seen on aerial photographs—with other information that cannot be so easily seen.

11.4.2 Stand Size

If the available aerial photographs are of good quality and suitable scale, it is often possible to delineate timber stands that are much smaller than it is practical to deal with. Where the difference between two adjacent conditions amounts to only one class (e.g., between large sawtimber and small sawtimber) or between poles and saplings, a 4 ha or 5 ha minimum stand size is customary. For conditions which differ by more than one class (e.g., sawtimber left in the middle of a clearcut or poles in overmature sawtimber), a 2 ha minimum stand size is acceptable. An even smaller stand size may be appropriate for special interest areas (endangered species habitat, archaeological sites, and so forth). A 0.5 ha pond in a timber stand might well be delineated as a separate "stand" to the best of the interpreter's ability. A gravel pit smaller than 2 ha might be separately delineated because of its distinctly different and more disturbing land use.

Differences in actual vegetation will generate timber stands generally between 2 ha and 40 ha in size. The average size may vary with timber type and history, but on most forest districts, it is between 10 ha and 20 ha. Keeping stands wholly within subcompartments has little effect on average stand size. Whatever effect exists is confined to subcompartment boundaries, and because these are topographically defined, they are often congruent with stand boundaries defined by existing vegetation anyway.

11.4.3 Selection of Photography

Select the best available photographs for the project at hand.

Use the largest scale photographs that cover the whole area (compartment or compartment group) being mapped. Stand delineation can be done well at 1:24,000 scale, and sometimes even at smaller scales. Often one must use what is available.

Use the best quality photographs available. Some photographs will have excellent detail in some areas of the photograph and very poor image quality in other areas. Some interpreters may feel that color photographs are vastly superior to black-and-white, but good black-and-white photographs will almost always be more useful than mediocre color photography.

Use the most recent, good-quality photographs that cover the area. If one has photographs that cover only part of the area and that is where a change has taken place, consider using two different sets of photographs. Change is occurring all of the time, and over a period of years, there will come to be a considerable difference between what the photographs show and what one finds on the ground. Most natural noncatastrophic change can be predicted and explained. Slow changes, such as increases in tree size, will, after a long time, eventually render aerial photographs unusable. On the other hand, a timber sale can make the photograph practically useless in less than a year. Use photographs recent enough to show any changes resulting from management. In many instances, however, newer cutting units may not show on any existing photographs. In that situation, consider the use of airborne video or satellite imagery to update the stand records.

11.4.4 How to Start

After selecting the photographs to be used, lay out the effective area of the photographs. This requires locating the principal point of each photograph, then stereoscopically locating the conjugate points. Using ink of a different color than will be used to mark stand boundaries, draw a line perpendicular to the line of flight with a ruler across one photograph of a pair, halfway between the principal point and the conjugate point. Draw another line parallel to the line of flight between the principal point and the photograph's side margin, about 2.5 cm in from the margin. Transfer these lines to the adjacent photographs under stereovision. When completed, each photograph will have a rough rectangle formed by two lines and two "crooked lines" and located in the middle part of the photograph. This is the photograph's effective area or "square one."

Always work within the effective area of the photographs because it has less distortion and fewer displacements. To tie stand boundaries together between photographs when transferring them to a base map, stand boundaries should be extended for 0.3 cm to 0.6 cm outside the effective area. This also helps the photointerpreter when moving from one photograph to another.

11.4.4.1 Calculate Scale

Although the nominal photographic scale may be 1:12,000 or 1:24,000, few if any photographs of the set will be at this scale. Scale is discussed in chapter 2. While there may be no need to determine scale for purposes of stand delineation, it will be required if any measurements are to be made from the photographs.

11.4.4.2 Add Compartment and Ownership Boundaries

To guide the mapping of stands in a certain management unit, such as a compartment or compartment group, one must place the boundaries on the photographs. Sometimes compartment boundaries correspond with physical features such as ridge tops. If it is a sharp ridge, there is little problem; if it is a broad ridge, one may have trouble locating its center on the photographs. Getting the boundary properly located becomes as much a map-to-photograph transfer problem as it is a photointerpretation problem. Because parts of subcompartment boundaries are also stand boundaries, subcompartment boundaries should also be put on the photographs. Similarly, property boundaries may also have to be added. Stand boundaries should be first transferred to the planimetric base so that stand areas can be accurately determined. Then ownership boundaries can be accurately placed as well.

11.4.4.3 Tools of the Trade

All stand delineation should be done stereoscopically. To draw the actual stand boundaries use Pilot Pens SC-UF or equivalents. They are inexpensive and give about the right line width, yet the ink is easily erased by a cotton swab moistened with ammonia. Use a color that can be seen easily, such as blue for stand boundaries and red for property boundaries.

11.4.4.4 Start From What Is Already Done

Many forested areas have had some if not all of their area mapped into stands at some time in the past. In all probability, current stand exam records were tied to the stands as they have been mapped earlier. A wholesale redelineation may make it impossible to use previously gathered field information, or make it possible only with a lot of questionable cobbling of the data. Accept what can be used from the previous mapping, and change what needs to be changed.

Where new cutting information does not exist on photographs, one may have to traverse the cutting unit in the field and plot the traverse on the base map. Where that is necessary, do it before beginning any new stand delineation, then transfer the stand boundaries from the base map back to the photograph. Where many unmapped cutting units have accumulated, which do not show on existing photographs, consider the use of satellite imagery such as SPOT-generated orthophotographs.

Adjacent compartments may have been mapped previously. While none of those stand boundaries will extend into the compartment being mapped now, they might have if based on vegetative criteria alone. Where that is the case, stand boundaries should join together across the compartment boundary. A first step in delineating new stands should thus be to carry the boundaries of stands in adjacent compartments into the compartment being mapped.

11.4.4.5 Do the Easy Part First

Look first for the boundaries between forest land and nonforest land. Nonforest land on which the vegetation may be managed, like grassland or shrubland, might be more finely divided into map units possessing different characteristics. Be careful of shadows, especially on north-facing slopes in the northern hemisphere and south-facing slopes in the southern hemisphere. One may mistakenly interpret lands as being forested when in reality one is seeing shadows. This is a good reason why all stand delineations should be done stereoscopically. The trees sticking up might give the keen observer some clue as to location of the stand's edge. Long, swooping, smoothly flowing stand boundaries are a sign of insufficient attention to detail, for stand boundaries are rarely smooth curves. They should exhibit roughness and short-run directional changes where the mapper includes or excludes clumps of trees or small openings.

11.4.4.6 Cardinal Rule on Stand Differences

When delineating stands, the cardinal rule is to look for differences and put boundaries between them. Worry about what the differences are later. Some people feel that they need to take stratum definitions into account when delineating stands. While that may sometimes be necessary, especially when the stratum definitions are unusual, delineations should generally concentrate on finding, not evaluating, differences.

To be useful, stratum definitions must be reasonably broad. If they are too narrow, their degree of refinement may exceed the ability of any photointerpreter to classify them. Given this breadth of strata, it would not be unusual to find two adjoining stands, both belonging to the same stratum, yet identified rightfully as two different stands. If the interpreter delineating stands goes over the photograph looking for stratum differences as the place to put boundaries, this distinction between stands might be missed. What will make stands look different on the photographs are differences in species, tree size, and stand density. These are generally the main characteristics upon which stratum definitions are based.

Without doubt aerial photography is a most important tool for forestry survey, but the information it provides is short-lived. The photograph represents the state of the forest at the moment the photography was acquired. It is most important that interpretation of the aerial photographs is done by foresters familiar with the region.

11.4.5 Transferring Features Between Photographs and Maps

Estimates of area are important for forest planning and resource inventory. Tilt and relief displacements in aerial photographs make direct area determination imprecise. The limitations can be overcome by transferring information from the photographs to a planimetric or topographic base map. The transfer may be done analytically or graphically (chap. 2). In decreasing order of sophistication, the methods of transfer are

- mathematical adjustment of points digitized directly from photographs
- use of a stereoplotter
- use of an instrument like the Zoom Transfer Scope
- use of orthophotographs.

11.5 FORESTRY APPLICATIONS

Olson (1992) lists three general uses of aerial photographs common to most forestry applications: land navigation, stratification and valuation. Resource specialists use aerial photographs to get from one place to another in many types of field activity. Navigation may be done by following one's progress on the photograph or by use of bearings and distances calculated from the photographs. Stratification is dividing the photograph into various land cover classes (as discussed in the preceding section) or the classification of inventory sample plots into simple forest/nonforest classes. Stratification is desired to reduce the amount of ground a field crew has to examine. Valuation is the act of determining the worth or value of a resource. Interpreters use aerial photographs to determine the amount and extent of a particular resource.

Nearly every field activity conducted in the forest can benefit from use of aerial photographs. This section discusses some of the more common uses for forest inventory, recreation surveys, roads and access, ecological classification, and urban forestry.

11.5.1 Forest Inventory

Resource inventories are accountings of goods on hand. Resource managers are interested in the kind, extent, and condition of the resource base. A goal of resource inventories is to collect the information that the manager requires at the least cost and to make the most use of the data once it is collected.

Interpreters use aerial photographs in forest inventory (Lund, 1988) to

- directly evaluate resource information such as vegetative type, crown width, area, tree heights, timber volume, land use class and distances between objects
- classify and map such attributes as soil and vegetation type
- define and coordinate areas of inventory and monitoring responsibility (i.e., separating forest land from nonforest land for timber inventories)
- create sampling frames and sample units including mapped stands (for stand-level inventories) and photography points or field plots for extensive forest surveys
- provide sources of information for pre- and post-stratification of sampled data
- store or document information directly on the photographs (plot location, historical information, and miscellaneous observations)
- illustrate reports and analyses
- develop a base from which to monitor and update changes in land cover and land use
- create aids for training, briefings and information transfer.

