PANCHROMATIC VERSUS INFRARED MINUS-BLUE AERIAL PHOTOGRAPHY FOR FORESTRY PURPOSES IN CALIFORNIA

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THE PROBLEM

ONE of the important current projects of the United States Forest Service is that of taking an inventory of the Nation's timber resource. As authorized by Congress, this inventory, known as the Forest Survey, includes, among other things, the determination of (a) our forest-land acreage, (b) the existing timber volumes on those lands, and (c) the present and potential timber growth.

The process of obtaining these facts in California begins with a classification of vegetation made on aerial photos. This classification serves in three ways. First, it provides the area inventory of the various timber and other vegetation types. Second, it gives a stratification of timber stands that minimizes the ground sampling needed for a reliable estimate of timber volumes and growth. And third, it provides an "in place" delineation of the vegetation classes that makes the Survey locally useful.

A second project being carried on with the Forest Survey for the California State Division of Forestry makes further use of aerial photos. By intensifying the Survey's vegetational classification, it provides additional information needed for local land planning and management activities.

Most of the classification techniques used on these projects have been described in articles by Wieslander and Wilson (6) and, with certain later modifications, by Jensen (2). In short, from stereoscopic study alone are obtained (a) the kind of vegetation cover or other condition occupying the land, (b) the age structure of tree stands based on the proportions of age classes present, (c) the densities of timber stands and all woody vegetation, and (d) the segregation of timber croplands from other lands. Then from ground observations, aided by whatever the photos can reveal, is obtained the species composition of the vegetational areas. Other classifications made are indirectly related to the aerial photos.

As a part of the State's project, State and County funds were provided in 1947 for over 11,000 square miles of new photography. This introduced consideration of the film-filter-scale combination that would best yield the desired information. Previous experience and the development of the classification system to be used were based on panchromatic minus-blue photography at 1:20,000 scale. On the other hand, several studies reported in the literature advanced the merits of other film-filter-scale combinations. But since those results could not be related to the objectives of the new photography, a local test seemed in order.

PREVIOUS TESTS

One of the earliest systematic tests concerning the relative merits of various film-filter combinations for forestry purposes was that of Ryker (3). Recognizing that chlorophyll preferentially absorbs certain wave lengths of light while reflecting or transmitting others, he obtained experimental aerial photography of

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four coniferous species in the pine region of California to explore the possibility that chlorophyll content of foliage might vary sufficiently between species to give a characteristic photographic tone for each species. By proper choice of film and filter, he hoped to accentuate these tonal characteristics. He expected tonal differences to be most pronounced in the infrared range and accordingly included in his tests an infrared-sensitive film designated as Eastman Panchromatic "K."

Ryker concluded from his tests that the chlorophyll content of foliage is more a function of the age and vigor of a tree than of its species. Of the various film-filter combinations tested, he was best able to distinguish tree species by using Eastman Supersensitive Panchromatic film in combination with a green filter which transmits only light with wave lengths of 460 to 620 millimicrons. Both crown shape and tone were used in identifying tree species.

The scale of Ryker's photographs was approximately 1:9,600, but even at this comparatively large scale, identification of species was limited principally to mature trees growing in open stands.

Spurr and Brown (4) studied experimental aerial photography of forested areas in Quebec, New England, North Carolina and Alabama. Both Kodak Super XX Panchromatic film and Kodak Type B Infrared film were used with various filters. Kodachrome and Aero Kodacolor film also were tested. Most of their photography was at scales ranging from 1:12,000 to 1:20,000.

They concluded that infrared photography with a minus-blue filter is superior to both panchromatic minus-blue and color photography for differentiating forest tree species by tonal contrast, since differences in photographic tone between species is greater in the infrared range than in the visible part of the spectrum.

On panchromatic film, Spurr and Brown found tonal contrasts to be unreliable as the sole criterion for species differentiation regardless of the filter used. Texture, shadow, and shape of crown also had to be considered and even then only broad distinctions could be made with certainty, such as softwood, hardwood, and mixed softwood-hardwood types. Panchromatic photography was found to be superior to infrared minus-blue photography for resolution of detail and for timber density determination, but these advantages were outweighed by the greater facility with which type boundaries could be delineated on the infrared.

Neither Kodachrome nor Aero Kodacolor film produced sufficiently good detail or color contrast to justify recommendation of its use for forestry purposes in the East.

THE CALIFORNIA TEST

The film-filter combinations selected to compare with the standard panchromatic minus-blue photography were the panchromatic green which Ryker found better than the others he tested and the infrared minus-blue recommended by Spurr and Brown. Other combinations were eliminated on the basis of the two studies mentioned and others, and the financial limitations.

Two photographic scales were used. One was the smallest—1:20,000—capable of yielding general identification of the required classification items on panchromatic minus-blue. The other was the largest—1:15,000—that appeared to be economically possible.

Since the classification work was to cover two individually distinctive vegetational regions in California, two sets of comparisons were needed, one representing the pine region of the interior and one the redwood region of the north coast. El Dorado County was chosen to represent the pine region and the Santa Cruz Mountains the redwood region.

In selecting the actual locations of the photography, every effort was made to cover the full range of timber stand conditions, vegetational types, and species composition common to each region. To accomplish this, three lines, each approximately 7 miles long, were designated in each region, together with a shorter supplementary line in the redwood region. Each of the longer lines was vertically photographed with panchromatic minus-blue and infrared minus-blue at 1:20,000 and 1:15,000 scales. Panchromatic green was used on one line in each region and only at the 1:15,000 scale since the reputed advantages in detail on that combination were not expected to be effective at 1:20,000. The supplementary line, covering marshland conditions, was photographed only with panchromatic minus-blue and infrared minus-blue at 1:15,000 scale.

The photography was done by Western Air Photos of Stockton, California. Standard procedures were followed insofar as practicable throughout to simulate the results that would be expected in an ordinary photographic project. All the photos were taken during the period June 10 to June 18, 1947 between the hours of 10:45 A.M. and 1:15 P.M. Atmospheric conditions were very good. In most cases, the several flights over each line were made in rapid sequence so that lighting conditions were practically identical. The aerial camera had a focal length of 8.25 inches and a negative size of 9×9 inches. Only fresh photographic film was used.

No special adjustment in focal length was made for the infrared photography because (a) the opportunities for obtaining such adjustment in either the test or subsequent project photography were limited; (b) tonal qualities are more significant than the last measure of image sharpness at the relatively small photo scales being considered; and (c) some experts believe that, regardless of scale, such adjustment is unnecessary for infrared photography using such as the minus-blue filter, which permits not only infrared light but also most of the visible light to activate the film.

Additional comparative photos taken with panchromatic minus-blue and infrared minus-blue at 1:20,000 scale in another part of the redwood region were later made available by Aero Service Corporation of Philadelphia. These confirmed the evidence from the test photos.

The photos from all film-filter-scale combinations tested were first given intensive stereoscopic study both in the office and on the ground. After considerable preliminary study to become acquainted with the heretofore unfamiliar infrared minus-blue and panchromatic green combinations, identifications made on the different sets of photos were compared and then checked on the ground. As an final step, the identification ratings assigned from the study (see tables appearing later) were checked over the full sets of photos, using regular Survey classification procedures. Throughout the study, possibilities for bias in favor of the panchromatic minus-blue photography resulting from longer and more extensive familiarity with that combination were recognized and, insofar as possible, minimized.

GENERAL RESULTS

Immediately evident upon looking at the photos from both pine and redwood regions was the striking difference in their over-all appearance. On the one hand were the panchromatic photos with variations in tree and shrub stands emphasized by the light background tones of the ground and herbaceous cover; on the other were the infrared photos with these variations obscured by a dark background. As between the panchromatic minus-blue and panchromatic green, the only noticeable difference seemed to be a slightly reduced contrast on the latter. Many individual vegetational features were, of course, more prominent at the 1:15,000 photo scale than at the 1:20,000. Representative samples of the photography from the pine region appear in Figure 1 and from the redwood region in Figure 2.

For superficial use of the photos, panchromatic photography held a distinct advantage over infrared in bringing out important vegetational features. But what about detailed stereoscopic study, such as was being done on the survey described here? Would this difference then be significant? And which film-filter combination would best reveal the minute features upon which the desired classifications frequently depend?

