ASSESSMENT OF FOREST STOCKING CONDITIONS BY MULTIPLE-STAGE REMOTE SENSING TECHNIQUES

by

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS--Continued

LIST OF TABLES

LIST OF ILLUSTRATIONS

ABSTRACT

Quantification of the proportion of forestland units that support arbitrarily defined minimum forest density levels that are associated with yields of natural resource products and uses would be helpful to: (1) set realistic bounds for implementing management systems, (2) appraise the suitability of forestland units for a particular management system, and (3) define priorities for operational programs among forestland units. Such a statistic may be obtained from solutions of forest stocking equations, which may be generated by applications of remote sensing techniques as described herein.

Forest stocking equations were developed from high altitude imagery for the forested area of the south one-half of the Prescott National Forest in north-central Arizona. However, the general methodologies may be suitable for the development of forest stocking equations elsewhere.

The synthesis of source data necessary for the development of forest stocking equations involved the assessment of forest density conditions from high altitude imagery, and the translation of these assessments to ground estimates of forest density conditions using standard 1:15,840 imagery as an intermediate adjustment basis. The source data were organized to develop probability density functions, from

which cumulative distribution functions were derived. The mathematical expressions of these latter functions are, by definition, forest stocking equations.

INTRODUCTION

A goal of efficient natural resource use dictates that forestland management systems be evaluated before they are implemented to "match" inherent characteristics of forestland units potentially available for implementation of such systems. If a particular management system should be considered as a means to increase the production and use of a natural resource mix, but only limited forestland units can be "matched" for implementation, the management system may be given low priority in future planning.

The previously-described activity is of special importance in Arizona, where an evaluation of potential forestland management systems (vegetation manipulation plans) for achieving specified goals of increased water yield has recently been completed (Ffolliott and Thorud, 1974). This evaluation involves the identification of "high potential" management systems, and, once identified, an assessment of the extent to which these "high potential" systems can be implemented. The latter evaluation may decide, in part, the operational feasibility of these programs.

If the operations feasibility of management systems is to be properly assessed, one of the first steps necessary in organizing this framework for natural resource decision-making is the identification of relevant descriptive resource populations. These might be vegetative, physiographic, or climatic populations.

Specifically, the study described herein was concerned with the identification of the proportions of forestland units that support ponderosa pine (*Pinus ponderosa*) density levels which may affect the yield of natural resource products and uses in Arizona. Unfortunately, commonly derived estimates of average parameters (mean forest density values) do not necessarily provide complete knowledge of vegetative characteristics. This is particularly true with frequently "skewed" forest population parameters.

It has been shown that clearly recognizable patterns of skewness in ponderosa pine forests in Arizona may develop as a result of shade intolerance of the species, restriction of number of species present due to harsh environment, or occurrence of periodic natural fires. All of these factors serve as a force that opposes the natural propensity of vegetation to assume a normal density distribution (Cooper, 1961). Basically, four pattern types have been recognized as being characteristic of ponderosa pine forests: (1) forest density, growth and species composition variation as a result of microenvironmental differences; (2) an even-aged group mosaic pattern with even-aged groups averaging about one-fifth acre in size, maintained as a result of periodic natural fires; (3) stand density variations within a single even-aged group, due to chance factors in early stand development; and (4) the pattern of spacing of individual trees in an even-aged stand. All of these patterns may account in part for the skewness of commonly derived average forest population parameters.

The quantification of a different statistic, the proportion of forestland units that support arbitrarily defined minimum forest density levels that are associated with yields of natural resource products and uses would be helpful to: (1) set realistic bounds for implementing management systems, (2) appraise the suitability of forestland units for a particular management system, and (3) define priorities for operational programs among forestland units (Ffolliott and Worley, 1973). Such a statistic may be obtained from solutions of forest stocking equations, which may be generated by applications of remote sensing techniques, as described herein.

A forest stocking equation describes the proportion of a forest (the dependent variable) that is stocked to an arbitrarily defined forest density level (the independent variable) (Ffolliott and Worley, 1973). Forest density is defined as a measure of the extent of crowding among the individual trees on a forested tract. Expressions of forest density include crown closure, basal area, numbers of stems, volume, etc.

The synthesis of forest stocking equations describing the proportions of forestland units that support arbitrarily defined minimum forest density levels is based upon the following mathematical procedures: (1) the development of functions (probability density functions) from the basic source data, and (2) the development of distribution functions (cumulative distribution functions) from the density functions. These distribution functions, by definition, are described as being continuous from the right and, therefore, can be considered as "exceedence functions."

Irrespective of what a particular forestland management system is designed to accomplish, the application of forest stocking equations will help to determine management potential and prescribe management feasibility (Ffolliott and Worley, 1973). Forest stocking equations can also be used in combination with other information to set management operational priorities. This application would combine knowledge of the proportions of management units in a forest that support minimum forest density levels, the output of the forest stocking equations, with selected criteria characterizing alternative management opportunities (minimum forest density levels, portions of forestland units meeting specified minimum forest density levels, etc.). Then, for a given forestland management system, forestland units are eliminated from consideration or ranked in terms of suitability by interpretations of the appropriate frequency distributions and the selected criteria.

The theory behind the development of forest stocking equations and the illustrations of the methodology of forest stocking equation synthesis from conventional ground inventories has previously been reported (Ffolliott and Worley, 1973). However, ground inventories are both time consuming and costly in terms of amount of necessary field and office data collection and evaluation, and monetary expense.

It is suggested herein that for many purposes, the use of remote sensing techniques to synthesize comparable source data may be a suitable alternative to conventional ground inventory.

The derivation of the mathematical functions which define forest stocking equations as synthesized by remote sensing techniques entailed the use of spectral and spatial parameters associated with the imagery of the areas of interest. Essentially, the synthesis of forest density data for the development of forest stocking equations, as described herein, involved a two-step procedure: (1) the assessment of forest density conditions on primary sampling units from high altitude imagery (1:120,000) taken by U-2 and RB 57-F aircraft, and (2) the translation of these assessments to ground estimates of forest density conditions utilizing conventional 1:15,840 black and white imagery as an intermediate adjustment basis.

Continual collection and assessment of basic source data by remote sensing techniques may allow for the frequent updating of management analyses. Such re-evaluations could provide information about changes in forestland management potentials with time by identifying the management status of forestland units at given points in time.

In this study, basal area is used as the expression of forest density. Basal area may be defined as the total cross-sectional area of the trees in a stand expressed in square feet. (In the United States, this measurement is taken outside the tree bark at 4 1/2 feet above the ground level.) Basal area was chosen as the expression of forest density because it has been found to be a consistent, easily determined, and widely used measure of forest density (Davis, 1966).

DESCRIPTION OF STUDY

Objectives

The specific objectives of this study were:

1. To develop methodologies suitable for the synthesis of source data required to develop forest stocking equations for ponderosa pine forests in Arizona, and elsewhere, by remote sensing techniques.
2. To develop forest stocking equations by applications of remote sensing techniques describing the proportions of forestland units that support arbitrarily defined minimum forest density levels in the ponderosa pine forests on the Prescott National Forest in Arizona.
3. To illustrate how stocking equations, as developed herein, can be used alone or in conjunction with other information to assist a land manager in decision-making.