Resource specialists use stratification and sampling to keep field costs to a minimum when inventorying large areas. In the simplest case, interpreters separate forested lands from nonforested lands and then collect data on the forested lands.

In very large area inventories, multistage or multiphase sampling is used. In this situation, more information is extracted from aerial photographs. For management type inventories, stands may be delineated and interpretations of forest type, stand size, density, and age made from the aerial photographs and ancillary data. Such information, along with predicted tree volume, is stored in a database.

In more complex inventories, data (such as interpreted forest type, tree height, crown diameter, canopy closure, aspect, and slope) are extracted from the aerial photographs of randomly or systematically selected areas. Later, field crews visit a subset of the sample units and collect additional information that cannot be interpreted from the photographs, such as tree diameter, basal area, tree age, and site index. Regression or prediction equations are then developed to predict the field information from the aerial photographic information. These equations are applied to all interpreted areas within the inventory unit. If geographic coordinates of the field sample units are recorded and the interpreted data from the aerial photographs and the field samples then stored in a GIS, crude maps showing the predicted values can be generated (Lund and Thomas, 1989). Thus, by using information extracted from aerial photographs and some field samples, statistics and maps can be generated for the entire inventory unit at a low cost.

Resource managers often have uses for two levels of inventory: those at the stand or project level (commonly called management, in-place, or intensive inventories) and those conducted over large areas such as a National Forest or state (often called forest survey or extensive inventories).

11.5.1.1 Stand-Level Inventories

Stand-level inventories are used for project planning, such as a prelude to silvicultural treatments (thinning, harvesting), wildlife habitat analyses, cultural resource surveys, and other activities demanding location-specific information. Section 11.4 describes how to delineate and map stands for nearly any purpose. Following the delineation of the stands, data are collected within selected mapped units using either walk-through reconnaissance or robust sampling strategies. Various options for stand inventory designs are given in Lund and Thomas (1989) and Lund et al. (1993).

Once data are collected, they are summarized and the resulting information is stored in a database keyed to each measured stand (or mapped polygon). Where a GIS is available, both the mapped information and the sample data can be easily accessed and updated.

11.5.1.2 Forest Surveys

Broad-scale inventories are used for forest planning, as input to state reports, and for national assessments. Such extensive information is useful for policy development decisions and for research—for example, on modeling carbon cycling and global climatic changes.

The first forest surveys in the United States were often done on parallel transects run at fixed intervals through the forests. The potential of aerial photography was not generally appreciated at that time. Aerial photographs were probably first used simply to navigate to the forest inventory plot areas by determining which roads gave best access and which terrain routes were easiest to travel by foot or pack animal.

Lund and Thomas (1989) describe a variety of sampling designs for forest surveys. Most that incorporate the use of remote sensing involve multiphase or multistage sampling. In both of these sampling schemes, several levels of data acquisition are used, often starting with satellite imagery or small-scale aerial photography and ending with the examination of a field plot on the ground. The same piece of terrain is examined in both situations. In multiphase sampling, the same size plot area is examined at each level. In multistage sampling, successively smaller areas are examined. Two-phase and two-stage sampling are the most common, but with the increasing availability of satellite imagery and small-scale aerial photography, interest in three or more phases and stages is increasing.

In a two-phase sampling system, large numbers of plots are classified at the first phase, using aerial photographic interpretation. A portion of these photographic plots are subsampled, usually taking advantage of strata identified on the photographs to improve ground plot sampling results, such as estimates of wood volume, growth, area of forest land, etc. (Bickford, 1952). The concept for this approach was an important breakthrough in the use of remote sensing in forest inventory, and was almost immediately accepted as the basis for establishing a sampling frame in the forest survey programs of the United States and other countries (Mattila, 1984). The use of two-phase sampling in forest inventory was enhanced in a multitude of studies of statistical efficiency.

At the same time as two-phase sampling was gaining acceptance, efforts were underway to use two-stage sampling. Although this had special appeal for certain studies (Colwell and Titus, 1976), two-stage sampling was never accepted to the degree that two-phase sampling has been accepted for forest inventory.

From the 1950s through the 1970s, special interest evolved in using large-scale and infrared photography to improve forest survey estimation procedures and processes (Losee, 1953; Haack, 1962; Heller et al., 1964; Bonner, 1977; Aldred and Lowe, 1978). This resulted in several attempts to use large-scale photographs in concert with small-scale photographs in two- and three-phase and two- and three-stage sampling (Haack, 1962). Application of three-phase sampling in forest inventories stalled for several years waiting derivation of statistical estimators. About this time, the use of aerial stand volume tables for estimating timber volumes from aerial photographs began to receive acceptance (Moessner, 1957; Pope, 1961; Haack, 1963; Sayn Wittgenstein and Aldred, 1967). Further extensions of the two-phase sampling concept involved such innovative concepts as use of equal volume stratification from aerial photographs (phase 1) coupled with 3-P sampling on the ground (phase 2) (Dippold, 1981). Special applications of two-phase sampling to multiresource sampling also emerged (LaBau, 1981; Czaplewski and Cost, 1986).

In the late 1960s and mid-1970s, interest in use of satellite imagery resulted in tests of applications to forest and rangeland surveys (Langley, 1969; Heller, 1975). Aldrich (1979) provided an excellent summary of the state-of-the-art of remote sensing relative to inventorying wildland resources. A later summary, specifically for forest inventory, was published by Duggin et al. (1990).

Satellite imagery brought new possibilities for multiphase and multistage sampling applications in forest inventory (Poso, 1984). Studies evaluated multiphase and multistage sampling of up to four levels (Frayer, 1979), but these were limited because estimators had not been derived. Sampling estimators were finally derived for multiphase sampling (Li et al., 1984) and were soon tested in forest inventory efforts in Alaska (LaBau and Schreuder, 1983). This Alaska four-phase system was planned to take advantage of regression sampling (Schreuder et al., 1984). Although there was promise in the use of satellite imagery (Hame and Tomppo, 1987), initially there were also many problems to overcome, such as registration errors among images and difficulties in handling the very large data sets for an extensive inventory (Winterberger and LaBau, 1988; LaBau and Winterberger, 1989).

A disadvantage of satellite-driven, multiphase sampling is that the same plot size has to be sampled or observed at each phase. For the four-phase design tested in Alaska (LaBau and Schreuder, 1983), this meant that it was necessary to evaluate 8-ha plots at each phase. Measuring an 8-ha plot on the ground is an imposing problem and was one reason the four-phase system was not pursued in Alaska.

An advantage of satellite-driven, multistage sampling is that it is not necessary to observe an area in its entirety from stage to stage as it is from phase to phase in multiphase sampling. In multistage sampling, subsets (generally subclusters) of the area observed at the satellite stage can be measured or observed on the ground or lower stages. The ground-stage plots may be 0.5-ha subclusters from a much larger area measured at the other stages. For instance, instead of being handicapped by the need to measure 8-ha plots on all phases in multiphase sampling, it is possible to measure a 4000-ha area on the satellite image, a subcluster of 40-ha sites on a high altitude photograph, a subcluster of 20-ha sites on a low altitude photograph, and a subcluster of 0.5-ha ground plots. Although this multistage approach shows much promise, it has not, to date, been accepted as the basis for national forest inventories in the United States.

11.5.1.3 Future Needs

In the future, there will be need for more general-purpose and fewer single-function inventories, especially at the broader levels. There will be need for combining inventories to reduce costs and confusion and for more timely information.

Multiple Resource Inventories: Past emphasis has been on single-function inventories. With declining budgets and increased concerns over the environment, more emphasis is being placed upon integrated- or multiple-resource inventories. General principles for integrating data collection activities are found in Lund (1986). Statistical procedures incorporating aerial photography and other forms of remote sensing with multiple resource inventories are found in Schreuder et al. (1992).

Combining Inventory Designs: Having two levels of inventories on a given piece of land can be costly and confusing. Broad forest surveys have not met the needs of the local forest manager very well in terms of in-place data and information. Recently, new approaches, allowing special linkages between extensive inventories and in-place needs have shown promise (Tomppo, 1993). Statistical procedures for combining extensive inventory ground samples with stand mapping are found in Lund and Thomas (1989).

A two-phase sampling design now being used in Alaska also shows such promise. It samples 2-ha sites on high-altitude, 1:60,000 scale aerial photographs and subsamples some of these photographic plots as measured ground plots. The system uses Landsat Thematic Mapper (TM) imagery to prestratify the sampling frame into the major classes of interest. One modification of this approach involves using map polygons from forest type maps as the prestratifying media, upon which two- or three-phase sampling is based. This approach shows promise for tying Forest Survey data sets to the National Forest Management Plans, by using lists of the National Forest Management Plan polygons as sampling frames.

Updating Inventories: Often there is need to quickly update both plot and stand information. One of the more encouraging recent developments in remote sensing applications to forest inventory and management involves the use of aerial videography. The advantages of this new form of remote sensing lies in the fast turn-around time for imagery and its relatively low cost. One enhancement that is being used is obtaining stereography using the videography, thus allowing for three-dimensional interpretation.