The answers to these questions were not always in favor of the same film-filter combination. For the needs of the California Forest Survey and the State's intensification, however, the panchromatic minus-blue had a definite total advantage over the infrared minus-blue. This advantage prevailed in both the pine and redwood regions. It also held at both the 1:20,000 and 1:15,000 photo scales. Between the panchromatic minus-blue and panchromatic green, what little difference did appear also favored the panchromatic minus-blue.

Continuance of panchromatic minus-blue was therefore recommended for the new photography in both the pine and redwood regions. Although the 1:15,000 scale would have permitted easier photo study, the 1:20,000 was also retained in order to obtain a maximum area coverage for the available funds.

While these conclusions were drawn only for the projects mentioned earlier, wider application seems probable because many aspects of the vegetation are involved in those projects. But in other applications the orientation of emphasis may differ. To avoid the risks of generalization and to provide as many opportunities as possible for relating this test with other requirements, details are necessary. These are presented in the following discussion and Tables 1 to 4.

DETAILED RESULTS

Vegetation-Cover and Other Land Status Elements

This classification of the natural vegetation cover and other land conditions according to their principal component parts is the starting point for the entire system. Besides furnishing its own useful information, it enters to some degree in all of the other classifications described in the following sections.

Twelve vegetation-cover and other land status elements* are recognized. Three of the vegetation-cover elements consist of trees—commercial conifers, noncommercial conifers, and hardwoods; two of shrubs—chaparral (including shrub-sized hardwoods) and sagebrush; and two of herbs—bushy herbs and grass. One subdivision of commercial conifers, the lodgepole pine—mountain hemlock type, is also distinguished. The other land status elements are marsh, bare ground, rock, cultivated, and urban—industrial. All of these were sampled, though some only meagerly. How their identification is affected by the film-filter-scale combinations used is summarized in Table 1.

Pine Region—On panchromatic minus-blue at 1:20,000 scale, all the elements sampled are generally identifiable, though seven of them sometimes require close study. Distinctive tone and crown-form characteristics set apart the lodgepole pine—mountain hemlock type (here containing only lodgepole

* Defined and illustrated in reference (2).

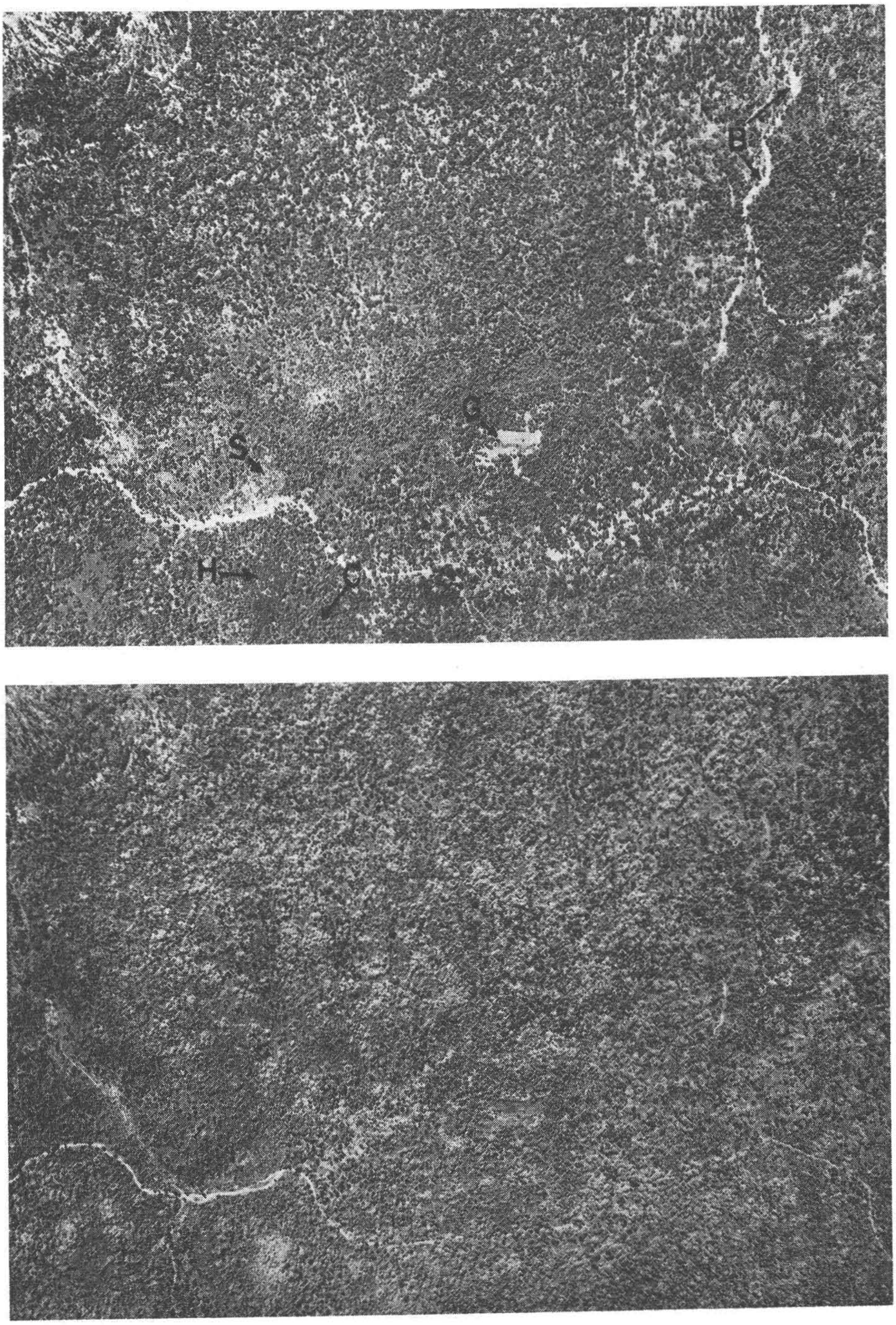

FIG. 1. Vertical photos of the same area in the pine region of California, showing commercial conifers, (C) and hardwoods, (H), in dense and open stands, chaparral, (S), grass, (G), and bare ground, (B). Scale 1:20,000.

Upper:—Panchromatic Film, Minus-Blue Filter. Lower:—Infrared Film, Minus-Blue Filter.