Study Area

The area studied was the forested portion on the south one-half of the Prescott National Forest in north-central Arizona (Figure 1). The study area covered approximately 90,000 acres of predominately ponderosa pine forestland. Intermixed with ponderosa pine were Douglas-fir

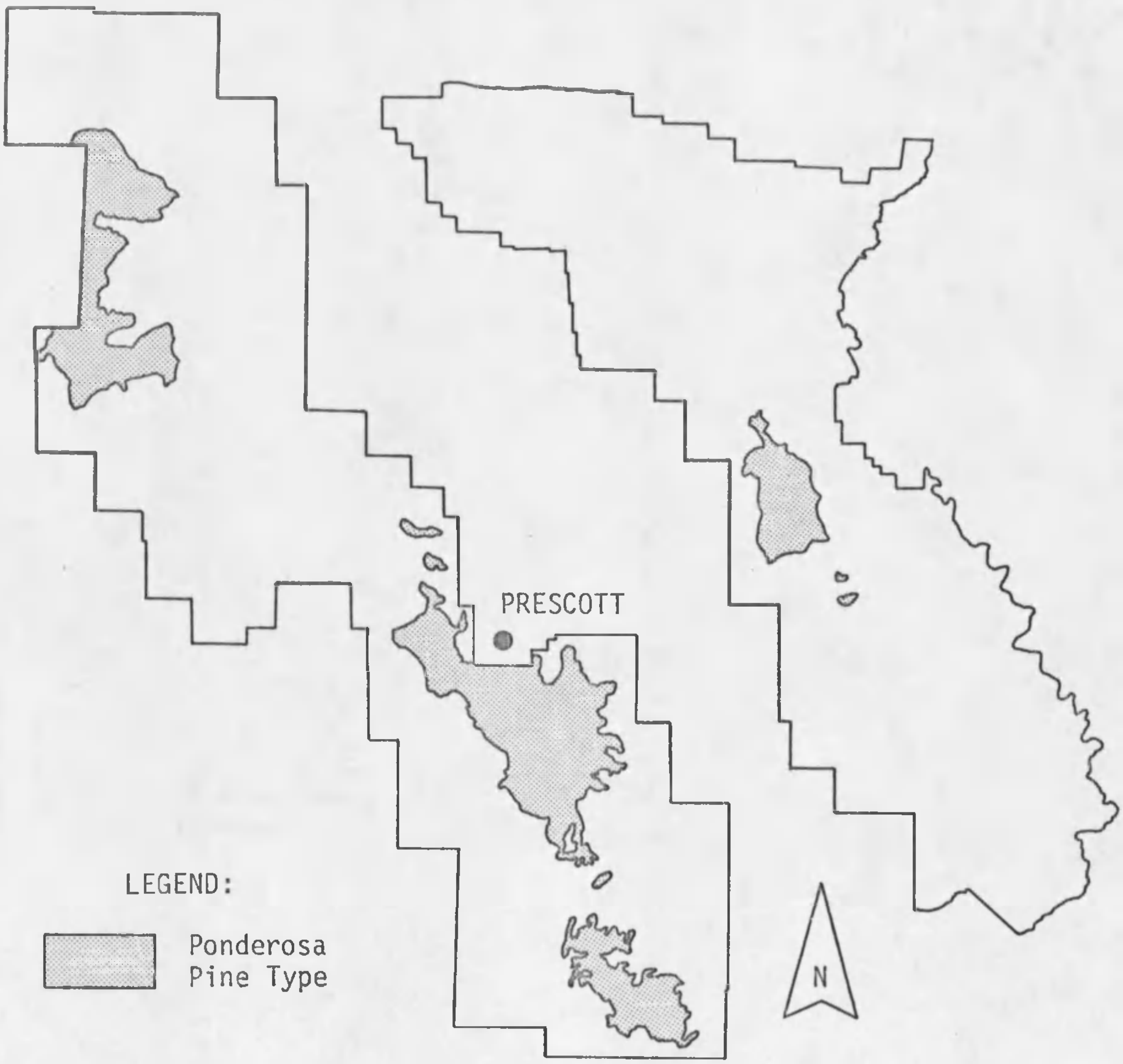

Figure 1. Map of Study Area

(*Pseudotsuga menziesii*) and white fir (*Abies concolor*) at higher elevations on north-facing slopes, and pinyon (*Pinus edulis*) and junipers (*Juniperus* spp.) at lower elevations. Gambel oak (*Quercus gambelii*) may be found throughout the study area at various elevations and slope-aspect combinations. Average site index for ponderosa pine is 60 feet at 100 years of age (Meyer, 1961).

As previously described, the ponderosa pine forest on the study area, like many ponderosa pine forests in other areas, is subject to clearly recognizable density patterns. This irregularity in forest density is expressed in the open, park-like appearance of the forest in some parts of the study area, and the even-aged group mosaic pattern of small dense stands in other parts.

Topography on the study area is quite variable, from rolling hills to relatively steep slopes. Elevations range between approximately 6,000 feet and 8,000 feet. Soils on the study area are variable, being comprised of basalt and sedimentary parent materials. Annual precipitation averages 20 inches, most of which occurs in the form of snow or rain in winter or rain during the summer monsoon season.

The ponderosa pine forest on the south one-half of the Prescott National Forest is important for range forage production and recreation use. However, part of this area is classified by the USDA Forest Service as commercially operable timberland and therefore is managed accordingly.

In addition to these valuable natural resource products and uses, this area also contributes water in the form of runoff from winter precipitation and recharge to ground-water for local water supplies and elsewhere in central Arizona.

Field Procedures

Field procedures were minimal and simply involved several reconnaisances within the study area to observe vegetation types and topography. Extensive ground-truth timber overstory survey data (Ffolliott and Solomon, 1974) were available. Thus, collection of this information was not necessary in this study.

Analytic Procedures

The synthesis of forest density data for the development of forest stocking equations by remote sensing techniques involved a three-step procedure:

1. Identification of primary sampling units and subsequent estimation of forest density conditions on standard 1:15,840 panchromatic imagery.
2. Identification of these same primary sampling units on high altitude imagery (1:120,000) taken by U-2 and RB 57-F aircraft and assessing forest density conditions on these sampling units.
3. Translation of these high altitude density assessments to ground estimates of forest density

conditions, utilizing the 1:15,840 scale forest density estimates as an intermediate adjustment basis.

Analysis of 1:15,840 Imagery

The first step required in the analysis of 1:15,840 imagery was the identification of the primary sampling units on the study area. The existing U.S. Public Land Survey network was used to delineate primary sampling units. A primary sampling unit was one square mile (640 acres) of land forested over one-half of its areal extent.