In another example of new applications of remote sensing to forest surveys, the USDA Forest Service and Minnesota Department of Natural Resources are testing a design to produce forest inventories every one to four years, rather than the current eight- to fifteen-year cycle. Permanent 0.4 ha-forest inventory plots are classified with remotely sensed imagery taken every four years. Field crews remeasure plots that are classified as disturbed or changed (e.g., clearcuts or regenerated stands). A subsample of the undisturbed plots is remeasured by field crews. This subsample provides data to build models that predict the current condition of each plot based on past conditions for each plot. This allows unbiased statistical estimates using prestratification and two-phase sampling for regression, which are simple and well developed methods in sample survey theory. Growth and condition of all other permanent plots (i.e., the undisturbed stratum) are estimated from previous field data that are updated using a growth and survival model. Landsat TM data are used to estimate a likelihood of change for each plot, but aerial photography or videography could be substituted. TM data will also be accurately classified into a small number of categories:

nonforest, hardwood forest, conifer forest; and high, medium, and low greenness (Befort, 1992). Registration accuracy between TM images and 0.4 ha-field plots is within 1 to 2 pixels (within 30 m to 60 m), using interactive computer imagery and aerial photographs, on which field crews have marked the plot location. Poststratification of these classifications will improve statistical efficiency. One-fourth of Minnesota will be classified each year using TM imagery.

11.5.2 Assessment of Insect and Disease Damage

Insects and disease cause extensive damage to forests. In the United States, millions of hectares are defoliated annually by spruce budworm *(Choristoneura fumiferana)*, western spruce budworm *(C. occidentalis)* or gypsy moth *(Lymantria dispar)*. Repeated defoliation causes growth loss, dieback of crowns, and tree mortality. Bark beetles, such as southern pine beetle *(Dendroctonus frontalis)*, or mountain pine beetle *(D. ponderosae)*, can kill large numbers of conifers. Disease caused by root decay fungi, vascular fungi, rusts, or air pollution can also cause extensive forest damage. Keeping forests healthy to reduce ecological, economic, and social impacts of insects and disease is an important element of sustainable forest management. Monitoring of insects, diseases, and their damage provides data needed to support decisions relative to the management of these sources of destruction.

Damage caused by many forest insects and diseases is highly visible. This is especially true of those that cause tree mortality or foliar injury. Many pests of economic importance, such as bark beetles and defoliating insects, fall into this category. Consequently systems to monitor insect and disease damage often include a remote sensing component.

When definitive information on the status and impact of forest pests is required, aerial photographs are often used. They have been used since 1925, when entomologists tried to detect pines killed by bark beetles in California using oblique aerial photography. Subsequent research done by USDA Forest Service in Beltsville, Maryland; Portland, Oregon; and later Berkeley, California, established many of the parameters for operational use of aerial photography for mapping and assessing damage caused by forest insects and disease.

When aerial photographs are used to map or assess forest damage, several key points must be kept in mind.

- Damage caused by insects and diseases is seasonal and dynamic. Unless historical data are desired, it is not possible to use archived photographs. Missions should be flown when damage is most visible.
- Damage caused by insects and diseases is most easily detected by a change of color in the forest canopy. Therefore color or CIR film must be used.
- In many cases, the numbers of dead and dying trees or a classification of damage on individual trees are the primary data derived from aerial photographs. Therefore, resolution is of importance. Large- to medium-scale photographs have been most widely used; positive transparencies are preferred over prints because they offer higher resolution (Hoppus, 1990) and more latitude in analysis.

11.5.2.1 Photographic Parameters

Scales and Formats: Photographs of a 23 cm x 23 cm format are the most widely used for assessing insect and disease damage. Scales for most applications range from 1:4000 to 1:24,000. Larger scales are used when counts of damaged, dead, or dying trees are made, but if survey requirements call for stratification of vegetation types and damage classes, smaller scales can be used.

Small-format (35-mm and 70-mm) photography has also been used for damage assessment (Heller et al., 1959a). Although these formats can provide images capable of resolving damage at a relatively low cost, they have not gained wide acceptance for operational use. The primary reason is that the relatively small area covered by each photograph makes it difficult to relate to exact ground location.

Photographs taken by high-altitude reconnaissance aircraft, such as NASA's ER-2, have become a popular means of mapping and assessing forest insect and disease damage over large areas. Camera systems include the Hycon HR 732, 23 cm x 46 cm frame camera, and the Itex KA80A and Iris II optical bar panoramic cameras. Panoramic cameras produce an image on standard 14 cm aerial film which can be 11 cm x 100 cm, 127 cm, or 132 cm. Lateral coverage is up to 140°—70° each side of nadir. These cameras are equipped with an f3.5, 61 cm focal length lens. From a flying height of 18,300 m above mean terrain elevation, an image of 1:30,000 scale is produced at nadir (Ciesla et al., 1982). High altitude reconnaissance aircraft and large-format cameras have proved to be a valuable tool for forest damage assessment because of their high spatial resolution and ability to cover large areas in a short time. One disadvantage of this format is scale change with distance from nadir; however, this can be compensated for with computer-generated, equal-area grid overlays (Liston, 1982)

Films: Both color and CIR films have been used for forest damage assessment. CIR films have the advantage of haze penetration and the ability to readily differentiate between hardwoods and conifers (Ciesla, 1977).

Natural-color films have been used primarily in western North America where atmospheric haze is less a problem, and conifers are the dominant forest cover. These films are favored because they are more capable of resolving subtle color differences in the crowns of dying trees. This information is often important in determining which year a tree was attacked and the species affected (Ciesla, 1977).

In the tropics, analysis of 1:10,000 scale multispectral aerial photographs (diapostives) on an additive-color viewer, with different combinations of color filters and light intensities, allowed detection of diseased poplar poles affected with dieback *(Cystopora chrysosperma* (Pers.) Fr.) and canker (*Dothichiza populea* Sacc. and Briad) complex (Misra and Shedha, 1983). Using the above technique it was possible to separate diseased, insect-infested, dead, and healthy trees.

11.5.2.2 Applications

Bark Beetles: Aerial photographs can be used to estimate the area infested by bark beetles, the numbers of trees attacked, and the volume killed. Resultant data are used to determine the magnitude of salvage or direct control action required. Aerial photographs have also provided information for estimating impacts of bark beetle outbreaks on forest resources.

Surveys to estimate damage caused by bark beetles make use of a double sampling approach, where counts of dead and dying trees are made on a large photographic sample and adjusted by a small sample of ground plots (Wear et al., 1966, Ciesla et al., 1967). Aerial photographs are examined stereoscopically to make counts of dead and dying trees on sample plots of a fixed size. Heller et al. (1959b) and Wear et al. (1966) determined that scales from 1:4000 to 1:8000 were most effective for this purpose.

In 1976, work was begun in the western United States to estimate losses caused by the mountain pine beetle in its two major hosts, ponderosa and lodgepole pines. A three-stage design consisting of aerial sketch mapping, aerial photography, and ground sampling was developed. Aerial sketch mapping was used to stratify infestations into damage classes. Color aerial photographs of 1:6000 scale were used to make tree counts on sample plots, and a small sample of ground plots was taken to adjust the photointerpreted estimate and gather volume information (fig. 11.15 — see color section). Ground samples were selected according to a probability proportional to size procedure (Bennett and Bousfield, 1979; Klein et al., 1979; White et al., 1983). Later, high altitude panoramic photography was used for both stratification and tree counts (Dillman and White, 1982; Klein, 1982). Unfortunately, both methods were too costly and time-consuming to be conducted regularly.

Caylor et al. (1982) scheduled three panoramic aerial photography missions over northern and central California to locate concentrations of bark beetle activity. The photographs were used to aid in planning salvage sales following a severe drought in 1975-76.

Damage caused by mountain pine beetle in lodgepole pine forests in southern British Columbia, Canada, was appraised using several scales and film formats (Gimbarzevsky et al., 1992). Twenty-three cm CIR and color photography was acquired at scales of 1:56,000, 1:19,000 and 1:8000; and 70-mm photography was acquired at scales of 1:6000 and 1:1000. The small scale 23-cm photographs were used to map broad classes of damage, and the larger scale 70-mm photographs, in combination with ground surveys, were used to estimate numbers of trees and volume affected. The 70-mm photographs served as guides for interpreting of the 23-cm photographs.

Defoliators: Color and CIR photography were acquired at scales of 1:6000 and 1:15,000 to estimate foliage protected from aerial application of biological and chemical insecticides against forest tent caterpillar *(Malacosoma disstria)*. The tests were conducted in bottomland hardwood forests in southern Alabama, where spring floods regularly inundate large areas, making classic pre- and post-treatment insect sampling difficult. The resultant photographs allowed ready differentiation of blocks of protected from untreated stands. Both color and CIR films resolved damage, but CIR provided better contrast between damaged and undamaged areas (Ciesla et al., 1971).

A similar approach was used in conjunction with a test of aerial applications of insecticides against pandora moth *(Coloradia pandora)*, a defoliator of ponderosa pine, during an outbreak which occurred on the Kaibab Plateau in northern Arizona (Ciesla et al., 1984b). CIR photographs, at scales of 1:6000 and 1:15,000, were taken immediately prior to spraying and approximately six weeks later, at the time of peak defoliation. Assessment of foliage protection was based on comparison of the two sets of photographs.

Susceptibility of stands of Douglas fir and true fir to defoliation by Douglas-fir tussock moth *(Orgyia pseudotsugata)*, relative to site and stand conditions, was rated on 1:8000 scale, CIR aerial photographs of the Blue Mountains in eastern Oregon (Heller et al., 1977). A model was developed to predict probability of defoliation for a given set of conditions. In general, the probability of defoliation was found to be higher in stands that were lower in elevation, on east-facing slopes, on ridge tops, of high tree density, had trees of large crown diameter, and in stands composed primarily of true fir and Douglas fir.