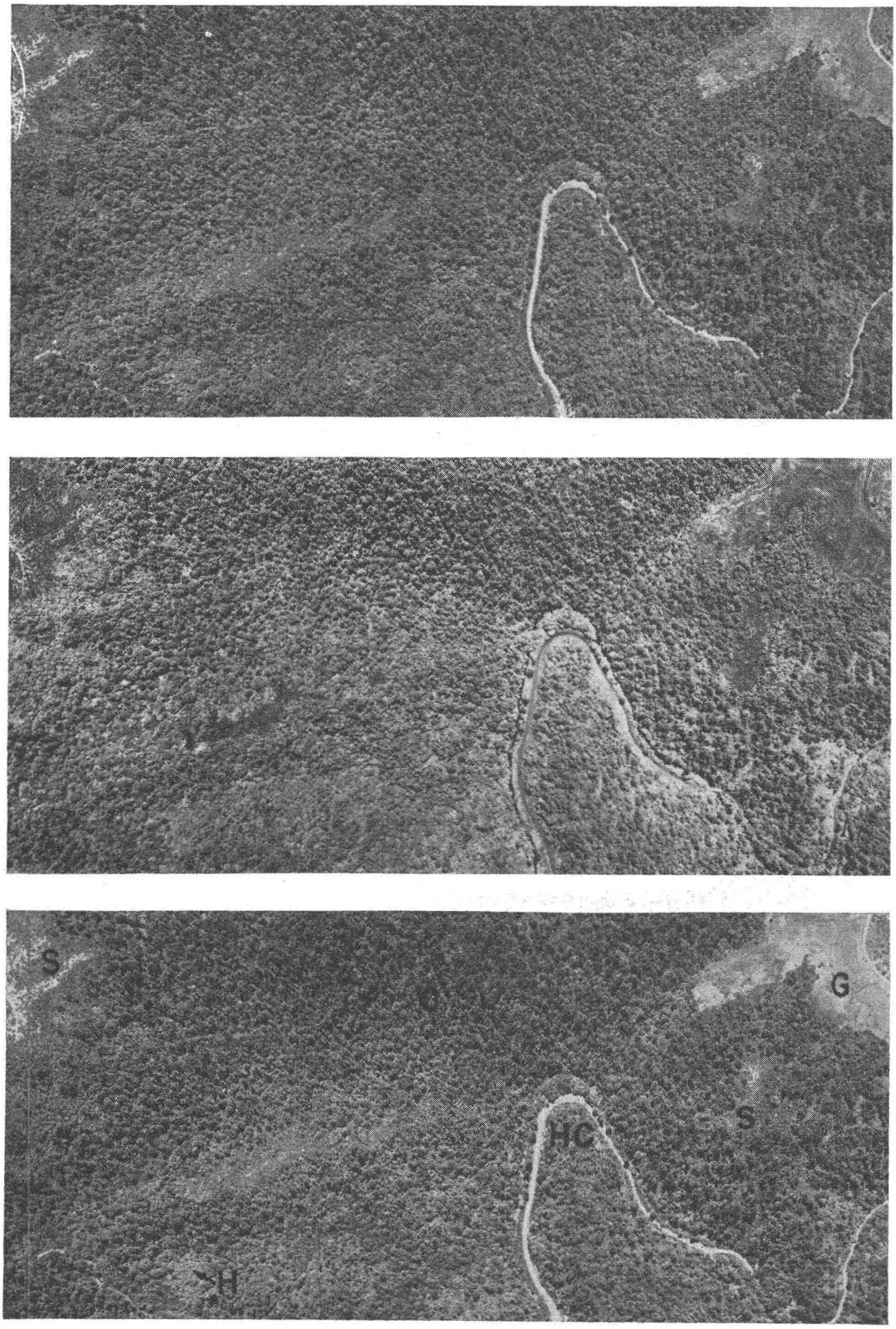

FIG. 2. Vertical photos of the same area in the redwood region of California, showing mature and immature commercial conifers, (C), and hardwoods, (H), dense and open, chaparral, (S), and grass, (G). Scale 1:15,000.

Upper:—Panchromatic Film, Minus—Blue Filter. Center:—Infrared Film, Minus—Blue Filter. Bottom:—Panchromatic Film, Green Filter.

pine), tonal and textural features the chaparral, and patterns the cultivated and urban—industrial. The commercial conifers, noncommercial conifers (represented here only by Digger pine), and hardwoods are likewise easily identified when full grown or well advanced toward that stage but as young trees they may require close study. Having nearly equal tones on this film-filter combination, it is only when they are not intermixed or have the height and crown-form development of older trees that separation is consistently easy. Bushy herbs

TABLE 1. RATING OF FILM-FILTER COMBINATIONS FOR THE IDENTIFICATION OF VEGETATION-COVER AND OTHER LAND STATUS ELEMENTS AT 1:20,000 AND 1:15,000 PHOTO SCALES IN THE PINE AND REDWOOD REGIONS OF CALIFORNIA

Region and element	Photo scale and film-filter				
	1:20,000		1:15,000		
	P-MB	IR-MB	P-MB	IR-MB	P-G
PINE REGION					
Commercial conifers	+	++	++	++	++
Lodgepole pine—Mt. hemlock type	++	++	++	++	0
Noncommercial conifers	+	−	++	−	0
Hardwoods	+	++	++	++	++
Chaparral	++	−	++	−	++
Bushy herbs	+	−−	+	+	0
Grass	+	−	++	+	++
Bare ground	+	−	++	−	++
Rock	+	−	++	+	0
Cultivated	++	++	++	++	++
Urban—Industrial	++	++	++	++	0
REDWOOD REGION					
Commercial conifers	+	−	+	+	+
Noncommercial conifers	++	++	++	++	0
Hardwoods	+	−	+	+	+
Chaparral	++	−	++	−	++
Sagebrush	+	−	+	−	+
Bushy herbs	+	+	+	++	+
Grass	++	−	++	−	++
Marsh	0	0	+	+	0
Bare ground	++	−	++	−	++
Cultivated	++	+	++	+	++
Urban—Industrial	++	++	++	++	0

P panchromatic film; IR infrared film; MB minus-blue filter; G green filter; ++ generally and easily identifiable; + generally identifiable but sometimes requiring close study; − inconsistently identifiable; −− generally unidentifiable; 0 no example.

(represented here only by Klamath weed), grass, bare ground, and rock are easily distinguished by tone and texture from the other elements but frequently appear like one another. A general field knowledge of local relationships usually permits adequate separation, however.

The infrared minus-blue at 1:20,000 also permits easy identification of lodgepole pine—mountain hemlock, cultivated, and urban—industrial. In addition, it provides a tonal contrast between commercial conifers and hardwoods that distinctly separates those two elements regardless of tree size or age. But none of the remaining elements is identifiable under all conditions. Heavily foliaged trees of the noncommercial conifer (Digger pine) duplicate the tone and shadow characteristics of commercial conifers, while the thinly foliaged trees are scarcely evident at all. Dry grass, leaf litter, and dark colored soil or rock appear in dark tones rather than in the light tones of panchromatic minus-blue. As a result, where they are intermixed with the similarly-toned chaparral, there appears to be more chaparral and less grass, bare ground, or rock than is actually the case. Only where the chaparral forms dense stands can it be adequately distinguished. Grass, bare ground and rock are also more like each other here than on the panchromatic minus-blue, but this again can be overcome by a general field acquaintanceship. Little, if any separation between bushy herbs (Klamath weed) and grass is possible.

Identification generally becomes easier with the additional detail of 1:15,000 photography, but the panchromatic and infrared continue to be significantly different.

On panchromatic minus-blue at 1:15,000, all the elements except one, bushy herbs, become easily identified. Its resemblance to grass still necessitates close study. Commercial conifers and hardwoods also still need close study where they occur in open stands and the conifers have rounded crowns like the hardwoods, but this condition is too limited in extent to influence the ratings.

On the infrared minus-blue at 1:15,000 several important identification weaknesses remain. Chaparral, bushy herbs, and grass can be separated from each other where intermixed, but very close study is needed. The same is true for the separation of rock from bare ground. Chaparral and bare ground remain, as at the 1:20,000 scale, partly inseparable and no gain is noticed with the noncommercial conifers.

The panchromatic green, which was limited to the 1:15,000 scale, presents the features much like panchromatic minus-blue. The only noticeable difference is a slightly reduced tonal contrast, which offers no significant handicap here but suggests the possibility of difficulty elsewhere if equal-textured elements are more nearly alike in tone. Specific indication of such difficulty here is the added study needed to separate one of the lesser chaparral species (bear clover) from bare ground.

Redwood Region—Easily identified on panchromatic minus-blue at 1:20,000 in this region are the noncommercial conifers (represented here only by knobcone pine), chaparral, grass, bare ground, cultivated, and urban—industrial. Tone, texture, and, for the last two elements, pattern differences usually provide ample evidence. Grass sometimes appears like bare ground and bushy herbs but can be separated from them through field acquaintanceship with local conditions. Closer study is needed for the commercial conifers, hardwoods, sagebrush, and bushy herbs. As in the pine region, similarity of tone between some of the commercial conifers and hardwoods necessitates study of other characteristics less easily seen, in order to separate those two elements when their trees are young and alike in size and shape. Older trees are clearly distinguishable through height and crown-form contrasts. The separation of sagebrush and bushy herbs, where both occur in the same locality, is handicapped by their tonal and textural similarities.

On infrared minus-blue at 1:20,000 generally easy identification is limited to the noncommercial conifers (knobcone pine), cultivated, and urban—industrial. Bushy herbs and sagebrush acquire contrasting tones, but both close study and field acquaintanceship are needed to detect the slight tonal and textural differences between the bushy herbs and grass. The remaining six elements cannot always be identified. With both tonal and other differences between most of the like-sized commercial conifers and hardwoods absent on this film-filter combination, definite separation between these two elements is possible only after the height and crown-form contrasts of increasing age develop.

Chaparral, sagebrush, grass, and bare ground are subject to the same limitation reported for chaparral in the pine region. Where either shrub element is mixed with grass or bare ground, the blending of tones is such as to prevent recognition of part or all of the grass or bare ground.