It was determined from a timber type map obtained from the USDA Forest Service that there were 141 primary sampling units (N) on the study area. An identification number was assigned to each primary sampling unit, and 50 (n) primary sampling unit identification numbers were randomly drawn. The randomly selected primary sampling units were then delineated on the 1:15,840 imagery, using flight line maps obtained from the USDA Forest Service to identify the locations of the sampling units on the photos. A 4-inch square template was used to draw sampling unit outlines on the photos. Once this was accomplished, a dot grid with 100 dots per 4-inch square was used to determine the areal extent of forest openings. The grid was dropped on the imagery over a delineated sampling unit, and dots which landed in forest openings were counted with aid of a

10 power hand lens. Forest openings 12 acres (each dot counted represented 6.14 acres per dot) or larger were outlined, and the number of dots landing in these delineated forest opening was recorded. It was hoped that this latter information could be used as a conversion divisor to place each average crown closure estimate on a per primary sampling unit basis. However, the areal extent of forest openings could not be adequately ascertained on the small-scale, high altitude imagery. As a result, this information was not utilized any further in the study.

Two variables, average crown closure of the dominant stand and average total height of the dominant stand, were required to assess forest density conditions (basal area per acre). Both of these variables are frequently used measures in aerial stand density and volume tables and were required to estimate density conditions using a photo basal area regression equation developed for ponderosa pine in Arizona (Moessner, 1964). Therefore, the next procedural requirement was the estimation of average crown closure (per cent areal extent of dominant and codominant tree crowns) and average total height of the dominant stand in each primary sampling unit.

The choice of using a dot grid to determine crown closure was made over other methods (random linear transects of the frame, crown closure comparator, comparative stereograms, and "tree cramming") because the dot grid method was considered as being more precise, easier to use, faster, and less prone to error introduction by use of different observers.

The dot grid with 100 dots per 4-inch square was randomly overlaid on each delineated sampling unit three times. A hand tallying device was used to assist in counting dots to reduce the possibility of error propagation due to miscounting by interpreters.

Since there were 100 dots per 4-inch square on the grid, the three estimates of dots landing on forest crowns were actually estimates of average crown closure; i.e., if 25 dots were counted, the per cent areal extent of forest crowns was 25 per cent. Average crown closure per primary sampling unit was then estimated by averaging the three dot counts for each sampling unit.

The next procedural step involved estimation of average total height of the dominant stand on each primary sampling unit. Three dots were randomly located on a plastic 4-inch square template. This template was placed on each sampling unit once, in exactly the same way, and the height of the nearest dominant or codominant tree to each dot was estimated twice. Tree heights were measured with a pocket steroscope and parallax bar, using a standard technique (Avery, 1966). Average total height of the dominant stand was estimated by averaging the two height measurements for each of the three trees measured on each sampling unit and estimating the mean of these averages for each sampling unit.

Analysis of U-2 Imagery

The small-scale, high altitude imagery used in this study was obtained from the National Aeronautics and Space Administration. These photos were 9 x 9-inch format color transparencies of Mission 155, flown on January 18, 1971, at a height of 60,000 feet, and taken with a camera having a 6-inch focal length. Approximate scale of the imagery was 1:120,000 (1/2-inch per mile).

Little information concerning high altitude forest density assessment was found in the literature. Much of the research into the possible forestry related uses of small-scale, high altitude aerial photography has been confined to studies on forest type delineation; tree species identification; and insect, disease, or stress damage detection and survey (Aldrich, 1968; Aldrich and Greentree, 1971; Carneggie, Roberts, and Colwell, 1966; Heller, 1968; Heller et al., 1966; Lauer, 1968; etc.). However, one attempt to study the possibility of using small-scale, high altitude imagery for multi-stage sampling in extensive forest surveys has been made (Langley, 1969, 1971). With a lack of methodologies in the literature, the need for developing new methodologies to analyze this type of imagery became obvious.

The first procedural step in the analysis of this small-scale aerial imagery was the delineation of the identical sampling units examined on the 1:15,840 photos. Mission 155 flight lines were overlaid on the timber type map obtained from the USDA Forest Service, and approximate locations of primary sampling units were identified on the map. Identical primary sampling unit locations were then delineated on plastic overlay covers used to protect the imagery. This was accomplished by drawing the primary sampling unit outlines on the covers using a 1/2-inch-square template and a 10-power hand lens. The primary sampling unit outlines previously delineated on the 1:15,840 imagery and on the timber type map were used to identify the identical sampling unit locations. Identification of identical primary sampling units was a tedious process. Identifying approximate locations on the basis of flight lines and the USDA Forest Service timber type map was not difficult.

A dot grid having approximately 36 dots per 1/2-inch square was developed to assess forest density conditions on the 1:120,000 scale imagery. This grid was actually a 35 mm slide that was produced by photographically reducing a larger dot grid having 36 dots per 1-foot square. Several colors (blue, black, brown, and orange) of dots were initially tried, and it was decided that black dots were best in terms of visibility on the 1:120,000 scale photos.

Crown closure was estimated at four different levels of magnification, 7X, 10X, 15X, and 25X, using a variable power binocular microscope. At each of the four levels of magnification, the following procedure was repeated three times to estimate numbers of dots landing on tree crowns on each primary sampling unit:

1. The small-scale grid was randomly dropped on a delineated sampling unit and a glass plate was placed over the photo and dot grid so as to hold them flat and to prevent damage and scratching of the photo protection covers.
2. Dots landing on what appeared to be tree crowns within the sampling unit outline were counted with the aid of a hand tallying device.

At each level of magnification, average crown closure per primary sampling unit was estimated by using the following formula:

$$\hat{CC}_{1:120,000} = [(d-D) X 100] \qquad (1)$$

where

$\hat{CC}_{120,000}$ = estimated crown closure per primary sampling unit

d = number of dots landing on tree crowns on a primary sampling unit

D = 36 (the number of dots per 1/2-inch square).

An attempt was made to estimate crown closure on the high altitude imagery using projection techniques as an alternative methodology. Outlined primary sampling units were projected on a fine textured screen via an overhead projector and a rectangular dot grid overlaid on the imagery. However, this method was abandoned because distortion due to lens irregularities, projector screen geometry, and optically dense imagery could not be overcome.

Synthesis of Ground Forest Density Data

The synthesis of ground forest density data necessary for the development of forest stocking equations required the translation of the high altitude forest density assessments to ground estimates of forest density conditions, utilizing the 1:15,840 scale forest density estimates as an intermediate adjustment basis. To predict ground forest density from high altitude crown closure estimates for each primary sampling unit, the following mathematical relationships were sequentially required:

$$\hat{Y}_{BA\ ground} = f(BA_{photo}) \tag{2}$$

$$\hat{Y}_{BA\ photo} = f(CC_{1:15,840}, HT_{1:15,840}) \tag{3}$$

$$\hat{Y}_{CC_{1:15,840}} = f(CC_{1:120,000}) \tag{4}$$

where

$\hat{Y}_{BA\ ground}$ = estimated ground basal area,

$\hat{Y}_{BA\ photo}$ = estimated photo basal area (BA_{photo}),

$\hat{Y}_{CC_{1:15,840}}$ = estimated average crown as determined from the 1:15,840 imagery ($CC_{1:15,840}$),

$HT_{1:15,840}$ = estimated average total height of the dominant stand as determined from the 1:15,840 imagery,

$CC_{1:120,000}$ = estimated average crown closure as determined from the 1:120,000 imagery.