During the late 1970s and early 1980s, the area of hardwood forests in the eastern United States defoliated by gypsy moth increased significantly. This made it difficult for survey teams to aerial sketch-map all of the infested area and produce defoliation maps of acceptable quality. In 1981, a 6475 sq km test site was established in central Pennsylvania and photographed by a NASA ER-2 with a panoramic aerial camera using CIR film. Defoliation was easily resolved and a two-level classification and map transfer system was developed based on monoscopic interpretation of the photographs (Ciesla and Acciavatti, 1982). A subsequent evaluation indicated that the effectiveness of aerial spray treatments based on foliage protection could also be done (Ciesla, 1984a).

Two years later, a pilot survey involving all or portions of Delaware, Maryland, New Jersey, and Pennsylvania determined that panoramic photography could be acquired over multistate areas within a specified time frame. All designated target areas were successfully flown over a two-day period (Ciesla et al., 1984a). Between 1983 and 1989, six annual defoliation surveys were conducted with panoramic photography over portions of the *L. dispar* outbreak area in the eastern United States (Acciavatti, 1990). Guidelines for mapping insect defoliation in eastern hardwood forests on high-altitude panoramic aerial photographs were developed (Ward et al., 1986).

Beech Bark Disease: Beech bark disease, which is caused by the association of a bark-infesting scale insect *(Cryptococcus fagisuga),* and a fungus of the genus *Nectria,* is a tree-killing disease of American beech *(Fagus occidentalis).* The insect was accidentally introduced from Europe and has gradually spread over much of the natural range of American beech in the northeastern United States. Shortly after the disease was discovered in West Virginia in 1981, a special survey was designed to inventory the distribution and intensity of damage on the Monongahela National Forest. A multistage sampling design was used, with 1:6000 scale CIR aerial photography (see sec. 11.5.1.2).

A range of damage symptoms associated with beech bark disease, including chlorotic, dead, and dying trees, was visible on the photographs. A dichotomous photointerpretation key was developed to aid in classifying symptomatic trees and identifying sources of photointerpretation error. The inventory provided estimates of the number and volume of infected trees (Mielke et al., 1984).

Oak Wilt: Decline and mortality of Texas live oak *(Quercus virginiana* var. *fusiformis)* by the vascular fungus *(Ceratocystis fagacearum)* is widespread in portions of central Texas. Groups of dead trees were visible on both 1:12,000 scale and high-altitude, panoramic CIR aerial photographs taken over damaged areas (Ciesla et al., 1984c)

Forest Decline: Forest decline, the gradual deterioration of tree condition and vigor which can ultimately lead to tree death, has affected a number of tree species. In the eastern United States, decline of red spruce and several hardwoods has caused recent concern. Some workers have suggested that increased levels of pollutants (e.g., acid rain, ozone, sulphur dioxide, and heavy metals) may play a significant role (Johnson and Siccama, 1983; Friedland et al., 1984).

In 1984, the USDA Forest Service initiated a regional inventory to assess the condition of the high-elevation spruce-fir forests in portions of New Hampshire, New York, and Vermont (Weiss et al., 1985). Sample blocks of 3240 ha each were established in each of four survey regions and photographed with 1:8000 scale, CIR film. Vegetation types containing a significant component of host type were defined, identified on the photographs, and stratified into three damage classes. One-hectare plots were established on the aerial photographs in each vegetation/mortality class, and counts of dead spruce and fir were made. A subsample of photographic plots, representing all vegetation/mortality groups, were ground surveyed to acquire data on tree condition, volume, and status of regeneration. Ground counts of dead and dying trees were used to correct aerial photographic counts, using double sampling with regression. This inventory provided base-line data on the health of these forests. In addition, complete area coverage of portions of the spruce-fir type in the Northeast was obtained with CIR film, at a scale of 1:20,000 or 1:24,000, for stratification of host type and classification into damage classes (Miller-Weeks, 1990).

A similar inventory was conducted in high-elevation, red spruce forests in West Virginia, using high-altitude, panoramic aerial photography (Mielke et al., 1986). Forests containing a component of host type were stratified into vegetation/mortality types, and ground surveys were conducted to acquire data on numbers of trees and volume affected by vegetation/mortality class.

Inventories to assess the status of tree mortality and decline in high-elevation, spruce-fir forests in the southern Appalachian Mountains of North Carolina, Tennessee, and southwestern Virginia were also conducted (Dull et al., 1988). These forests have been severely damaged by the balsam woolly adelgid *(Adelges piceae).* Color and CIR photographs, at a scale of 1:12,000, were used to map and classify all of the spruce-fir type in this region into damage classes. Ground surveys provided additional data on numbers of trees killed. Base-line data from this survey were digitized and entered into a GIS for analysis, display and storage, and to provide a base line from which future change can be monitored.

Concern over a decline of sugar maple *(Acer saccharum)* prompted a statewide inventory of the health of Vermont's hardwood forests in 1985. Preliminary investigations indicated that a range of damage types, indicative of hardwood decline, could be identified on 1:8000 scale CIR photographs. Interpretation guides were developed to aid tree classification on aerial photographs (fig. 11.16). A total of 175 aerial photographic samples were established across the state. Each sample was divided into 144 cells of 1 ha, which were classified into vegetation/damage classes. A subsample of cells was drawn from each class for tree counts and a subsample of these cells was selected for ground data acquisition (Kelley and Eav, 1987). A similar approach was used for assessing oak decline in portions of Arkansas, North Carolina, and Virginia (Oaks et al., 1990).

Table 11.5 is an example of a dichotomous key for identifying hardwood decline and mortality. Murtha (1972, 1978) developed a similar key for labelling stress symptoms seen on forest trees and then suggested possible causes for the symptoms (table 11.6, fig. 11.17 — see color section). He recognized four distinct injury symptoms or Damage Types.

Damage Type I: trees are totally defoliated
Damage Type II: trees are partially defoliated
Damage Type III: tree foliage shows a color change, and
Damage Type IV: tree foliage shows a near-infrared change.

Subcategories of these types are based on minor variations in the tree response. For example, Damage

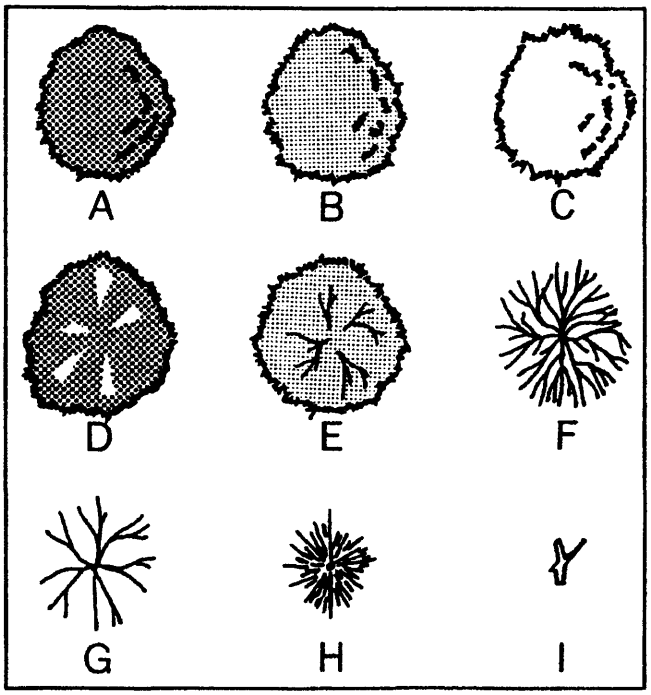


Fig 11.16. Guide to aid in classifying tree condition in central Vermont on large scale CIR aerial photographs: A - apparently healthy hardwood, B - slightly chlorotic hardwood, C - acutely chlorotic hardwood, D - hardwood with full complement of healthy foliage and "flags" of chlorotic or dying foliage, E - hardwood with branch dieback, F - recently dead hardwood, G - older dead hardwood, H - recently dead conifer, I - snag (Ciesla et al., 1985).

Type IIE is a conifer displaying a thin crown through premature loss of the older foliage age classes, while the current-year age class is green and still on the tree.

Since the key (table 11.6) was originally published, it has been reconfirmed that the photointerpreter's a pri-

Table 11.5. Dichotomous key to aid in classifying hardwood decline and mortality with CIR, August-early September photographs in areas of Vermont (Ciesla et al., 1985).