Although both panchromatic minus-blue and infrared minus-blue yield easier identification at the 1:15,000 scale than at 1:20,000, only three elements gain enough to have their ratings changed (Table 1). All three are on the infrared minus-blue, the added tree-crown detail obtained making it possible to separate like-sized commercial conifers and hardwoods, and increased textural detail permitting easy separation of bushy herbs and grass. One element—marsh—not sampled at 1:20,000, can be identified with about the same need for close study on both film-filter combinations. Neither combination produces distinct tonal or textural contrasts between marsh and grass when the marsh is completely covered with low vegetation.

The panchromatic green is again like the panchromatic minus-blue, the only difference between them being the same lessened tonal contrasts noticed in the pine region. Here, too, the differences are not enough to change the identification ratings.

Age-Class Elements

This second group of elements subdivided the trees into age classes that are significant to the estimation of present timber and cordwood volumes and future growth probabilities, and to forest management. Commercial conifers are recognized in mature, large immature, and small immature, and reproduction classes;* the lodgepole pine—mountain hemlock type and hardwoods in mature and immature classes. All but the commercial-conifer reproduction are applied without exception. Only part of that age class is gotten from photo study, the rest from ground observations.

Since these age-class elements are identified on aerial photos by relative tree size and crown form rather than by foliage characteristics, the film and filter used may seem to have little if any significance. This conclusion is not entirely valid in practice, however. Tree size and crown form cannot be evaluated without first recognizing the kind of trees (vegetation elements) being studied—and that is affected by film-filter combination. The problem therefore is a two-fold one, and the film-filter ratings (Table 2) are considered in that light.

Pine Region—On panchromatic minus-blue at the 1:20,000 scale, generally easy identification of the age-class elements is limited to the mature commercial conifers and mature hardwoods. Both of these have height and crown-form characteristics that distinguish them under all except special local conditions which give little difficulty if some field acquaintanceship is possessed. Large immature commercial conifers are likewise distinct except near the lower limit of the class and in open stands. The vegetation-element problem of separating the commercial conifers, non-commercial conifers, and hardwoods then enters. For the same reason, small immature commercial conifers and immature hardwoods require close study wherever they are intermixed or occur with the noncommercial conifers. The lodgepole pine—mountain hemlock age classes need close study because of the sometimes minor tree-form and size differences between them.

On the infrared minus-blue at 1:20,000, all the commercial conifer (excluding reproduction) and hardwood age classes are generally easy to identify be-

* Defined and illustrated in reference (6).

cause of this film-filter combination's tonal contrast between the two vegetation elements. With such a tonal distinction evident, there is little difficulty in judging the desired tree sizes. The somewhat uncertain separation of small immature commercial conifers and immature hardwoods from the noncommercial conifer (Digger pine) does not seriously affect this classification. Close study of the lodgepole pine—mountain hemlock age classes is needed here for the same reasons that apply to the panchromatic minus-blue.

With the increase in photo scale from 1:20,000 to 1:15,000, all age classes except commercial conifer reproduction become easy to identify on all film-filter combinations. The additional tree detail obtained both offsets the tonal weakness of panchromatic minus-blue and makes clearer the slight difference between the lodgepole pine—mountain hemlock age classes. There is no significant difference between the two panchromatic combinations for the age classes sampled.

TABLE 2. RATING OF FILM-FILTER COMBINATIONS FOR THE IDENTIFICATION OF AGE-CLASS ELEMENTS AMONG TIMBER AND HARDWOOD TREES AT 1:20,000 AND 1:15,000 PHOTO SCALES IN THE PINE AND REDWOOD REGIONS OF CALIFORNIA

Region and element	Photo scale and film-filter				
	1:20,000		1:15,000		
	P-MB	IR-MB	P-MB	IR-MB	P-G
PINE REGION					
Commercial conifers					
Mature	++	++	++	++	++
Large immature	+	++	++	++	++
Small immature	+	++	++	++	++
Reproduction	−	−	+	+	+
Lodgepole pine—Mt. hemlock type					
Mature	+	+	++	++	0
Immature	+	+	++	++	0
Hardwoods					
Mature	++	++	++	++	++
Immature	+	++	++	++	++
REDWOOD REGION					
Commercial conifers					
Mature	++	++	++	++	++
Large immature	++	++	++	++	++
Small immature	+	−	+	+	+
Reproduction	−	−−	+	−−	0
Hardwoods					
Mature	+	+	++	+	++
Immature	+	−	+	+	+

P panchromatic film; IR infrared film; MB minus-blue filter; G green filter; ++ generally and easily identifiable; + generally identifiable but sometimes requiring close study; −inconsistently identifiable; −− generally unidentifiable; 0 no example.

The commercial conifer reproduction presents a special problem. Some of the trees in this age class are too small to form distinct images on the photos. Others, large enough to form images, are not always distinguishable from associated vegetation. On panchromatic minus-blue at 1:20,000, dense stands of reproduction down to shrub size can be separated from other low growth by a very slight textural difference. Individual trees are not distinguishable from chaparral, hardwoods, or noncommercial conifers. On the infrared minus-blue at 1:20,000, both stands and individuals can be separated from small hardwoods by tonal contrast but nothing differentiates them from chaparral. At the 1:15,000 scale more general identification is possible. Individuals down to shrub size then become recognizable on panchromatic (both minus-blue and green), and thickets are separable from chaparral on infrared.

Redwood Region—Here, on panchromatic minus-blue at 1:20,000, tree heights and crown forms yield easy identification of the mature and large immature commercial conifers under all the conditions sampled. Small immature commercial conifers (especially clumps of redwood sprouts) and the hardwood age classes, on the other hand, are so nearly alike in photo appearance that very close study of their minor tree-tip and tonal differences is generally needed to separate them. As in the pine region, the commercial conifer reproduction is but partially recognizable, here being most visible when mixed with the common chaparral species on redwood cut-over lands.

The infrared minus-blue at 1:20,000 also permits easy identification of mature and large immature commercial conifers through their distinctive height and crown-form characteristics. Mature hardwoods can be recognized by crown forms after close study. But only the more obvious of the small immature commercial conifers and immature hardwoods are identifiable, even very close study frequently failing to reveal any tonal, tree-tip, or other difference between them. The commercial conifer reproduction is inseparable from other low vegetation.

At the 1:15,000 photo scale, the film-filter combinations yield more nearly equal results although the advantage is still with panchromatic minus-blue. On that combination the added crown-form detail obtained makes it possible to identify mature hardwoods easily, and most of the commercial conifer reproduction through close study. A smaller gain in detail is found on the infra-red minus-blue, but it is enough to make the small immature commercial conifers and immature hardwoods generally separable. The commercial conifer reproduction remains unidentifiable, however. Again, no important difference between the two panchromatic combinations is apparent.

Density Classification

Third consideration is given to the density of the vegetation. Two viewpoints enter. One, the Forest Survey, grades timber-stand densities for their relationships with timber volume, growth, and degree of stocking. The other, the State project, grades the density of total woody vegetation cover for its effect on livestock grazing.

Five classes of density*—dense, semidense, open, very open, and unstocked—are given recognition. Each class embraces a range in proportion of ground covered by the vegetation. As far as the film-filter-scale combinations are concerned, however, identification problems hinge on the kind of vegetation being graded rather than on the percentage of ground covered. The following summary (Table 3) therefore considers all densities together in terms of the three ways they are applied: sawlog timber stand (mature and large immature commercial conifers), total timber stand (mature, large immature, and small immature commercial conifers, together with what reproduction is seen), and total woody vegetation cover (all trees and shrubs combined).

Pine Region—On panchromatic minus-blue at 1:20,000 the two timber density classifications are generally feasible though somewhat handicapped by the tonal similarity between commercial conifers, noncommercial conifers

* Defined and illustrated in references (2) and (6).

(Digger pine) and hardwoods. This necessitates close study to include the smaller sizes of commercial conifers when they are intermixed with the other two vegetation elements. Less difficulty is encountered with the sawlog stand, because of better height separation, than with the total stand. The density of total woody vegetation cover is easily classified through the good tonal and other contrasts obtained between the two groups of elements considered.

On the infrared minus-blue at 1:20,000, the two timber classifications can be made easily as a result of the tonal contrast obtained between commercial conifers and hardwoods. The confusing existing between commercial conifers and Digger pine seldom has enough effect to degrade the otherwise ++ rating.