The mathematical expressions of these relationships were needed so that, with multiple substitution of the variables in the former mathematical expressions, the following prediction relationship could be assessed:

$$\hat{Y}_{BA\ ground} = f(CC_{1:120,000}\ HT_{1:15,840}) \tag{5}$$

The following equation was used to associate ground estimates of basal area with photo estimates of basal area (Larson, Moessner, and Ffolliott, 1971):

$$\hat{Y}_{BA\ ground} = 28.04 + 0.852\ (BA_{photo}) \tag{6}$$

This equation, determined through linear regression, was developed for ponderosa pine forest in north-central Arizona. The correlation coefficient was 0.78.

A regression equation used to develop a photo basal area table for ponderosa pine in Arizona was employed to associate estimated photo basal area with estimated average crown closure and estimated average total height of the dominant stand, as determined from measurements on the 1:15,840 scale imagery (Moessner, 1964):

$$\hat{Y}_{BA\ photo} = -0.81620(HT_{1:15,840}) - 0.83765(CC_{1:15,840}) + 0.01902(HT_{1:15,840})(CC_{1:15,840}) + 0.00545(HT_{1:15,840})^2 + 0.01831 \cdot (CC_{1:15,840})^2 + 55.32472. \tag{7}$$

This equation was developed from source data gathered in ponderosa pine forests in north-central Arizona. The correlation coefficient was 0.84 and the standard error of estimate was ± 20 square feet (or ± 38 per cent of the mean plot basal area) for a 95 per cent confidence.

A linear regression was used to quantify the unknown association between estimated average crown closure determined from measurements on the 1:15,840 scale imagery and estimated average crown closure as determined from measurements on the 1:120,000 scale imagery. A regression equation associating these two variables was developed for each data set (data gathered under each of the four levels of magnification) of high altitude imagery density estimates (Table 1).

Conceptually, it was now possible to obtain the ground estimates of forest density required for the development of forest stocking equations from estimates of average

Table 1. Regression Equations Associating Estimated Average Crown Closure on 1:15,840 Scale Imagery and on 1:120,000 Scale Imagery

Equation Number	Level of Magnification	Equation
8	25X	$Y_{CC_{1:15,840}} = 12.840234 + 0.185147\ CC_{1:120,000}$
9	15X	$Y_{CC_{1:15,840}} = 15.861638 + 0.118088\ CC_{1:120,000}$
10	----------------------------not significant------------------	
11	7X	$Y_{CC_{1:15,840}} = 12.777337 + 0.164732\ CC_{1:120,000}$

crown closure determined from the 1:120,000 scale imagery and estimated average total height of the dominant stand as determined from the 1:15,840 scale imagery, through substitution of variables in the regression equations which were used to approximate the required mathematical relationships.

RESULTS AND DISCUSSION

Evaluation of Methodologies

Analysis of 1:15,840 Imagery

The analysis of variance for a test of observer variation in crown closure estimation can be found in Appendix A. Four observers assessed forest density conditions on 25 primary sampling units selected at random. This test showed that the aforementioned technique allowed an interpreter to estimate average crown closure per primary sampling unit within ±15 per cent for a 90 per cent confidence ($S_{\bar{X}}$ = 0.28 per cent), the desirable precision. Further analysis showed that the average of two dot counts per primary sampling unit would satisfy the previously stated confidence limits and desirable precision, averaging three dot counts would allow for estimation of average crown closure per primary sampling unit within ±15 per cent for a 95 per cent confidence. Averaging of five dot counts would allow for estimation of average crown closure per primary sampling unit within ±15 per cent for a 99 per cent confidence. However, this preliminary survey, like other studies (Axelson, 1956; Pope, 1960), indicated that, perhaps because of the great amount of personal judgment in estimating crown closure from aerial photos, the inherent subjectivity of crown closure estimation may account for discrepancies between crown closure estimates of different interpreters on the same sampling unit. Some of this variation between interpreters may also result from the relative inexperience of several of the interpreters. Inexperienced photointerpreters tend to overestimate crown closure by ignoring small stand openings or including portions of crown shadows (Avery, 1966). Other factors which are interrelated and may account for some of the variation in crown closure estimates between interpreters and between individual observations are: (1) geometric quality of the camera, (2) shutter efficiency, (3) film and filters, (4) exposure time, (5) camera vibration and image motion, (6) focal length, (7) scale variation on the photo, (8) temporal (season and time of day) variation, (9) atmospheric conditions, (10) spectral remission of the forest, (11) processing, (12) finish material, (13) type and magnification of measurement instruments, and (14) method (Nielsen, 1971).

Crown closure was estimated within ±15 per cent, for a 95 per cent confidence ($S_{\bar{X}}$ = 0.25 per cent), on the 50 (n) primary sampling units. This suggests that the precision of the 1:15,840 crown closure methodology was satisfactory. However, it should be emphasized that only one observer estimated average crown closure per primary sampling unit.

The reliability placed on the accuracy of estimation of any observer, even though the precision may be well within the desired limits, is dependent upon the skill of the observer. Again, because of the inherent subjectivity and personal judgment in estimating average crown closure from aerial photos, more confidence should be placed on the estimates of skilled photointerpreters than those of unskilled photointerpreters.

Tree heights were estimated within ±15 per cent, for a 95 per cent confidence ($S_{\bar{X}}$ = 2.3 feet). This level of precision appears to be consistent with levels of precision determined in other studies (Allison and Breadon, 1960; Andrews, 1936).

The analysis of variance for the tree height data can be found in Appendix B. This analysis indicates that, for more intensive surveys, it may be desirable to increase the number of trees measured on each primary sampling unit to get a better estimate of average total height of the dominant stand.

No attempt was made to test for observer variation in height measurement because the methodology used was a standard tree height measurement technique. However, variation in tree height measurements between observations and between observers may be attributed to the same factors which may affect crown closure estimates (Nielsen, 1971). Variation in tree height measurements between observers may be lower because determination of tree height is a much less subjective procedure than determination of crown closure (Avery, 1966).

It is interesting to note that one study indicated that photo scale variation may not be associated with errors in tree height measurements between observers, but some undetermined vegetative characteristics (crown shape or tree size) may be more important sources of error propagation (Johnson, 1958).

Analysis of U-2 Imagery

The analysis of variance for the high altitude crown closure data can be found in Appendix C. For each level of magnification, 25X, 15X, 10X, 7X, average crown closure per primary sampling unit was estimated within ±15 per cent for a 95 per cent confidence ($S_{\bar{X}}$ = 0.76 per cent).

Variances were equal for data gathered under each level of magnification. However, there was a significant difference between estimates of average crown closure per primary sampling unit. Since the data were required to predict average crown closure per primary sampling unit as observed on the 1:15,840 imagery from estimates observed on the high altitude imagery, it was decided that data collected at all four levels of magnification should be subjected to regression analysis to determine which set of estimates provided the most significant regression equation in terms of prediction capability. As a result of this analysis, it was determined that the crown closure estimates obtained with 25X magnification provided the most significant results.

Not only did the 25X level of magnification provide for significant results, but it also proved to be the easiest of the four levels of magnification to use. This may be due to the fact that differences in image coloration may be more perceptible to observers at this level of magnification.