1.	Little or no foliage present, bare branches visible	2
1a.	Foliage present in at least part of crown	5
2.	Branch pattern dendritic, color light gray or white	3
2a.	Branches radiating from a central main stem, color light gray or white	**Dead conifer**
3.	Fine branches abundant, color light gray or blue gray (white if white or gray birch)	**Recent dead hardwood**
3a.	Fine branches less abundant or entirely missing, color white	4
4.	Some fine branches still present	**Older dead hardwood**
4a.	Only main stem or one or two lateral branches present	**Snag**
5.	Foliage color red, magenta or red brown	6
5a.	Foliage color pink, white, yellow or yellow orange	9
6.	Crown conical or deeply lobed, foliage color normally dark red-brown or red violet	**Living conifer**
6a.	Crown rounded, widespreading or multiple, foliage color red, light reddish brown or magenta	7
7.	Foliage color light reddish-brown	**Foliar injury by leaf miners or leaf skeletonizing insects**
7a.	Foliage color red or magenta	8
8.	Dead branches visible in crown	**Hardwood with top or branch dieback**
8a.	Dead branches not visible in crown	**Apparently healthy hardwood**
9.	Foliage color yellow or orange-yellow	10
9a.	Foliage color white or pink	12
10.	Foliage color yellow	11
10a.	Foliage color yellow-orange or orange	**Hardwood with early fall coloring**
11.	Crown shape conical	**Dying conifer (spruce or fir)**
11a.	Crown shape rounded	**Dying hardwood**
12.	Foliage color pink	**Slightly chlorotic hardwood**
12a.	Foliage color white	**Acutely chlorotic hardwood**

Table 11.6. Dichotomous key to photo interpretation of forest tree injury symptoms (Damage Types) with large-scale (>1:4000) aerial photographs (after Murtha 1972, 1978). There are two logical choices for each numerical division in the key, while the alphabetical choice at a numerical level leads to a Damage Type or to a further sub-choice. The choice is determined by the most obvious symptom.

If the most obvious symptom is a change in form, go to 1a;
If the most obvious symptom is a change in foliage color, go to 1b

1a. MORPHOLOGICAL change is the most prominent characteristic of the injury symptom 2
2a. TYPE I Injury: the trees are perceived as being totally defoliated 3
3a. Limbs and smaller branches gone, only the main trunk remains or, the bark exfoliated and branches are bleached white .... **Damage Type IA**
3b. Limbs and branches are present, and dark toned 4
4a. Conifer 5
5a. There are a few scattered individuals ..... **Damage Type IB**
5b. There is a large extensive group .... **Damage Type IC**
4b. Deciduous Hardwood (many large spreading branches ... 6
6a. Scattered individuals .... **Damage Type ID**
6b. There is a large extensive group .... **Damage Type IE**
2b. Type II Injury: the trees show some partial defoliation through the presence of some bare branches, contained shadows, or malformation 7
7a. Defoliated branches are concentrated at the top or towards the top of the tree 8
8a. Conifer .... **Damage Type IIA**
8b. Hardwood .... **Damage Type IIB**
7b. Defoliated branches are scattered throughout the crown, with or without loss of limbs or branches; malformation or branch breakage may be present 9
9a. Conifer 10
10a. Malformation or breakage in crown ..... **Damage Type IIC**
10b. No malformation or breakage of branches 11
11a. Current year's foliage is missing .... **Damage Type IID**
11b. Current year's foliage present, older age class or classes of foliage missing (premature loss of older foliage .... **Damage Type IIE**
9b. Hardwood 12
12a. Malformation or branch breakage ...... **Damage Type IIF**
12b. No malformation or breakage of branches .... **Damage Type IIG**

1b. PHYSIOLOGICAL: discoloration of foliage is the prominent character of the injury symptom 13
13a. Type III Injury: the foliage is discolored when it is compared to normal foliage 14
14a. Normal-color photograph 15
15a. Current foliage chlorotic or yellowish 16
16a Conifer 17
17a. Few branches affected .... **Damage Type IIIA**
17b. All or nearly all branches affected ...... **Damage Type IIIB**
16b. Hardwood 18
18a. Few branches affected .... **Damage Type IIIC**
18b. All or nearly all branches affected ..... **Damage Type IIID**
15b. Some or all foliage red-brown or necrotic 19
19a. Conifer with red-brown foliage 20
20a. Only current foliage red-brown 21
21a. All or nearly all of the crown affected 22
22a. All trees topographically stratified ...... **Damage Type IIIE**
22b. Affected trees not topographically stratified, older foliage dark-green, red-brown or absent 23
23a. Older foliage dark-green, red-brown, or absent 24
24a. Dark green old foliage .... **Damage Type IIIF**
24b. Red-brown old foliage .... **Damage Type IIIG**
23b. Older foliage absent .... **Damage Type IIIH**
21b. Only a few or scattered branches with current foliage red-brown, or damage concentrated toward crown top 25
25a. Terminal leader or upper crown foliage red-brown or necrotic .... **Damage Type IIIi**
25b. Lateral branches affected .... **Damage Type IIIJ**
20b. Only older foliage red-brown, current foliage green 26
26a. All or nearly all branches affected ...... **Damage Type IIIK**
26b. Few branches affected .... **Damage Type IIIL**
19b. Hardwood with red-brown (necrotic) foliage 27
27a. Few branches affected .... **Damage Type IIIM**
27b. All or nearly all the crown affected ..... **Damage TYPE IIIN**
14b. CIR Photograph 28
28a. Foliage is a darker or lighter magenta than is the foliage of a comparable unaffected tree 29
29a. Foliage is a darker magenta .... **Damage Type IIIOa**
29b. Foliage is a lighter magenta .... **Damage Type IIIOb**
28b. Foliage of suspect tree not a magenta hue 30
30a. Foliage appears mauve or yellow; if mauve, foliage is chlorotic, return to key item number 15a; if yellow, foliage is necrotic or red-brown, return to key item 15b
30b. If tree crown appears cyan, dark bluish, blue-green, silvery, or silvery green, then tree is defoliated, return to key item number 2a.
13b. Type IV Injury: Foliage in the tree crown shows no prominent or obvious injury symptom, but the foliage age class spectral differences do not appear to be as obvious as they photograph in original transparencies 31
31a. Foliage age class differences are prominent; tree is normal .... **Undamaged**
31b. Foliage age class differences are lost 32
32a. Red filter optical density or digital scanning indicates that the tree foliage is darker than it should be when compared to a known normal tree (This damage type is synonymous with Damage type IIIOb) .... **Damage Type IVA**
32b. Red filter optical density or digital scanning indicates that the tree foliage is lighter than it should be when compared to a known normal tree (This damage type is the forerunner of Damage Type IIIOb) .... **Damage Type IVB**

ori knowledge affects interpretation. This includes awareness of potential or extant environmental stresses, manifestation of the injury symptom on the plant, and the effect of the stress symptom on spectral reflectance change.

The interpreter has to expect the unexpected in environmental stresses. More than one stress can cause any given symptom. Although many spectral studies have been done, a database of spectral changes resulting from environmental stresses does not exist.

Injury symptoms (damage types) change with time. A specific stress may cause a sequence of symptoms on one tree which is seen in a temporal data set. Conversely, the sequence of symptoms may show on a series of trees at one point in time. The sequence of symptoms can be used to identify an environmental stress. Murtha (1982) demonstrated the application of symptomology to obtain the "symptom signature" of SO_2 stress on conifers (fig. 11.18) and hardwoods (fig. 11.19). The symptom signatures are flow diagrams of the progression of injury symptoms from the point of initial stress to the death of the plant.

11.5.3 Recreation

Planning, monitoring, and managing recreation resources can be aided by photointerpretation. Aerial photographs can provide a great deal of information needed in managing forest and water resources for recreational use, and many recreation applications employ the same basic photointerpretation techniques that are used for other applications described in this *Manual*. This section addresses inventory, planning, and monitoring applications for dispersed recreation, developed facility areas, water-related recreation, and user studies.

Douglass (1974) found that most recreation land managers wanted to know what aerial photographs could do for them, but they were unable to give detailed descriptions of the information that they needed to solve their recreation-related problems. Fifteen years later the same difficulty still existed (Douglass, 1989). In those cases where the needs were clearly established, a satisfactory application was developed.

11.5.3.1 Dispersed Recreation Trails

Planning and Layout: Trail layout can be planned on aerial photographs by locating the end points of the proposed trail and connecting them using the trail criteria. Grades of 3 percent to 10 percent are acceptable for hiking trails. Less than 3 percent grades will cause drainage problems and should be avoided when possible. Leaf-off photographs of a scale of 1:15,840 or larger will be needed to determine grade.

A general map of hazards and potentials on selected land types can be compiled by interpreting very-small-scale photographs, permitting large areas of land to be classified quickly. Also, small scales permit viewing of large land and water areas. Leaf-off color photography, at a scale of 1:118,000, has been used to map erosion hazards, landslide hazard, high timber productivity, campground suitability, scenic sensitivity, and off-road vehicle use impacts. In recreation planning, a hazard map can be used to locate areas to avoid and areas to use. High-value-timber growing sites and high hazard areas can be avoided while highly scenic sensitive and stable sites can be sought. The criteria for categories can be established on each forest by the recreation, soils, and engineering staff, and then applied by the photointerpreter to the area to be classified and mapped.

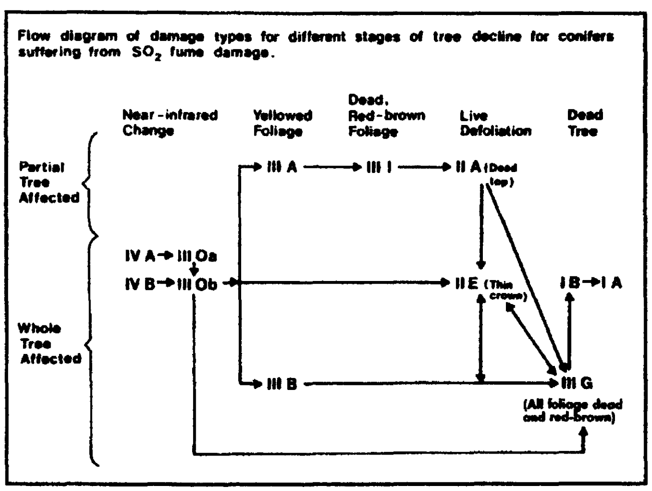


Figure 11.18. Sequence of injury symptoms (Damage Types after Murtha, 1978) used to obtain SO_2 symptom signature for conifers (Murtha, 1982).