TABLE 3.—RATING OF FILM-FILTER COMBINATIONS FOR THE IDENTIFICATION OF VEGETATION DENSITIES AT 1:20,000 AND 1:15,000 PHOTO SCALES IN THE PINE AND REDWOOD REGIONS OF CALIFORNIA

Region and element	Photo scale and film-filter				
	1:20,000		1:15,000		
	P-MB	IR-MB	P-MB	IR-MB	P-G
PINE REGION					
Sawlog timber stand	+	++	++	++	++
Total timber stand	+	++	++	++	++
Total woody vegetation cover	++	−	++	−	++
REDWOOD REGION					
Sawlog timber stand	++	++	++	++	++
Total timber stand	+	−	+	+	+
Total woody vegetation cover	++	−	++	−	++

P panchromatic film; IR infrared film; MB minus-blue filter; G green filter; ++ generally and easily identifiable; + generally identifiable but sometimes requiring close study; − inconsistently identifiable.

Classification of the total woody vegetation cover is limited by the inability to judge the density of chaparral where that vegetation element occurs intermixed with bushy herbs, grass, or bare ground.

At the 1:15,000 photo scale, all film-filter combinations permit easy classification of the two timber densities, the added details provided overcoming the tonal weakness of panchromatic photography. However, the gain is not enough to offset the tonal weakness of infrared minus-blue with respect to total woody vegetation cover. Panchromatic minus-blue has a slight advantage over panchromatic green for total tree and shrub cover because of its better tonal contrast with certain chaparral species.

Redwood Region—On panchromatic minus-blue at 1:20,000, the classification of density is easy for sawlog timber because of the distinctive heights of the elements considered, and for total woody vegetation cover because of the tonal and other differences evident. Density of the total timber stand usually requires close study because of the little difference between small immature commercial conifers and the hardwoods.

On infrared minus-blue at 1:20,000, only the density of sawlog timber can be generally classified. Again, this is easily done by means of height contrasts. Neither total timber stand nor total woody vegetation can be classified by density under all conditions; the first because of the frequent inability to distinguish between small immature and commercial conifers and the hardwoods, and the second because of the difficulty in separating chaparral or sagebrush from grass or bare ground.

The 1:15,000 scale photos yield no more density information here than the 1:20,000 photos except in the case of total timber stand, which becomes generally classifiable with close study on infrared minus-blue. Significantly, the total woody vegetation cover remains, as in the pine region, partially unclassifiable on the infrared minus-blue.

TIMBER CROPLAND CLASSIFICATION

This classification pertains to whether or not the land appears to possess the climate and soil qualities essential for producing commercial timber crops. From it comes the location and acreage of commercial timberland, one of the primary objectives of the whole effort.

Since this classification involves climate and soil qualities, which are not themselves visible on the photos, indirect evidence must be relied upon. Proper interpretation of the occurrence and character of all the elements heretofore discussed, in the light of known local plant-habitat relationships, provides that evidence. However, much technical judgment and skill are required because of the wide interplay between natural relationships and artificial disturbances. What the climate and soil can normally support is often altered by man's activities. Positive classification is not always possible, especially where most or all of the timber has been removed, but doubtful areas for which ground checks must be made are usually recognizable as such on the photos.

Table 4 lists the primary criteria that would be used in the areas sampled.

TABLE 4.—RATING OF FILM-FILTER COMBINATIONS FOR THE IDENTIFICATION OF TIMBER CROPLAND CRITERIA AT 1:20,000 AND 1:15,000 PHOTO SCALES IN THE PINE AND REDWOOD REGIONS OF CALIFORNIA

Region and Element	Photo scale and film-filter				
	1:20,000		1:15,000		
	P-MB	IR-MB	P-MB	IR-MB	P-G
PINE REGION					
Occurrence of commercial conifers	+	++	++	++	++
Form and vigor of commercial conifers	+	−	++	+	++
Density of tree stands	++	++	++	++	++
Density of chaparral stands	++	−	++	−	++
Indicator species of hardwoods and chaparral	−	+	−	+	0
Exposed rockiness	+	−	++	+	0
Soil drainage	++	++	++	++	++
Intensive land use	++	++	++	++	++
REDWOOD REGION					
Occurrence of commercial conifers	+	−	+	+	+
Density of tree stands	++	++	++	++	++
Density of chaparral stands	++	−	++	−	++
Indicator species of hardwoods and chaparral	+	++	++	++	++
Intensive land use	++	++	++	++	++

P panchromatic film; IR infrared film; MB minus-blue filter; G green filter; ++ generally and easily identifiable; + generally identifiable but sometimes requiring close study; −inconsistently identifiable; 0 no example.

Pine Region—On panchromatic minus-blue at 1:20,000, all but one of the criteria can be generally identified. The factors that make the density and intensive land use (cultivated and urban—industrial) criteria easy to identify have been mentioned in preceding sections. Poor soil drainage (meadows) is easily recognized by the tonal difference between grass growing on wet and dry situations. Of the criteria provided by the timber trees themselves, one—their presence or absence—involves the problem of vegetation-element identification. The other—their form and vigor—is based upon the shape and density of the tree shadows. Close study is sometimes needed to identify these shadow characteristics. The ease of detecting exposed rockiness, which is done through textural indications, varies with the degree of rockiness but close study generally reveals as much as is significant. With regard to the only criterion—indicator species—not always identifiable, comments appear in the following "Species" section.

The infrared minus-blue at 1:20,000, as would be expected from earlier discussions, permits easy recognition of the occurrence of commercial conifers, density of tree stands, and intensive land use. Poor soil drainage (meadows), by the same means as on panchromatic minus-blue, is also easily identified here, although the grass tones are reversed. Close study can identify enough of the more important, particularly hardwood, indicator species to justify a + rating for that criterion. None of the other three criteria are always identifiable; the density of chaparral and exposed rockiness for reasons given in preceding sections, and the form and vigor of commercial conifers because of the slight shadow differences presented. On this film-filter combination, trees over a wide range of foliage density have uniformly dense shadows.

The gains in detail obtained with the 1:15,000 scale result in easy identification for all but one of the criteria on panchromatic minus-blue. Lack of tonal distinction still prevents consistent recognition of key indicator species. On the infrared minus-blue, the gains make shadow characteristics (form and vigor) of commercial conifers and the texture of exposed rockiness recognizable through close study but subtract little from the tonal handicap affecting density of chaparral. For the criteria adequately sampled by panchromatic green, recognition is identical with panchromatic minus-blue.

Redwood Region—Panchromatic minus-blue at 1:20,000 provides identification of all the criteria applied in this region, with three of them—the two density criteria and intensive land use—being easily identified for reasons already given. Close study is needed for the occurrence of commercial conifers when small trees are involved and for certain indicator species that are indistinctly marked.

Three criteria also are easily identified on infrared minus-blue at 1:20,000 The density of tree stands offers no problem because of the distinctive heights of the trees. Likewise intensive land use because of its patterns. The indicator species, though not so obvious, deserve ++ rating for the good tonal distinctions presented between some important groups. Offsetting these, however, is the inconsistent identification of commercial conifer occurrence and chaparral density for reasons discussed in the "Vegetation Elements" section.

At the 1:15,000 scale, the film-filter combinations yield equal results except in the case of chaparral density. Its identification remains handicapped on the infrared minus-blue through lack of tonal distinction.

Species

Another useful photo classification could be built around the identification of individual plant species. The indicator-species criterion for identifying timber croplands is a simple form of such a classification, based on a few key species, now being made. Another form, a classification of all dominant species, is a part of the State's project, but it is made through ground observations because past experience has found very limited possibilities of doing this from photos alone. Nevertheless, a comparison of the film-filter-scale combinations with respect to individual species seemed worth including in this study.

Pine Region—The most important species sampled here include 9 of coniferous trees, 7 of hardwood trees, and 8 of chaparral.

At the 1:20,000 scale, 2 of the conifer, 3 of the hardwood, and 3 of the chaparral species are generally identifiable on panchromatic minus-blue; 1 of the conifers, 3 of the hardwoods, and 5 of the chaparral species on infrared minus-blue. Duplication occurs with 1 conifer, 2 hardwoods, and 1 chaparral species. Neither film-filter combination provides tonal or other distinction between the important timber species, at best offering only partial separation of the pine and fir groups. Mature trees are usually the only ones distinguishable. For the hardwoods, infrared minus-blue holds a distinct advantage because of its tonal contrast between California black oak, a good timber cropland indicator, and all other species. On panchromatic minus-blue that species is distinguishable from only some of the others. With chaparral, the most significant indicator—chamise—is most completely identifiable on panchromatic minus-blue.