A test was undertaken, using the crown closure estimation technique with the 25X level of magnification, to assess observer variation (Appendix D). Four observers estimated crown closure on the same 50 primary sampling units, using the previously described technique. Variances of the observers were equal, and each observer was able to estimate average crown closure per primary sampling unit within ±15 per cent for a 95 per cent confidence ($S_{\bar{X}} = 0.84$ per cent). However, as with crown closure estimation on the 1:15,840 imagery, observer means for each section were significantly different for some individuals.

Again, it should be emphasized that the inherent subjectivity of crown closure estimation, coupled with the lack of experience of several of the observers, may account for these differences. More confidence may be placed on the estimates of experienced photointerpreters. In addition to these factors and those previously listed as affecting crown closure estimation, one factor appeared to have made crown closure estimation on high altitude photos more difficult. There were large areas of dark shadow within outlined primary sampling units and throughout the imagery, and it was difficult to discern between shadow, ground, and ponderosa pine crowns in these very dark areas. It was felt that the amount of shadow was primarily related to time of day (sun angle). Possibly observation with the 25X level magnification was more successful because observers were better able to detect subtle differences in image coloration within the shadow areas. These differences were difficult to ascertain in the shadow areas when crown closure was estimated with the other levels of magnification.

Synthesis of Ground Forest Density Data

The association between estimated average crown closure on the 1:15,840 scale imagery and the 1:120,000 scale imagery was the principal unknown in the chain of required information. A linear regression was used to determine this association for estimates of high altitude crown closure obtained at each of the four levels of magnification (Table 2). Three of the four regression equations developed had significant F values at the 90 per cent confidence level (Appendix E). Only data gathered with the aid of 10X

Table 2. Regression Equations of Average Crown Closure as Determined from the 1:15,840 Scale Imagery Versus Estimated Average Crown Closure Determined from the 1:120,000 Scale Imagery

Equation Number	Intercept (a)	Slope Coefficient (b)	Correlation Coefficient (r)	r^2	$S_{y.x}$ (per cent)
$8_{(25)}$	12.84	0.18	0.38	.15	± 5.44
$9_{(15X)}$	15.86	0.12	0.25	.06	5.71
$10_{(10X)}$	------------not significant------------				
$11_{(7X)}$	12.78	0.17	0.33	.11	5.56

magnification was not significantly correlated with estimated crown closure on the 1:15,840 imagery.

The statistical significance of these equations suggests that $CC_{1:120,000}$ is a good predictor of $\hat{Y}_{CC_{1:15,840}}$. The regression equations developed may be suitable for preliminary types of surveys, but they may not be suitable for more intensive work. However, these equations were used to illustrate how stocking equations may be derived by multiple-stage remote sensing techniques.

The relatively low correlation coefficients may have been largely due to the previously described high altitude imagery shadow factor. If more control could have been exercised on the time of day that the high altitude imagery was taken, shadow effects caused by the angle of the sun in ravines and perpendicular slopes facing away from the direction of the sun would have been reduced. As a result, more significant regression equations may have been developed using the previously described methodologies.

The following procedural steps were employed to synthesize estimates of ground forest density for each primary sampling unit and for each level of magnification used to obtain high altitude crown closure estimates:

1. Crown closure estimates obtained on 1:15,840 scale imagery were predicted from the 1:120,000 scale crown closure estimates utilizing Equations (8),

(9), or (11), depending upon the level of magnification used to obtain the data.

2. Photo estimates of basal area were obtained by utilizing the results of Step 1 and the estimates of average total height of the dominant stand as determined from the 1:15,840 scale imagery and Equation (5).
3. Ground estimates of basal area were synthesized by utilizing the results of Step 2 and Equation (6).

Development of Forest Stocking Equations

Forest stocking equations describing the proportion of a forest that is stocked to an arbitrarily defined forest density level were developed from basic source data synthesized by the previously described methodology. Since the primary sampling units examined on the study area were selected by random sampling techniques, the premise that the sampling of ground forest density within the study area was unbiased was assumed. Therefore, the proportions of the primary sampling units which were stocked to minimum forest density levels represent the proportions of the south one-half of the Prescott National Forest that were stocked to corresponding minimum forest density levels.

The synthesis of forest stocking equations entailed the following mathematic procedure: (1) the organization of the basic source data into probability density functions (cumulative frequency distributions), and (2) the development of cumulative distribution functions (cumulative frequency distributions) from the probability density functions. These cumulative distribution functions can be described as being continuous from the right and, therefore, can be considered as "exceedence functions."

The probability density functions and the cumulative distribution functions for the ground forest density estimates, using the different levels of magnification, are given in Tables 3, 4, and 5.

The stocking equations describing the cumulative distribution functions in Tables 3, 4, and 5 were developed by subjecting the cumulative distribution functions to regression analyses. The stocking equations for these cumulative distribution functions, the correlation coefficients, and the standard error of the estimate values are presented in Table 6.

A graphical representation of Equation (12) (Table 6) is illustrated in Figure 2. On this graph, the proportion of area stocked (per cent) is given in increments of 10, while minimum basal area (square feet per acre) is given in intervals of 5. For most purposes, a graphical representation of the stocking equation will suffice, since mathematically solving stocking equations for numerous intermediate basal area levels may become overly time-consuming. However, these stocking equations can be solved

Table 3. Actual Distribution of Forest Density Levels from 25X Magnification, High Altitude Crown Closure Estimates

Basal Area Level (square feet/acre)	Frequency of Occurrence	Per Cent Stocked to Minimum Basal Area
0	0	100
59	2	100
60	8	96
61	11	80
62	7	58
63	3	44
64	5	38
65	3	28
66	2	22
67	1	18
68	1	16
69	2	14
70	2	10
71	2	6
91	1	2

Table 4. Actual Distribution of Forest Density Levels from 15X Magnification, High Altitude Crown Closure Estimates

Basal Area Level (square feet/acre)	Frequency of Occurrence	Per Cent Stocked to Minimum Basal Area
0	0	100
59	1	100
60	6	98
61	10	86
62	13	66
63	2	40
64	6	36
65	3	24
66	1	18
68	3	16
70	7	10
72	2	6
92	1	2

Table 5. Actual Distribution of Forest Density Levels from 7X Magnification, High Altitude Crown Closure Estimates

Basal Area Level (square feet/acre)	Frequency of Occurrence	Per Cent Stocked to Minimum Basal Area
0	0	100
58	1	100
59	3	96
60	6	92
61	11	80
62	7	58
63	3	44
64	4	38
65	3	30
66	3	24
67	2	18
68	3	14
69	1	8
71	1	6
72	1	4
92	1	2

Table 6. Stocking Equations for the Ponderosa Pine Type on the South One-Half of the Prescott National Forest[a]

Equation Number	Equation	r	$S_{y.x}$ (per cent)
$12_{(25X)}$	$\hat{Y} = 1691.67 - 42.73\ (X) + 0.27\ (X)^2$	0.98	± 7.92
$13_{(15X)}$	$\hat{Y} = 1707.29 - 42.97\ (X) + 0.27\ (X)^2$	0.96	± 11.47
$14_{(7X)}$	$\hat{Y} = 1569.27 - 38.38\ (X) + 0.24\ (X)^2$	0.98	± 7.03

[a] $\hat{Y}$ = proportion of area stocked to minimum basal area level; X = basal area level in square feet per acre.