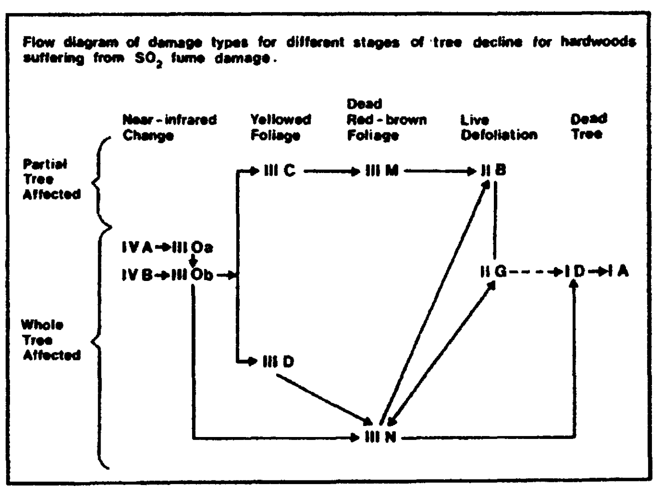


Figure 11.19. Sequence of injury symptoms used to obtain a symptom signature for SO_2 injury to hardwoods (from Murtha, 1982).

Trail Inventory: Trails that are part of a managed trail system can be inventoried on leaf-off aerial photographs of medium to large scale. The standard scale of 1:15,840 will be satisfactory if larger scale imagery is not available. When viewed stereoscopically with even slight magnification, the linear trails are easy to locate and map. Unmapped or abandoned trails can be located and included in the trail inventory. In many eastern United States forests, old tramroads or small-gauge railroad beds can be located on leaf-off photographs. Tramroads are a potential source for additional trail mileage that can be developed with minimal cost.

Unplanned or unwanted trails that occur because of user impacts will be seen on large- and medium-scale aerial photographs. Early spring, CIR photography has been used to highlight areas worn by foot, off-road vehicle, or horse traffic where trails were not planned (Douglass, 1974).

Monitoring Trails: Trail use can be monitored indirectly by using aerial photographs to track vegetation changes and soil erosion caused by use or insufficient maintenance. Washouts, bridge damage, and trail blockages can be observed, as can braided trails, unauthorized campsites, and switchback cutting. Color or CIR photographs taken in spring at the height of the ground cover growth but before full leaf-out, will provide the best opportunity to monitor trail damage; however, most leaf-off photographs will be of value. Here again, photography of a scale of 1:12,000 or larger will be best but will require a large number of photographs; therefore, smaller scale photographs should be tried if available.

Trying to count trail users by type (walkers, runners, bicyclists) for management purposes presents a difficult task if done from ground check stations. In contrast, aerial photography captures an instant-point-in-time view. Stereoscopic small-format photographs can be acquired at near-vertical view from a light plane or helicopter flown along the trail. Vertical photographs would not be necessary and might be inferior to low-oblique photographs unless adjacent vegetation obscures the trail.

11.5.3.2 Vistas

Planning: Location of potential vista sites can be done through stereoscopic interpretation of large- to medium-scale photographs. Leaf-on photography is desirable for vista analysis because screening by vegetation must be taken into account. When available, topographic maps should be used in conjunction with aerial photographs to get the first approximation of the vista locations. If the view is not obstructed by topography, it can then be checked on the aerial photographs for vegetation screening.

In developing the "seen area" for the vista, select the point on the vista and the point to which the vista view is intended to include. Draw a thin pencil line connecting these points on one photograph of the pair. Next, draw a line between the same two points as they appear on the second photograph. When viewed stereoscopically, the line will float in space between the two points unless there is an obstruction. Obstructing features will cause the line to split apart into two separate lines. Areas where vegetation causes the line to split can be marked for potential clearing.

Monitoring Vistas: Management of recreation resources requires that the vista areas be maintained for the purpose they were established. Overuse and vegetation regrowth can be monitored with aerial photographs. Leaf-on photography is best for checking the growth of screening vegetation, while leaf-off or early spring photography is preferable for monitoring erosion and spreading of the cleared area through overuse or unauthorized activities. Color or CIR film is recommended, however, panchromatic leaf-off photography can be used. Large-scale photography will provide easier site analysis but medium-scale photography will mean fewer photographs.

11.5.3.3 Developed Facilities

Planning and Layout: Aerial photographs can provide a great deal of information for planning the development of recreation facilities such as campgrounds, picnic areas, waterfronts, and winter complexes. Detailed site maps can be compiled photogrammetrically.

A study by Olson et al. (1969) demonstrated that aerial photographs could be used to inventory potential recreation sites at the rate of 75 sq km to 130 sq km per day. Similarly, Douglass (1970, 1974) used very-small scale, color photography to inventory river corridors in Pennsylvania and Tennessee for potential developed recreation sites. All three studies produced a very high rate of success in locating and mapping potential sites.

Marina and boat launch locations require access from both land and water. Topographic, geological, and soils interpretations of the parameters controlling waterfront developments can be made with large to very small-scale photography. Problems to be avoided or overcome can be identified. In-water routes, distance to open water, and in some instances, approximate water depth can be estimated or measured. Waterway constrictions and hazards can be identified and mapped.

Success of the photointerpretation planning process appears to depend more upon the site standards defined than upon the photographs used. Recreation site planning has been successful at scales ranging from 1:6000 to 1:60,000. However, the parameters describing the required sites need to be established and followed. Standards pertaining to area, vegetative cover, topography, accessibility, and drainage should be established and developed into a key to be followed throughout the inventory process.

Limiting factors can be used to eliminate potential sites. Undesirable settings, such as dumps or pollution hazards, can be used for screening. Medium- to small-scale photography will provide a better overview of relationships that might be overlooked on the large-scale photographs. Color photography taken during early leaf-on or autumn periods is recommended. However, medium-scale, leaf-off, panchromatic photographs will provide the required information.

Pre-engineering layout can be made on the photographs to aid in cost estimation and environmental impact analysis. Preliminary estimates on road and trail length, water and powerline layouts, and sewage disposal fields or stabilization ponds can be made using large- to medium-scale photography. Leaf-off panchromatic photography will be sufficient for most layout work.

Monitoring Impacts on Developed Facilities: User activities and traffic flow will have adverse impacts on land around developed recreation sites. General wear and tear on the sites and specific acts of vandalism will need to be monitored. Erosion, unplanned trails and parking spots, uncontrolled vehicle use, and stressed or dead vegetation can be detected and mapped. Periodic aerial photographic interpretation will provide managers with information on where and to what extent recreation impacts the sites. Large-scale leaf-on, color or CIR photographs will depict dead or dying overstory trees. Early spring photography will show erosion and trail damage best.

11.5.3.4 River Corridor Analysis

Shoreline Planning: River corridor analysis is usually done by making notes and observations about the shoreline on maps while riding in boats or canoes. Although fun, the technique is neither efficient nor accurate. Many terrain and vegetation details will be missed. Also, on-site mapping can be less accurate than aerial photographic mapping.

Aerial photographs can be used to do the terrain analysis for potential development sites, put-in points, and sanitary facility locations. As with the inventory of developed recreation sites, a key should be made from the development standards for each type of site to be located. For example, a canoe put-in site would need an access road to a low-banked shore point and enough level area to construct a vehicle turn-around and parking places. If picnic and sanitation facilities are to be provided, other space and soil requirements will need to be considered.

Nearly level, well-drained sites are required for shoreline recreation sites. High, residual soils or terraces will provide the proper site characteristics. Terraces, high and low, can be differentiated on photographs (chap. 3). The season of the photography does not matter much in general terrain analysis; however, leaf-off photography at a large scale will make hazard location more accurate.

The Minnesota Division of Parks and Recreation has used leaf-off, 1:15,840 scale, BWIR photography to locate potential canoe landing sites (Jensen and Meyer, 1976). Potential sites were then photographed on panchromatic film at a scale of 1:2400 to complete the final selection and determine what would be needed for development.

Another river corridor recreation project was done on the Clarion River in Pennsylvania, using 1:59,000 scale, early spring photography (Douglass, 1974). Only six hours of photointerpretation and mapping were required to inventory potential recreation sites along 21 km of the river corridor. An 80 percent correct classification was achieved in predicting potential developed-use recreation sites by activity use. A 93 percent accuracy was achieved if only potential sites were considered and the activity-use prediction was ignored. No errors of omission were found during the field checking.

The technique described for finding intervisible points for vista planning in section 11.5.3.2 can be used to map shoreline that is visible from points on the water surface. This will help in planning timber harvesting, road building, and other cultural activities that need to be screened from view of the recreational users on the river. The isolation factor used in the Outdoor Recreation Spectrum system for classifying National Forest System land can be checked by using the intervisible points technique.

Stream Characteristics: Rapids, free-flowing channels, and small islands can be detected on rivers and large streams using photography at most scales. Douglass (1974) successfully mapped rapids, shallows, and main channels of the Allegheny River using scales of 1:59,000 and 1:118,000. Caron et al. (1976) reported that color film proved superior to other films tested for detection of underwater detail within the Mississippi River. However, they reported that scales smaller than 1:12,000 did not produce enough detail to be reliable for vegetation interpretation.

Although detection of objects in and along a river is possible on small-scale photographs, the transfer to maps is difficult and time consuming (Douglass, 1974). Precision in mapping the shoreline requires leaf-off photography. Usually, the river edge is already delineated on maps, and only updating is required.