The only addition gained from the 1:15,000 scale is that sugar pine, a timber tree, becomes partly separable from ponderosa pine on panchromatic minus-blue through its evident branching habit while it remains indistinguishable on infrared minus-blue. The panchromatic green differs very little from panchromatic minus-blue except for one of the chaparral species. The weak tonal difference of that species is less visible on the panchromatic green.

Redwood Region—The most important species sampled here include 3 of coniferous trees, 7 of hardwood trees, and 8 of shrubs (chapparal and sagebrush).

At the 1:20,000 scale, 1 of the conifer, 2 of the hardwood, and 2 of the shrub species are generally identifiable on panchromatic minus-blue; only 1 of the conifers on infrared minus-blue. The same conifer (knobcone pine) is easily recognized by its tone in both cases. The 2 timber conifers (redwood and Douglas-fir) usually can be separated on panchromatic minus-blue by tone when the trees are mature, but not when they are young; on infrared minus-blue their tones usually are inseparable regardless of age. Although few hardwood species are individually recognizable, group-identification of tanoak—madrone, the live oaks, and alder—boxelder is generally possible on both film-filter combinations through tonal differences. A similar group-identification of considerable significance occurs with the chaparral, but in this case infrared minus-blue renders it more distinct than panchromatic minus-blue.

The 1:15,000 scale produces no apparent gain in the identification of tree species. However, 2 additional shrub species become recognizable by textural differences on the panchromatic minus-blue and the two identifiable on that combination at 1:20,000 now also become recognizable on the infrared minus-blue. No difference between panchromatic green and panchromatic minus-blue is noted for any of the species sampled.

ANALYSIS

Explanation of Diagrams

Most of the foregoing results can be explained through analysis of the spectral diagrams shown in Figures 3A–3D. Correlations between the results and diagrams will be brought out following a brief discussion of the diagrams themselves. It should be kept in mind, with reference to these diagrams, that the ordinate is plotted on a logarithmic scale in all except Figure 3C.

Determination of the reflectance of light from the foliage of a limited number of hardwoods and conifers has indicated reflectance spectra which for the most part fall within the two broad bands shown in Figure 3A. Low reflectance from the blue and red ends of the visible spectrum is largely attributable to absorption of these wave lengths of light by chlorophyll. The extremely high reflectance in the infrared range is due to the almost complete transmission of infrared light by chlorophyll. On striking the upper surface of a hardwood leaf, infrared light passes through the many chloroplasts of the palisade parenchyma and penetrates to the foam-like spongy parenchyma which, like foam, reflects light to a

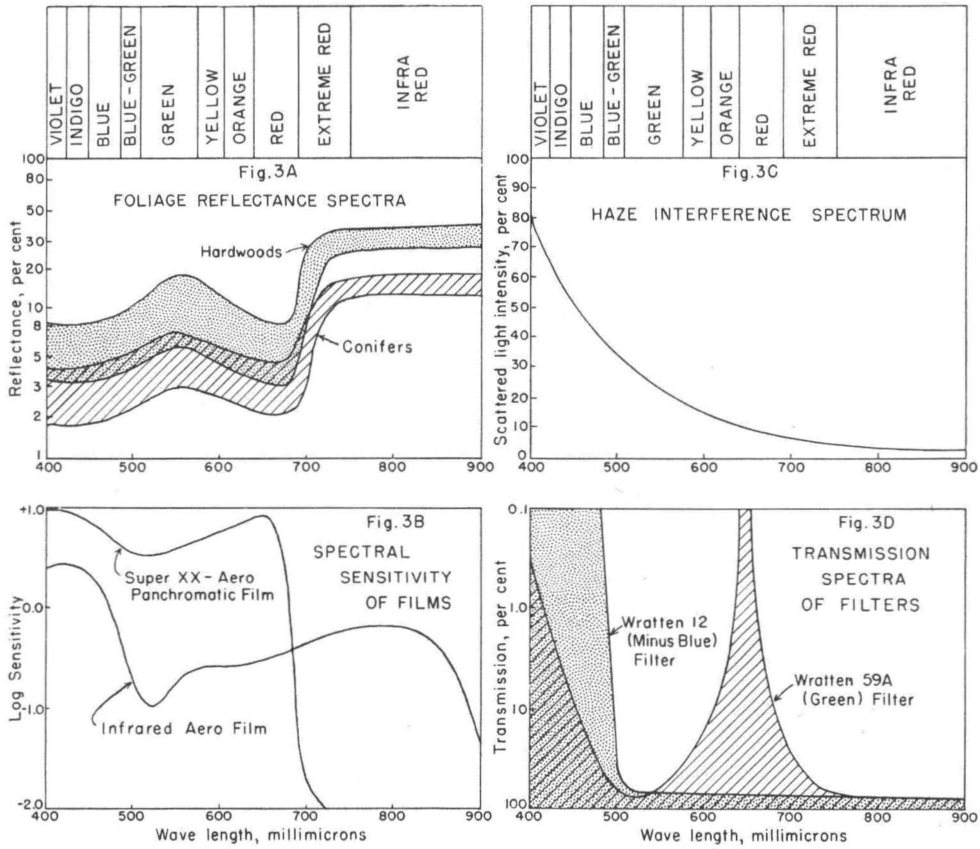

FIG. 3. Spectral diagrams for foliage reflectance, film sensitivity, haze interference, and filter transmission involved in the experimental photography of the pine and redwood regions of California.

very high degree. Much of this reflected light then passes back through the chloroplasts and emerges from the top surface of the leaf. The absence of a similar spongy mesophyll in coniferous needles partially explains the lower reflectance of infrared light from them shown in Figure 3A. The situation is notably different in the green part of the spectrum in that much of the green light is reflected directly by the chlorophyll instead of being transmitted through it. Consequently, the internal leaf structure might be expected to have less influence on foliage reflectance in the green range than in the infrared. This is indicated in Figure 3A by overlap of the conifer and hardwood curves in the green, but not in the infrared. The fact that conifers generally reflect less light than hardwoods throughout the entire visible and infrared range, as shown in Figure 3A, is believed due primarily to basic differences between the two groups as regards density, size, shape and orientation of foliage.

The sensitivity spectra of the panchromatic and infrared films used in this test are given in Figure 3B. These are reportedly the same films as those tested by Spurr and Brown. Ryker's panchromatic film also had essentially the same sensitivity spectrum as that shown in Figure 3B.

The haze interference spectrum diagrammed in Figure 3C is based on Rayleigh's law that the intensity of scattered light varies inversely as the fourth power of the wave length. It is in essential agreement with the haze interference spectra obtained in actual aerial photographic tests by Von Kujawa and others, as reported by Clark (1).

Figure 3D shows the transmission spectra of the two filters used. It will be noted that the Wratten 12 filter excludes most of the light from the blue end of the spectrum and that the Wratten 59A excludes some of the blue and much of the orange-red light.

Photographic Detail

A study of the diagrams permits theoretical consideration of the relative suitability of various wave lengths of light for obtaining maximum clarity of detail in aerial photography of a forested area.

Exclusion of light from the blue end of the visible spectrum would seem desirable because, within that part, haze interference is at a maximum and foliage reflectance is at a minimum. However, in one respect the utilization of blue light would be of advantage. Since shaded areas are illuminated largely by diffuse skylight, the light they reflect to the camera is predominantly from the blue end of the spectrum. Exclusion of this blue light therefore increases the darkness of shaded areas and decreases the amount of photo detail discernible within them.

Orange-red light theoretically should be excluded because of glare in this part of the spectrum. Ryker ascribed the loss of detail in his experiments, when orange-red light was not excluded, primarily to glare caused by (a) specular reflections of the sun's disc from the sunny side of tree crowns, and (b) secondary reflections of light rays from the ground and undergrowth upward through the trees. In both cases, light passing to the camera seemed inordinately rich in orange-red wave lengths. Ryker concluded that "it may be stated as an axiom that when using Super Pan film for photographing timber, any filter which transmits orange and red radiations is useless."