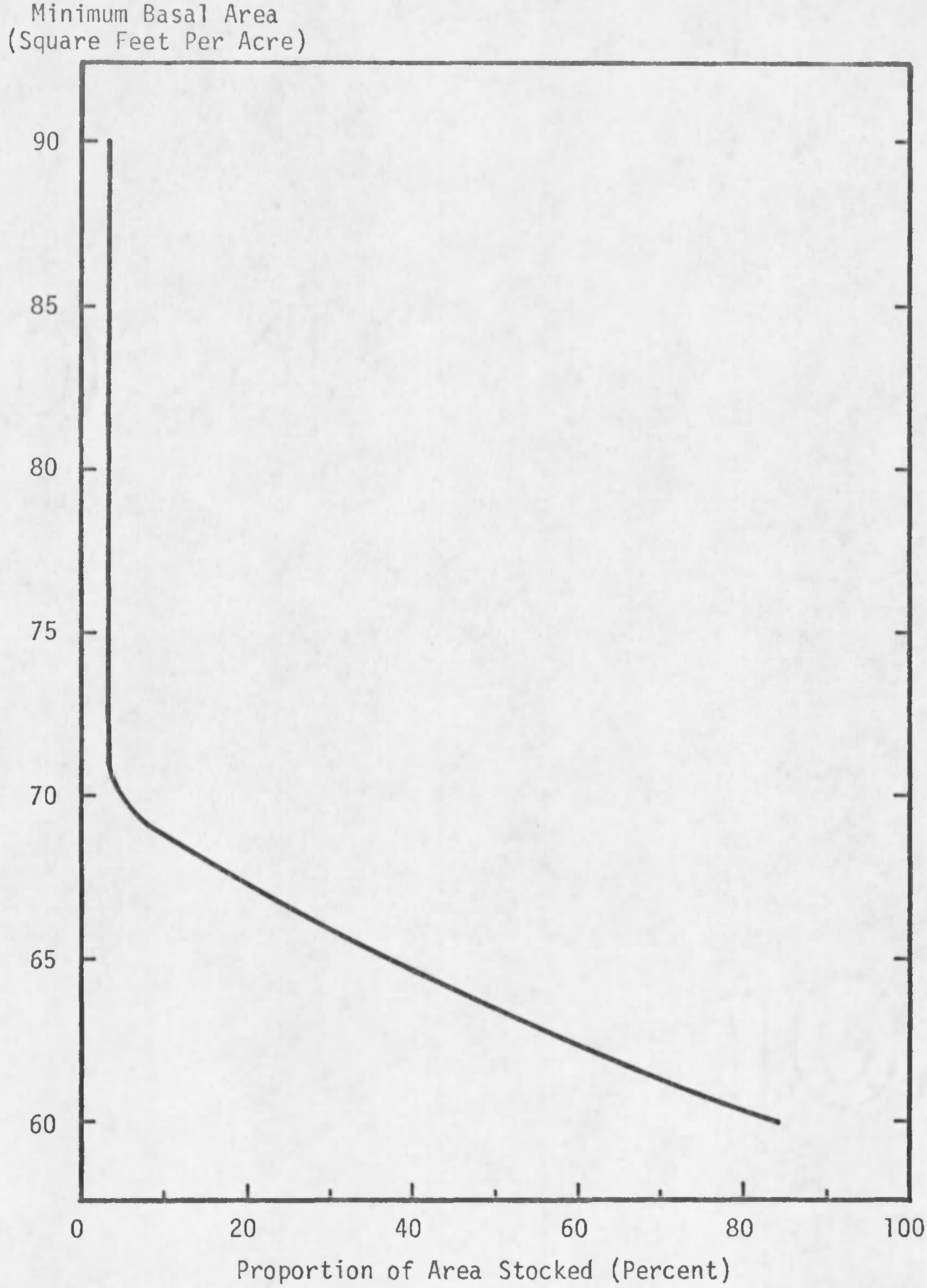

Figure 2. Graphical Representation of a Stocking Equation Developed for the South One-Half of the Prescott National Forest

in terms of the proportions of the area stocked to any intermediate basal area level.

Uses of Forest Stocking Equations

It has previously been shown that stocking equations can be developed from conventional ground inventories (Ffolliott and Worley, 1973). These stocking equations, generally developed from ground survey sampling, may provide a great deal of information to a land manager as to the feasibility of imposing a forest management treatment (harvesting, thinning, and so forth) on a particular management unit. However, stocking equations developed by multiple-stage remote sensing techniques may provide information about areas larger than a management unit. These stocking equations may provide information that would allow a land manager to index management units according to the proportions of a management unit which yield levels of natural resource products and uses associated with arbitrarily defined minimum forest density levels.

As a specific example, if stocking equations similar to those developed herein were synthesized for the remainder of the Prescott National Forest or for other national forests in Arizona, qualitative statements about natural resource products and uses on these areas could be made. Potentially useful information could be derived directly from the stocking equations as developed herein, or in combination with other information such as inventory-prediction equations. The latter management decision-making technique would combine knowledge of the proportions of management units in a forest that support minimum forest density levels, the output of the forest stocking equations, with selected criteria characterizing alternative management opportunities. Examples of how this qualitative information may be derived can be illustrated utilizing Figure 2 as a basis.

Setting Priorities for Forest Management

Forest stocking equations developed by multiple-stage remote sensing techniques may help a forest manager to obtain a more adequate description of the characteristics of the forest.

For example, let us suppose that a silvicultural management treatment calls for a uniform thinning of all timber in the south one-half of the Prescott National Forest to a basal area level of 60 square feet per acre, the presumed "optimum" in terms of sawtimber potential. It is assumed that the proportion of the ponderosa pine stand stocked to a minimum basal area level which corresponds to the basal area level prescribed by treatment will, subsequently, represent the proportion of the stand that will be placed under treatment. The graphical representation of the stocking equation (Figure 2) indicates that 84 per cent of the ponderosa pine type could meet the treatment stocking objective. This suggests that by reducing the uniform thinning treatment slightly, virtually the entire area could be placed under treatment. Although maximum management potential may be reduced, the outcome may be more favorable in the long run, since a larger proportion of the area has been brought under treatment.

In addition to providing information potentially useful to determine treatment feasibility on a single management unit, this information could be used as a basis for setting operating priorities on a number of management units.

Setting Priorities for Watershed Management

Snowmelt from the ponderosa pine forest in Arizona accounts for a large proportion of the annual surface runoff that supplies water for the reservoir systems in Arizona and for recharge of the groundwater aquifers (Thorud and Ffolliott, 1972). It has been suggested that forest management methods may be used to increase snowmelt water yield if trees and their density levels affect snowpack accumulation. Basic research does indicate that forest density and management practices which reduce forest density may affect snowpack accumulation. Research conducted in Arizona indicates that snowpack accumulation decreases as forest density increases.

Much of the research has been conducted for the purpose of obtaining information which might ultimately lead to the development of management guidelines for increasing water yields from snowpacks. If these management guidelines are to be implemented, knowledge of the proportions of the forest which support ponderosa pine density levels which may affect snowpack accumulation would be useful. This knowledge may be obtained from forest stocking equations developed by multiple-stage remote sensing techniques.