Monitoring of River and Shoreline: Recent aerial photographs are an excellent source of information on cultural developments along the shoreline. Cabin sites, campgrounds, sewage disposal, bridges, and obstructions can be inventoried with most scales of photography. Monitoring unauthorized or impromptu river access sites and their impacts will require scales larger than 1:10,000.

Rivers are dynamic, and recreation managers must keep up with the changes. Aerial photographs can provide much of the data required to provide safe, high-quality management to river recreation. Photographically derived information can be entered into a GIS for future use. Major channel changes, island erosion and accretion, and bank erosion can be monitored.

Generally, leaf-off photography at large- to medium-scales will provide the best compromise between detail and "photo shuffling." The large-scales will provide better detail where it is needed, but they will require more photographs. Early spring CIR photography is recommended for monitoring because it will highlight the ground cover, seeps, and leaking septic fields.

Pollution entering a river can be detected if it changes the color of the water enough to be discerned on the aerial photographs (chap. 17). Color film at any of the common scales will provide good records of the pollution entry point and of its spread. Medium- or small-scale photography could be the best choice if the river is large because it will be more likely to include shoreline for reference.

11.5.3.5 Lake Analysis

Planning Recreational Lake Use: Lakeshore inventory of potential recreation sites, access points, points of interest, and hazards can be located and evaluated using the techniques described in the preceding paragraphs. In order for the photographic interpretation to be effective, the recreation planners should develop an interpretation key based upon the characteristics required of each type of development. Each type of facility being considered should be given area, slope, vegetative cover, and locational parameters. Relationships to existing roads, trails, and hazards need to be defined.

Large- to medium-scale photography is used for the site selection and layout. However, small-scale photography will provide a synoptic view of the lake and provide an up-to-date look at its relationship with the surrounding resources.

In those cases where a new impoundment is being considered, aerial photographs can be used to plan most aspects of the development as well as to provide an accurate record of the conditions existing prior to the development. Vegetation of the proposed shoreline, existing roads and trails, potential hazards, and landscape features seen from the lake surface can be predicted using aerial photographs. Historical photographs can be used to check for hazards such as old wells, abandoned mines, and family cemeteries that might not appear on present-day maps.

Inventorying and Monitoring Lakes: Lake inventories can be completed using medium-scale photography with any film type. The inventory should count, locate, and describe each lake according to the accepted definitions in the study. Lake descriptions will include the class of lake as determined by its origin, area, and depth as estimated from the bank's steepness or lake size. Slope can be measured using parallax measurements.

Herrington and Tocher (1967) inventoried mountain lakes with 1:19,000 scale, panchromatic photography. They located the lakes and either determined or estimated the area, origin, depth class, and elevation. A full-intensity photographic inventory of the lakes, including parallax measurements and shoreline cover analysis, took an average of 90 minutes per lake.

In recent years, there has been an increase in monitoring aquatic plant growth in recreational lakes because of their impact upon swimming, boating, and fishing. As discussed in chapter 17, color and CIR film give adequate separation of most macrophytes.

11.5.4 Access Roads and Trails

A primary requisite to forest operations is access, which is usually accomplished by road. The use of remote sensing in planning, constructing, and maintaining forest roads assures that the shortest, most efficient routes are chosen.

Road construction and maintenance is an expensive part of any forestry activity. Before considering new road construction, current road systems should be reviewed. Many forestry practices are conducted in second growth areas where abandoned roads may already exist. Current or archival aerial photography and maps can be useful in locating old grades that can be updated at a fraction of the cost of new road construction.

Access roads are typically categorized as main haul roads, which are commonly already in place as trunk highways or county roads; secondary all-weather roads; and intermittent or spur roads. These three types differ in their requirements for width of subgrade and surfaced width, maximum grades, minimum curve and switchback radius, backslope and fillslope ratios, and ditch width. The choice of the type of forest road needed is influenced by the amount and type of traffic, desired travel speed, frequency and season of use, and funds available for construction and maintenance. The basic engineering of a main haul road is similar to that of a main highway, and the engineer can readily adapt the methods used in highway engineering. Main haul roads provide all-weather, year-around access through major forested areas. They are constructed to withstand heavy use and accommodate all types of vehicles. Secondary roads are usually all-weather surfaced roads that provide access from main haul roads to log-staging areas from timber-cutting jobs, camping and recreation facilities, and intensely managed stands, such as seed cone nurseries. Intermittent or spur roads, which may be for temporary, seasonal, or year-around use, provide access from secondary roads to such management areas as logging shows and planting regeneration stands. Aerial photography can be of great value as a tool for planning all types of forest roads and road networks.

Terrain conditions will affect route selection, cost, and feasibility of constructing forest roads. Reconnaissance should employ all possible tools to reduce fieldwork, including topographic maps and aerial photography. Reconnaissance should locate primary and alternative routes, and show easily identifiable control points such as rock outcrops, favorable stream crossings, and switchback flats. Grade between control points can also be measured on aerial photographs. Photographically identified features include those that that increase cost of construction, such as rivers, streams, wetlands, excessively steep slopes, rock outcrops, and unstable soils as well as those that would decrease costs, such as saddles, switchback flats, and favorable stream and river crossings.

Building materials are required for all road construction, and experienced photointerpreters can identify landforms likely to provide these materials (chap. 3). Granular materials are the most commonly used materials for road surface or subgrade. Unconsolidated granulars can be found in naturally occurring deposits, or consolidated rock can be crushed to obtain the needed materials. As described in chapter 3, some landforms that are likely to yield suitable granular deposits are alluvial fans, beach ridges, or glacial deposits such as outwash plains, eskers, and kames. Mine tailings, which may provide suitable construction materials, can easily be identified on aerial photographs.

A recent survey for subsurface, unconsolidated gravel deposits used the airborne Thermal Infrared Multispectral Scanner (TIMS). The USDA Forest Service in cooperation with NASA successfully located an estimated 3 million cu m of subsurface gravel-bearing deposits on the Kisatchie and DeSoto National Forests in Mississippi and Louisiana, respectively. TIMS aided the search process by detecting thermal differences associated with the difference in thermal inertia of gravel and adjacent nongravel deposits (Burns et al., 1992).

11.5.5 Regeneration Surveys

Remote sensing techniques are used extensively in locating suitable sites for regeneration, planning, and executing planting and seeding operations and also for conducting survival surveys. Hoppus and Greenup (1988) list advantages of aerial photographs over ground surveys. Aerial photographs provide (1) rapid, large area coverage, (2) a permanent record in a map-like format, (3) lower cost per area surveyed, and (4) access to areas inaccessible or difficult to reach on the ground.

The first step in forest regeneration is locating potential planting or seeding sites. Site features such as accessibility, size, aspect, and slope, which are used to determine method of regeneration, amount of seed or planting stock, and species to be regenerated, can be measured on medium- or large-scale aerial photographs. Current stocking, evidence of disease, insect or rodent problems, and presence of vegetation, which will determine the need for clearing or site preparation and will influence silvicultural decisions, can also be interpreted.

After a plantation has been established, survival or stocking surveys are often conducted to determine the success of regeneration. Hoppus and Greenup (1988) report that experienced interpreters can detect coniferous seedlings, approximately 1 m tall, on 1:15,840 scale, panchromatic photographs, and divide the survey area into three categories: areas which were not obviously fully stocked, areas which were partially stocked, and areas which appeared not stocked. Aerial photographs can thus be used in stratifying plantations for ground survey; planning treatment for brush, pests, replanting or fertilizing; validating treatment; increasing confidence in the measurement of tree density and stocking; updating ground surveys on a frequent basis; and establishing patterns of mortality, which may allow determination of the causes of seedling death.

When choosing or planning aerial photography for regeneration surveys, the photography must be of a suitable type and scale and should be timed to maximize the spectral differences between the seedlings and other vegetative growth present. Leaf-off photography is ideal for the identification of conifer seedlings. Panchromatic, color, and CIR films are all suitable for stocking surveys during leaf-off conditions. Leaf-off photography is not always practical, however. In temperate or mountainous regions, snow may cover seedlings, or long winter shadows may make regeneration undetectable. Stocking surveys that are flown during leaf-on conditions should be flown with color or CIR film in mid- to late-growing season when the reflectance differences between conifer and deciduous foliage are maximum in both the visible and near-infrared wavelengths. The optimal scale will be determined by the size of the seedlings, size and density of competition, timing and type of photography, and quality of the camera and film used.

11.5.6 Ecosystem Classification

Hierarchical classification systems using ecological principles have been developed for geographic scales ranging from local to global. Using bioclimatic approaches, several researchers have developed ecological land classifications: Holdridge (1967), Udvardy (1975), Walter and Box (1976), and Bailey (1989a, 1989b). Wertz and Arnold (1972) developed land stratification concepts for regional and land unit scales. Other classifications proposed at regional scales include those of Driscoll et al. (1984), Gallant et al. (1989), and Omernik (1987) in the United States, and those of Wiken (1986) and the Ecoregions Working Group (1989) in Canada. Concepts have also been presented for ecological classifications at subregional to local scales in the United States (Barnes et al., 1982), Canada (Jones et al., 1983), and Germany (Barnes, 1984).

Aerial photography plays an important role in forest ecosystem classification, specifically in mapping ecosystems at various scales. The works of the Canadian Committee on Ecological Classification and research by the Canadian Forestry Service, Forest Management Institute set the standard in the late 1960s and 1970s. At that time, many national parks in Canada were mapped according to an aerial photographic interpretation basis for ecosystem classification.