Infrared light might at first seem to be very suitable for photographing vegetation from the air because within this range foliage reflectance is at a maximum and haze interference is at a minimum. However, within the infrared, hardwoods reflect so much more light than conifers that the range in reflectance may be too great to be spanned and still give good clarity of photo detail. When infrared film is given an "optimum" exposure, most of the hardwoods are overexposed while most of the conifers and all of the shadows are underexposed, with consequent loss of detail throughout.

This leaves only green light to be considered. It seems to be more useful than other wave-lengths chiefly because of its relative freedom of the various disadvantages previously mentioned. Thus, green is theoretically better than blue because it has less haze interference, better than orange-red because it has less glare, and better than infrared because it imposes a narrower range to be spanned between highlights and shadow. As shown in Figure 3A, maximum foliage reflectance rarely exceeds 20% in the green as compared with nearly 50% in the infrared. At the same time, this is sufficiently high reflectance of green light so that an unduly long exposure need not be given to activate the film, even though other wave-lengths are largely excluded.

Considering film sensitivity, Figure 3B shows that Infrared Aero film is highly sensitive in the blue and red ends of the visible spectrum as well as in the infrared, and that it has a very low sensitivity to green light. Theoretically, then, this film would seem to have exactly the wrong sensitivity spectrum for obtaining maximum clarity of vegetational detail. In addition other factors, listed below, also may contribute to this loss of detail. They are largely attributable to limitations of present-day photographic equipment and are partially remediable:

(1) Infrared film has a somewhat lower photographic resolving power than panchromatic film. Tupper and Clark (5), using a low contrast test objective and a lens relatively free of aberrations, determined the photographic resolving power of Super XX Aero Panchromatic film to be 50 lines per millimeter as compared with 45 lines per millimeter for Infrared Aero film.

(2) Most aerial cameras have a fixed focal length and have been focused for the visible wave lengths of light on the assumption that only panchromatic aerial photography will be taken with them. Although the focal length for most lenses is only about 0.5% greater for infrared than for panchromatic photography, some authorities believe this is sufficient to detract somewhat from the clarity of the image if the correction is not made, especially if a deep red filter such as the Wratten 89 is used.

(3) Most aerial camera lenses have been color-corrected only for the visible wave lengths of light on the assumption that only panchromatic photography will be taken with them. Thus an achromatic lens which has been corrected to bring both violet and yellow light to focus in the same plane cannot be adjusted to simultaneously bring infrared light into sharp focus.

The cumulative effects of these deficiencies on infrared minus-blue photography with regard to the vegetational problems under consideration here have been detailed in an earlier section. Specifically, the inability to distinguish between the thin-foliaged Digger pines and commercial conifers; the tree-tip details of young redwoods and associated hardwoods; and the minor textural differences of shrubs, grass, bare ground, and rock are all consequences of the general loss of detail on infrared minus-blue photography. No instances were observed in which infrared minus-blue gave greater clarity of detail than the panchromatic combinations..

Panchromatic photography with a green filter theoretically might be expected to yield maximum photo detail for the following reasons: (a) in the blue end of the visible spectrum, it offers a compromise by partially excluding haze interference and partially exposing for detail in shaded areas; (b) in the green, where foliage reflectance is higher than elsewhere in the visible spectrum, it combines maximum passage of light through the filter with high sensitivity of the film, relative to that of infrared film; (c) in the red end of the visible spectrum, it partially excludes light which might otherwise be so intense as to cause glare; and (d) in the infrared range, it completely excludes light, thus avoiding problems in over- and under-exposure brought about by the great range in reflectance between highlights and shadows.

The fact that our results showed no appreciable differences in photo detail between panchromatic minus-blue and panchromatic green photography indicates that, for these two combinations, factors (a) and ((c) of the preceding paragraph are of minor importance at scales of 1:15,000 or smaller, although Ryker's results would seem to establish their importance at scales of 1:10,000 or larger. As smaller scales are employed, reliance upon minute photo detail becomes progressively less, and the importance of tone becomes somewhat greater. For example, Ryker was able to make considerable use of such characteristics as the visibility of individual branches and the tufted nature of the top of the tree crown, neither of which is ordinarily discernible at a scale of 1:15,000 or smaller.

Photographic Tone

Differences in photographic tone, the feature found most significant to the classifications tested, also bear relationship with the preceding theoretical consideration. For example, the over-exposure of hardwoods and under-exposure of conifers on infrared photography may be disadvantageous, as previously mentioned, by causing loss of photographic detail; but this same characteristic may produce tonal contrasts which readily permit the photo separation of hardwoods from conifers. In Figure 3A the reflectance bands for hardwoods and conifers are seen to be rather widely separated in the infrared, but to overlap within the visible part of the spectrum. This is in keeping with the results from the pine region, in which the hardwoods are contrastingly lighter in tone than the conifers on infrared minus-blue photography, whereas on panchromatic some species of hardwoods appear slightly darker than certain coniferous species. (Compare areas labelled "H" and "C," Figure 1.) Consequently, in the pine region all classifications involving mixtures of these two elements are more easily made on infrared minus-blue photography than on either of the panchromatic combinations.

The results obtained from the redwood region point to the risk of making indiscriminate generalizations, however, as in that region neither film-filter combination has a distinct tonal advantage for separating commercial conifers from hardwoods. Redwoods, the most important commercial conifer there, appear in much the same tone as the common associated hardwoods on both the panchromatic and infrared photography. (Compare areas labelled "H," "C," and "HC" in Figure 2.) This is attributed primarily to the orientation of redwood foliage in flat horizontal sprays which, despite their lack of a distinct spongy mesophyll, are able to reflect large amounts of infrared light to the camera.

The photographic tone of any given tree is influenced by many factors, including density, size, shape and orientation of foliage; chlorophyll content; proximity of other trees; nature of the understory; season of the year; direction of the sun's rays; condition of the atmosphere; slope; aspects; and position of the tree image relative to the photo center. In view of this formidable array of factors, it may seem too much to expect photographic tone to have any diagnostic value whatever in the photo identification of tree species, However, differences in the reflectance spectra of various species of trees growing in a mixed stand do result in unique tonal appearances for some species on panchromatic photography and for others on infrared. It follows that a greater number of species frequently can be identified under these conditions from a study of both panchromatic and infrared photography than from either kind alone.

In the classification of vegetation elements other than trees, both panchromatic combinations, for the most part, provide good tonal contrasts that distinguish shrubs from herbaceous vegetation, leaf litter, bare ground and rock. (See areas labelled "B" in Figure 1 and "S" and "G" in Figure 2.) The absence of such contrasts on infrared minus-blue limits the possibilities for making several important classifications with that film-filter combination. The primary factor that produces this advantage in favor of the panchromatic combinations is the dark tone of dry grass and other associated herbaceous vegetation on the infrared minus-blue. This vegetation, common throughout California, consists primarily of annuals which begin growth as green plants during the winter or spring of each year and dry to a yellow or brown color with the onset of the summer rainless season. The latter is also the chief photographic season. Although direct evidence is lacking, it seems plausible that the dehydration and collapse of the spongy mesophyll accompanying this death of the leaves decreases their reflectance of infrared light and thereby produces the dark tone noted above.

With regard to information other than that required for the vegetational classifications considered, experiments in the East have suggested that the high degree of absorption of infrared light by water might be used to evaluate soil moisture content from infrared minus-blue photography, the wettest soil photographing darkest in tone. In California, swampy spots in meadows of the pine region appear lighter in tone on the infrared minus-blue photos than do nearby dry spots. This is explained by the fact that the swampy areas are covered with green grass which appears light in tone on infrared photos because of the high transparency of the chlorophyll to infrared light. The dry grass in adjacent areas is brown in color and photographs darker in tone on the infrared film. Although the grass is only a few inches high, it completely masks the soil from the aerial camera.

In and around brackish swamps of the redwood region, vegetation is less indicative of soil moisture than in the pine region, since the vegetation cover is more complex and its greenness bears no correlation with wetness of the site. As in the pine region, the vegetation masks the ground from the camera.

Because abundant soil moisture constitutes an ideal condition for the dense growth of hydrophytic vegetation, it would seem that the only instances in which a dark photographic tone on infrared photography might be directly indicative of a wet soil as reported in the East, are those where, for some abnormal reason, such as the recent burning or cultivation of an area, the soil is practically devoid of vegetation.