Information obtained from a stocking equation can be used in conjunction with snowpack inventory-prediction equations to determine the areal extent of present snowpack accumulation patterns and to predict the magnitude of on-site snowpack accumulation. This information can also be used to evaluate the potential effects of management practices on snowpack accumulation patterns and amounts and assist in evaluating the feasibility of implementing management guidelines on an area.

Based on measurements of snow accumulation and melt taken on study plots of different forest density levels in Arizona, snowpack inventory-prediction equations, which describe snowpack conditions associated with different forest densities as functions of readily available or easily obtainable expressions of forest attributes, have been developed (Ffolliott and Thorud, 1972). These regression equations, describing snowpack accumulation as a function of the measured forest attributes, such as basal area, sum of diameters, bole area, and volume, were found to be significant for the measured snowpack conditions.

An example of a snowpack inventory-prediction equation for ponderosa pine in Arizona (Ffolliott, 1970) is:

$$\hat{Y} = 95.2 - 32.9 (\log X) \qquad (15)$$

where

$\hat{Y}$ = predicted per cent of peak snowpack accumulation

X = basal area in square feet per acre.

This particular equation was chosen for its simplicity. More complex multiple regression equations have been developed, but data required for these solutions are more difficult to obtain, and these equations are not easily applied to large areas.

The predicted per cent of peak snowpack accumulation associated with various forest density levels may be considered as a key management measure because this quantity should conceptually be one of the better indices of potential snowpack water yield (Ffolliott and Thorud, 1972).

The utilization of stocking equations in conjunction with snowpack inventory-prediction equations will be demonstrated with Figure 2 and Equation (15). The results of the following procedure are presented in Table 7.

The first step is to determine the proportion of the area stocked to the forest density levels of interest. This

Table 7. Calculation of Per Cent of Area Stocked to Desired Forest Density Levels and Calculation of Acreages

Basal Area Level (square feet/ acre)	Per Cent Stocked to Minimum Basal Area	Per Cent Stocked to Basal Area Level	Acreages (Acres)
55	100.0	15.5	13,987
60	84.5	47.5	42,864
65	37.0	33.0	29,779
70	4.0	0.5	451
75	3.5	0.4	361
80	3.1	0.1	90
85	3.0	0.0	90
90	2.9	2.9	2,618

information was obtained from Figure 2. Acreages of the forest that are stocked to the desired forest density levels were obtained by reading the value from the curve for the desired density level, then subtracting the percentage obtained from the curve for the next higher density level. By multiplying the total acreage of the area by the per centage of the area stocked to the various forest density levels of interest, the acreages of the various forest density levels of interest are obtained.

By solving Equation (15) for the various forest density levels, it becomes possible to predict the areal extent of the various percentages of peak snowpack accumulation. If peak snowpack accumulation for the area has been estimated for a given year, it is possible to calculate on-site snowpack water equivalent and volume for the various forest density levels by multiplying the acreages of the various forest density levels by the solutions of Equation (15). The summation of these on-site quantities is the magnitude of on-site snowpack water equivalent for the watershed.

The results of the above procedure,aassuming that peak snowpack accumulation for a particular year was 10 inches of water equivalent, are given in Table 8. For purposes of illustration, the total acreage of the study area is used in the calculations (90,240 acres).

Table 8. Calculation of Quantity of On-Site Peak Snowpack Accumulation

Basal Area Level (square feet/ acre)	$\hat{Y}$	Water Equivalent (inches)	Acreages (acres)	Peak Snowpack Accumulation (acre-inches)
55	37.94	3.79	13,987	53,010.73
60	36.70	3.67	42,864	157,310.88
65	35.56	3.56	29,779	106,013.34
70	34.50	3.45	451	1,555.95
75	33.51	3.35	361	1,209.35
80	32.59	3.26	90	293.40
85	31.72	3.17	90	285.93
90	30.91	3.09	2,618	8,089.62
				327,769.20

The results displayed in Table 8 can be used in a number of ways. A land manager may use this information to index peak snowpack water equivalent or volume between watersheds, management units, or water-years. It provides information about the per cent snowpack accumulation patterns, and allows the land manager to assess the extent to which a water yield improvement technique involving reduction of forest density can be implemented.

For instance, the results displayed in Table 8 would allow a land manager to qualitatively say that approximately 37 per cent of peak snowpack accumulates under 60 square feet of basal area per acre. Approximately 47.5 per cent of the ponderosa pine type on the south one-half of the Prescott National Forest is stocked to 60 square feet of basal area per acre (Table 8). Therefore, 47.5 per cent of the ponderosa pine type accumulates 37 per cent of peak snowpack water equivalent.

Setting Priorities for Range Management

Just as forest stocking equations can be used in combination with snowpack inventory-prediction equations, they can also be used in combination with equations describing herbage-timber relationships to assess herbage productivities. For example, equations developed for ponderosa pine stands in north-central Arizona (Clary and Ffolliott, 1966) may provide a basis for estimating the amount of herbage produced under existing distributions of forest density, or the amount of herbage to be produced if the forest density distribution is altered. This latter information could be used by a range specialist to answer such questions as "What proportion of forest units is stocked in excess of a given timber density level considered maximum to allow acceptable forage production for allotment management?"

Tables similar to Table 8 could also be developed by combining forest stocking equation information with equations depicting herbage-timber relationships. For example, Equation (16) is an equation which predicts herbage production (pounds per acre) as a function of basal area (square feet per acre) for unthinned ponderosa pine stands; Equation (17) predicts herbage production for thinned ponderosa pine stands (Clary and Ffolliott, 1966).

$$\hat{Y} = 808.0 - 331.4 (\log X) \tag{16}$$

$$\hat{Y} = 1355.0 - 606.0 (\log X) \tag{17}$$

where

$\hat{Y}$ = estimated herbage production (pounds per acre)

X = basal area (square feet per acre).

Basic information that can be derived from stocking equations and the above mentioned herbage-timber relationship is presented in Table 9. As with snowpack-inventory prediction, this information can be combined with knowledge of acreages to determine total herbage production for an

Table 9. Herbage Production for Thinned and Unthinned Ponderosa Pine Stands in Arizona

Basal Area Level (square feet/ acre)	Per Cent Stocked to Basal Area Level	Herbage Prod. Unthinned (lbs/acre)	Herbage Prod. Thinned (lbs/acre)
55	15.5	232	300
60	47.5	218	277
65	33.0	207	256
70	0.5	197	237
75	0.4	187	219
80	0.1	177	202
85	0.1	169	186
90	2.9	160	171
		1,547	1,848

area. The difference between columns 3 and 4 can be used to determine the effects of reducing forest density on herbage production.

Setting Priorities for Wildlife Management

Wildlife managers may find forest stocking equations particularly useful for evaluating wildlife habitat. If forest stocking equation information can be combined with browse production or animal use relationships, a wildlife manager may be able to index wildlife habitat among areas or years. The previously described herbage-timber relationships or animal use relationships such as those presented in Table 10 (Reynolds, 1969) may be utilized in combination with stocking equations. Similar tables or prediction equations relating basal area to some index of animal usage may be developed for various wildlife species or indices of animal usage such as deer beds, deer pellet groups, rabbit pellet numbers, squirrel nests, turkey roost trees, etc.