Ecosystem classification and management, although not a new concept, has received renewed attention from public land management agencies such as the USDA Forest Service and other public and private organizations. Ecosystems vary in size from the entire earth to specific local sites. A recently developed hierarchical framework contains four major levels, mapped and managed at different size and unit scales (National hierarchical framework, 1993):

Ecoregion	over 3000 sq km	smaller than 1:1 million
Subregion	300 to 3000 sq km	1:1 million to 1:125,000
Landscape	4 to 400 ha	1:125,000 to 1:24,000
Land Units	1 to 4 ha	1:24,000 and larger

Overall, the hierarchical framework of ecological units provides a basis for assessing resource conditions at multiple scales. Ecoregions have broad application for modeling and sampling, primarily for strategic planning, global research and modeling, and global assessment. Subregions apply to the national and regional level for strategic planning and multiagency analysis and assessment. The landscape scale is used at the forest level for area-wide planning and watershed analysis. The land unit scale is used for project and management area planning and analysis and also provides information on the distribution of terrestrial and aquatic biota, forest growth, succession, and health.

Each level requires spatial information on conditions affecting natural communities, soils, hydrologic functions, landforms and topography, lithology, climate, air quality and natural processes for cycling plant biomass and nutrients. Some of these attributes can be extracted from aerial photographs (see chaps. 3, 4, and 5). The use of aerial photographs for ecosystem classification and management follows rules similar to those for other resource-related tasks (Greer et al., 1990). Perhaps the most common use of aerial photographs is for delineating vegetation or land cover units. This is generally done by delineating polygons by physiognomic class, dominant species, canopy cover, size, crown condition, and vertical and horizontal diversity (sec. 11.4). Transfer of polygons into a GIS can be done with various processes such as analytical stereoplotters (Bobbe et al., 1992) and other methods described in this chapter and chapter 2.

11.5.7 Urban Forestry

Urban forestry is the multiple-use management of vegetation, particularly trees, in urban areas. This vegetation is part of a complex urban fabric that includes people and many artificial and natural surfaces. Proper urban forest management can enhance various social and environmental benefits derived from trees (e.g., increased real estate values, improved sense of community, reduced energy use and air pollution) while minimizing the costs associated with maintaining an urban forest.

Urban foresters generally have management jurisdiction over public vegetation along streets and in parks that often comprise only a minority of the vegetation in urban areas. However, urban foresters can influence the selection, placement, and maintenance of privately owned trees through education, incentives, and/or ordinances and can thus direct the total urban forest structure to maximize overall benefits at a minimal cost.

Information on privately owned trees is important for comprehensive urban forest management. These trees greatly influence the city's physical and social environment, and if improperly selected and maintained, they can facilitate the spread of fire, insects, and tree diseases.

Aerial photographs offer visual access to vegetation on private property and provide a wide range of useful urban forestry information—species composition (often only to genera), tree health, tree size, and vegetation configuration and location. Aerial photointerpretation is a relatively simple and cost-effective method for obtaining urban forest data while providing a more comprehensive view than many current inventories that focus on publicly maintained trees. Although aerial photographs contribute relatively little to the direct, day-to-day management of public vegetation, because this vegetation is easily accessible, the photographs facilitate planning, management, and research.

When conducting an urban aerial photographic analysis, the principal considerations are date, type, and scale of photography. For analyzing vegetation attributes, it is desirable to have photography taken during leaf-on seasons though much of the existing urban aerial photography is leaf-off. CIR photography is best for discerning vegetative health and, when used with a yellow (minus-blue) filter, it is less affected by atmospheric haze than are natural color or panchromatic films. Scales of 1:12,000 or larger are best for interpreting urban vegetation. With larger scales (1:1200–1:6000), the cost and handling time are greater but magnification is generally not required to distinguish objects on the photograph. At scales smaller than 1:12,000 even with magnification, it is often difficult to distinguish urban ground objects with certainty. Viewing photographs stereoscopically facilitates identification of small trees that can be difficult to locate in grass areas because of similar reflectance patterns.

One main advantage of aerial photographs in urban forestry is that it is relatively easy to determine the amount and location of various land use and cover types. These attributes are particularly valuable in understanding the interaction between people and trees. Tree cover (the amount or percentage of area occupied by trees when viewed from above) varies within cities and often relates to land use. Studies of tree cover help reveal the influence of trees on the city environment (Rowntree, 1984).

As discussed in chapter 9, urban aerial photographic data collection can address land use and/or land cover types. Land use types, such as residential, commercial and industrial, can be as refined or as broad as needed. For example, residential land use can be subdivided by building density or by single versus multifamily housing. The more refined the land use categories, the more time required for data collection and analyses. Common land cover types include tree/shrub, grass/low ground vegetation, soil, building, road, other impervious cover, and water. Again, the more cover types considered, the more time required for data collection and analyses.

Various methods have been used to quantify urban forest cover. The crown-cover scale method estimates tree cover within an area using a cover template guide (Moessner, 1947). The template displays a range of crown cover densities with corresponding percentage values. Use of the template is fairly subjective and relies on the aerial photointerpreter's skills to classify crown cover within limited discrete cover classes on the template. The transect method involves laying lines across the photograph and measuring the amount of the line that crosses each land use and/or land cover type (Canfield, 1941; Jim, 1989). This method works well for measuring street tree cover which is generally a linear feature.

The dot-grid sampling method is fairly common and involves recording land use and/or land cover type beneath a series of dots overlaid on the photograph (e.g., Barrett and Philbrook, 1970; Gering and Bailey, 1984). Dots can be laid in a systematic grid pattern (equal distance between dots) or random fashion. Systematic dots are easier to collect data from but have the disadvantage that they might follow systematic features (e.g., roads or street trees that are equal distances apart) and lead to inaccurate results. Mean and variance of land cover data can be calculated from the transect and dot grid sampling methods (Mendenhall, 1979; Greig-Smith, 1983).

The scanning method is the most accurate and integrates well with a GIS, but requires specialized equipment. The shape and area of each cover type are delimited in its exact position on acetate overlaid on the aerial photograph. Area or cover measurements are then made from these acetate markings using specialized equipment (e.g., digitizers, scanners, area meter). Measurements can also be made directly off the photograph using a planimeter. If a computer scanner is used, the cover information can be easily transferred and can provide useful data for GIS. This method is the most accurate because it measures all of the cover types in a region and does not rely on sampling procedures. However, use of the scanning method is limited by relatively large time investments and the need for specialized equipment.

Information extracted from aerial photographs and managed with a GIS has been used to enhance ground-based street tree inventories; map wetland, woodland and other critical habitats in urban areas; and also to map tree canopies around residences to evaluate their contribution to building energy conservation (Laverne, 1992). Linking urban forest information with a GIS also facilitates locating potential tree planting sites and determining vegetation spatial relationships (e.g., forest patches or corridors) that influence wildlife habitat and other urban forest attributes.

One common application of aerial photography in managing urban vegetation is for insect and disease surveys. Aerial photographs are often used as part of an integrated pest management program to aid in detecting susceptible tree species or infected trees (e.g., determining locations of elm trees, *Ulmus* spp., as part of a Dutch elm disease control program). Aerial photographs also aid in determining the location of highly stressed or dead trees that may pose a safety hazard.

Urban tree stress indices have been quantified from CIR aerial photographs. Lillesand et al. (1979) used microdensitometric analysis to develop equations to quantify tree stress of roadside maples in Syracuse and Rochester, New York, and reported that aerial predictions of tree stress were as reliable as ground estimates. A test of this procedure on Monterey pines *(Pinus radiata)* in Carmel, California, however, indicated that variations occur in ground cover beneath urban trees. Variations among cities and in crown morphology among tree species influence spectral tree crown measurements and limit the ability of microdensitometry to quantify urban tree stress (Nowak and McBride, 1993).

Urban tree cover data are also being combined with individual tree measurements to quantify urban forest attributes such as biomass, leaf surface area, evapotranspiration, and pollutant uptake rates (McPherson et al., 1993). This type of urban forest-wide information is useful for developing models to quantify the effects urban forests have on the surrounding environment (e.g., water cycling, city temperatures, building energy use, air quality). Aerial photographs have also been used to assess the visual impact of development on urban forest stands (Schroeder, 1988).

Aerial photographs can help quantify urban forest change and development. Analyses of historical documents and aerial photographs of Oakland, California, indicate that tree cover has changed from approximately 2 percent in 1850 to 16 percent in 1939, 20 percent in 1959, 21 percent in 1988, and 19 percent in 1992 (influence of 1991 fire) (Nowak, 1993). Analyses of historical change can be used to project potential urban forest change and to assist in appropriate urban forest planning and management.

With appropriate field checks, aerial photographic analyses provide relatively low-cost data that can enhance urban vegetation planning, management and research activities. These activities can be enhanced even further when aerial photographic analyses are conducted in conjunction with ground data analyses that can significantly improve the overall urban vegetation database.

11.5.8 Conclusion

Use of, and demand for, remotely sensed data has increased substantially in forestry applications. Although digital imagery such as that obtained from airborne videography and satellite systems is becoming popular for change detection and large area reconnaissance, aerial photographs remain the mainstay for most resource management activities. In order to meet the increasing information needs of resource managers, photographic interpretation, and other forms of remote sensing, as well as the related technologies of digital image processing, global positioning system, and GIS, will continually be depended upon to help manage and protect the forest resources.

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