One definite advantage of infrared photography to be gained through tonal characteristics is in the recognition of the exact course followed by small streams overhung by hardwood trees, a very common feature in California. The jet black appearance of the water is in such sharp contrast to the light tone of the hardwoods that a water course usually can be readily traced on the infrared photos even though visible only intermittently. (Compare Figure 2B with 2A and 2C.) If underwater detail is desired, however, as in estimating the suitability of lakes and streams for recreational purposes, aquatic life, or dam construction, infrared photography is not suitable because of the great extent to which water absorbs infrared light. Photographic interpretation for military purposes has shown that under optimum conditions panchromatic photography will reveal underwater details to depths of 20 or 30 feet.

Because of the greater tonal contrast between vegetation and soil or rock, panchromatic photography was found to be superior to infrared in the California test for determining the exact course of winding forest roads. (Compare roads in vicinity of "B", Figure 1; also note the main highway, Figure 2.)

Shadows

For an explanation of the differences found between panchromatic and infrared photography with regard to shadow characteristics, reference to Figure 3A is helpful. Because of the very high reflectanse of infrared light by fully illuminated hardwood crowns and the very low reflectance of light from shaded areas, an exposure for infrared photography which does not grossly over-expose hardwoods is of too short duration to record details of shaded areas, with the result that all shadows tend to appear jet black, Consequently, it is to be expected that panchromatic will be more effective than infrared photography in bringing out differences in shadow density.

This is in keeping with results noted throughout the pine region. Because denseness of pine foliage is usually indicative of timber-site quality, it becomes possible to distinguish good timber cropland, poor timber cropland, and non-timber sites through study of shadow details and densities. These features are visible on panchromatic photography but not on infrared. The absence of apparent shadows from very sparsely foliaged pines on infrared minus-blue photography can be explained on the basis of the small "islands" of shadow blending with the dark photographic tone of the ground itself whether the ground is bare or covered with herbaceous vegetation. The lighter photographic tone of the ground on panchromatic photography permits sufficient contrast to detect these fine tree shadows.

Also explainable on this basis is the difficulty of determining shrub density on infrared minus-blue photography. The shrubs themselves, their shadows, and the litter-covered ground so blend together that the shrubs alone are lost. On panchromatic photography the individual clumps of brush usually stand out quite distinctly. (See area "5" Figure 1.)

The relative inability to discern details in shaded portions of the forest floor on infrared minus-blue photography does not constitute a serious disadvantage in the Survey classifications, because usually enough of the forest floor is in sunlight to determine its composition. For certain other forestry uses of aerial photographs, however, such as the accurate plotting of section corners, the measurement of individual tree heights, or the delineation of roads, trails, and contours, these dense shadows may completely obscure needed detail in the particular area of interest.

Scale of Photography

In comparing the merits of the two scales of photography, two considerations are paramount: (1) the relative ease and accuracy of interpretation of the photos, and (2) the relative cost of their procurement and interpretation.

As indicated by Tables 1–4, the relative ease and accuracy of interpretation of many features is considerably increased by use of the larger scale of photography. This is true of both infared and panchromatic photography, but the gain is greatest on the panchromatic. Further gains on the infrared minus-blue photography are limited by the tonal deficiencies previously discussed.

In areas containing very tall trees, the larger scale of photography can even be of disadvantage. The increased stereoscopic parallax of trees at the larger scale makes difficult the simultaneous stereoscopic fusion of tree crowns and forest floor. This can best be appreciated by first studying a stand of tall trees stereoscopically on two large-scale photos having the conventional 60% overlap, and then on two photos of the same area at the same scale but having, say, 90% overlap. The photos having the greater overlap are much more easily studied because they have much less stereoscopic parallax and thus permit easier stereoscopic fusion throughout the area of interest.

This leads to consideration of the cost factor. Either increasing the scale or decreasing the stereoscopic parallax increases the amount of photographic film and paper required to cover a given area, the number of flight lines which must be flown, the number of prints which must be interpreted, the number of tie-ins which must be made between photos in extending such features as type boundaries and drainage nets, and the number of orientations which must be made in transferring the photo data to a map. The cumulative cost effect of these factors may be appreciable, and in any particular case must be weighed carefully against the consequent advantages in ease and accuracy of interpretation of the photos.

Comparison with Previous Tests

In reconciling our results using a green filter with those of Ryker, it is important to keep in mind that: (a) Ryker's photography was at a scale of 1:9,600 whereas ours was at a scale of 1:15,000 and 1:20,000, with the result that minute photo detail was more important and tonal contrast less important in Ryker's test than in ours; and (b) Ryker was concerned primarily with species identification of mature trees of four coniferous species growing in a particular area, whereas the scope of our objective was much broader as can be seen in Tables 1–4.

Because of the above differences, no direct comparison of our results with those of Ryker is possible. From such indirect comparisons as can be made, Ryker's conclusion that panchromatic photography with a green filter was the most suitable of the combinations he tested is not at odds with our results. It is also in complete agreement with theoretical considerations regarding the most suitable wave lengths of light for aerial photography of vegetation.

Spurr and Brown concluded from their tests that infrared minus-blue is the best film-filter combination because it combines much of the good tonal contrast (e.g. between hardwood and conifer) of normal infrared photography with much of the good resolution of detail of panchromatic minus-blue photography. In contrast, our test found that although infrared minus-blue has certain advantages, it is not satisfactory for the vegetational conditions and photo uses involved in the California Forest Survey, largely because it sacrifices both photo details and fine tonal gradations obtainable on panchromatic minus-blue and panchromatic green photography.

In reconciling our results with those of Spurr and Brown, the following factors must not be overlooked. (a) In the East, where hardwoods constitute a much more important part of the vegetation than in the West, experiments were concerned primarily with the separation of conifers from hardwoods, and with the identification of key species in each group. On the other hand, the California Forest Survey is concerned with a great variety of vegetation forms and seeks much additional information, as shown in the tables. (b) In California, grass usually has turned from green to yellow or brown by the time of year when most aerial photography is taken. This grass appears light in tone on panchromatic photography and thus stands out clearly from dark-toned trees and shrubs (Figures 2A and 2C), whereas on infrared minus-blue photography it assumes the same tone as many of the trees and shrubs (Figure 2B). Grass is for the most part green in the East when the photos are taken and on infrared film contrasts to better advantage with woody vegetation than in the West. (c) In California, there frequently is an intermingling of exposed bare ground with trees and other vegetation, whereas in the East such exposed ground usually is grass-covered. This bare ground mostly appears light in tone on panchromatic photography and dark in tone on infrared minus-blue, the latter producing an undesirable blending with the vegetation and its shadows (see Figures 1A and 1B).

CONCLUSIONS

As shown by the discussion of Tables 1–4, panchromatic minus-blue photography yields slightly more information for the objectives of the California Forest Survey than does panchromatic green, and much more than is obtainable from infrared minus-blue photography. The latter comparison holds for both the 1:15,000 and 1:20,000 photo scales, with no significant gains to be expected from making a focal-length adjustment for infrared. However, considerably more information can be obtained from a study of both panchromatic and infrared photography than from either alone. This suggests that for certain projects, especially in areas inaccessible for supplementary ground study, simultaneous photography with two or more cameras employing different film-filter combinations may be justifiable, despite the increased cost of photography.

Although, for purposes of the Forest Survey in California, the net advantage from the interpretational standpoint is in favor of 1/15,000 scale photography, continued use of the 1:20,000 scale will be made as long as funds do not permit obtaining the desired coverage at a large scale.

It is apparent that determination of the most suitable film-filter-scale combination for aerial photography is a local problem, dependent upon both the nature of the vegetation and the specific objectives which are to be achieved through use of the photos. There is considerable danger in making broad generalizations. For example, if the separation of hardwoods from conifers had been the sole objective of this test, infrared minus-blue photography would have proved superior in the pine region and panchromatic minus-blue in the redwood region.

The selection of a film-filter-scale combination therefore is worthy of careful consideration for each project in which extensive use of new photography is contemplated. The detailed results reported from this study combined with an analysis of spectral diagrams of the type shown in Figures 3A–3D may give helpful clues to what may be expected in any given area from the various combinations now available. Better still would be an actual preliminary test. Such a test would cost only a very small fraction of the total cost of any extensive project and might avoid much inaccurate photo interpretation and unnecessary field work caused by unsuitable aerial photography.

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