Readers desiring metric equivalents of the values presented in this thesis will find a table of conversion factors in Appendix F.

Table 10. Relation of Herbaceous Understory, Deer Pellet Groups, and Deer Beds to Basal Area of Mature and Immature Tree Age Groups, Kaibab Plateau, Arizona 1963

Basal Area Class (sq. ft./ acre)	Herbaceous Understory: Mature Trees (lbs/acre)	Herbaceous Understory: Immature Trees (lbs/acre)	Deer Pellet Groups: Mature Trees (no./acre)	Deer Pellet Groups: Immature Trees (no./acre)	Deer Beds: Mature Trees (no./acre)	Deer Beds: Immature Trees (no./acre)
0-40	150	120	170	195	0.0	0.0
41-80	120	70	335	240	0.10	0.40
81-120	95	40	270	100	0.50	0.45
121-160	75	20	240	90	0.20	0.45
161-200	55	10	170	280	0.10	1.15

Source: Reynolds (1969).

CONCLUSIONS

Forest stocking equations, describing the proportion of the forested area of the south one-half of the Prescott National Forest that supports minimum forest density levels can be developed by multiple-stage remote sensing techniques. The methodologies developed in this study may be suitable for the synthesis of source data from high altitude imagery required to develop forest stocking equations for ponderosa pine forests in Arizona and elsewhere.

The precision of the methodologies utilized to determine crown closure on the high altitude imagery was within the desired confidence level. However, there were significant differences between estimates of various observers on the same primary sampling units. Observer variation may be attributed to inexperience or a number of other factors. Shadow effects caused by the angle of the sun at the time the imagery was taken may, in part, account for observer variation. Shadow effects may also account for the variation of crown closure estimates obtained under the four different levels of magnification utilized to interpret the high altitude imagery.

The precision of crown closure estimates from the 1:15,840 imagery was within the desired confidence level. However, there were significant differences between estimates of several observers on the same primary sampling units. Observer variation may be attributed to a number of factors.

The precision of tree height measurements from the 1:15,840 imagery was comparable with that of other studies. However, a greater number of tree height estimates on each primary sampling unit may be required to obtain more accurate estimates of average total height of the dominant stand for more intensive work.

Regression analysis was used to obtain equations predicting crown closure as observed on 1:15,840 imagery from estimates obtained on high altitude imagery. These regression equations were developed for high altitude crown closure estimates obtained under four different levels of magnification (25X, 15X, 10X, and 7X). Only 10X magnification did not produce significant regressions.

It was felt that, although data collected under the other three levels of magnification provided significant regressions, these regression equations may not necessarily be useful for prediction purposes for intensive work. Shadow effects on the high altitude imagery, in addition to other factors, may account for the coefficient of determination values for the regression equations.

Forest stocking equations, as developed herein, can be used alone or in conjunction with other information to assist a land manager in natural resource decision-making.

Illustrations of forest stocking equation utilization showed how these equations may be used to set priorities for forest management, watershed management, range management, and wildlife management.

It is believed that high altitude imagery can be used to obtain gainful information through the development of forest stocking equations. Utilization of high altitude imagery and multiple-stage remote sensing techniques could significantly reduce the costs for obtaining information necessary for rational decision-making in natural resource management.

It is suggested that further studies be undertaken to determine if significant stocking equations can be developed from other types of high altitude imagery, such as color infrared or panchromatic transparencies. It is also suggested that attempts be made to develop forest stocking equations by directly determining the relationship between forest density estimates obtained on high altitude imagery and ground estimates of forest density. Potentially, the latter studies would entail intensive ground survey and aerial survey. Ultimately, significant prediction equations could be developed.

APPENDIX A

ANALYSIS OF VARIANCE, 1:15,840 CROWN CLOSURE TEST FOR OBSERVER VARIATION

Source of Variation	df	SS	MS	F[d]
P[a]	24	10,256	427	106.75 s
I[b]	3	1,672	557[c]	19.21 s
I x P	72	2,095	29	7.25 s
Error	200	757	4	
Total	299	14,775		

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[a] P = primary sampling units.

[b] I = individuals.

[c] F = value calculated with MS for I x P.

[d] = Tested at $\alpha = .05$.

APPENDIX B

ANALYSIS OF VARIANCE, TREE HEIGHT MEASUREMENTS

Source of Variation	df	SS	MS	F[d]
P[a]	47	93,209	1983	73.44 s
T[b]	2	845	422[c]	1.08 ns
T x P	94	36,559	389	14.41 s
Error	144	3,897	27	
Total	287	134,509		

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[a] P = primary sampling units.

[b] T = Trees.

[c] F value calculated with Ms for T x P.

[d] Tested at $\alpha = .05$.

APPENDIX C

ANALYSIS OF VARIANCE, HIGH ALTITUDE CROWN CLOSURE ESTIMATES

Source of Variation	df	SS	MS	F[d]
P[a]	49	67,963	1387	49.54 s
M[b]	3	3,340	1113[c]	11.84 s
M x P	147	13,772	94	3.36 s
Error	400	11,120	28	
Total	599	96,195		

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[a] P = primary sampling units.

[b] M = levels of magnification.

[c] F value calculated with MS for M x P.

[d] Tested at $\alpha = .05$.

APPENDIX D

ANALYSIS OF VARIANCE, HIGH ALTITUDE CROWN CLOSURE POST-SURVEY

Source of Variation	df	SS	MS	F[d]
P[a]	49	58,972	1,204	34.4 s
I[b]	3	35,158	11,719[c]	42.77 s
I x P	147	40,224	274	7.83 s
Error	400	14,057	35	
Total	599	148,413		

---

[a] P = primary sampling units.

[b] I = individuals.

[c] F value calculated with MS for I x P.

[d] Tested at $\alpha = .05$.

APPENDIX E

ANALYSIS OF VARIANCE, REGRESSION OF AVERAGE CROWN CLOSURE AS DETERMINED FROM THE 1:15,840 SCALE IMAGERY VERSUS ESTIMATED AVERAGE CROWN CLOSURE AS DETERMINED FROM THE 1:120,000 SCALE IMAGERY

Level of Magnification	Source of Variation	df	SS	MS	F[a]
25X	Regression	1	246.44	246.44	8.31 s
	Residual	48	1423.02	29.64	
15X	Regression	1	105.41	105.41	3.23 s
	Residual	48	1564.04	32.58	
10X	Regression	1	62.55	62.55	1.86 ns
	Residual	48	1606.90	33.58	
7X	Regression	1	183.02	183.02	5.91 s
	Residual	48	1486.44	30.96	

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[a] Tested at $\alpha = .05$.

APPENDIX F

METRIC CONVERSION TABLE

Unit Used		Metric Equivalent
1 inch	=	2.540 cm
1 foot	=	0.3048 m
1 sq ft	=	929.000 cm^2
1 acre	=	0.405 hectare
1 sq ft/acre	=	0.230 m^2/hectare
1 sq mile	=	2.590 km^2
1 sq inch	=	6.452 cm^2
1 inch/mile	=	1.578 cm/km
1 acre-inch	=	102.800 m^3
1 lb/acre	=	1.121 kg/hectare

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