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USE OF FOREST ATTRIBUTES IN SNOWPACK INVENTORY-PREDICTION RELATIONSHIPS FOR ARIZONA PONDEROSA PINE

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Use of forest attributes in snowpack inventory — prediction relationships for Arizona ponderosa pine

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ABSTRACT—Inventory-prediction equations describing snowpack accumulations as functions of readily available or easily obtained measurements of forest density and land form were developed for use in Arizona ponderosa pine (Pinus ponderosa *Laws.*). *Although empirical, these equations include forest density measurements assumed to index interception of input precipitation, obstruction of direct-beam solar radiation, and radiation emission from trees onto the snowpack. Measurements of land form factors index the quantity of direct-beam solar radiation.*

INVENTORY-prediction relationships between snowpack conditions and forest attributes may be helpful in predicting water yields from snowmelt and potential water yields resulting from land management changes. However, unique measurements not normally obtained in forest product inventories often are required to apply these relationships. Snowpack inventory-prediction techniques developed from readily available or easily obtained input data provide an alternative.

Processes influencing snow accumulation and melt have been discussed more than they have been evaluated. The separation of forest effects on interception, shading, shelter from winds, and thermal radiation phenomena is difficult because a given tree, or part of a tree, may affect several processes simultaneously (*1*). This separation is particularly difficult in empirical studies, although some of these processes perhaps can be indexed.

Processes which affect snowpack conditions, and which conceivably can be indexed by measurements of forest density, include interception of input precipitation, obstruction of direct-beam solar radiation, and radiation emission from trees onto the snowpack. The quantity of direct-beam solar radiation, important in the energy balance associated with snowpack conditions in forests, possibly can be indexed in terms of *potential* direct-beam solar radiation (*3*) determined by land slope and aspect.

The purpose of this article is to document the relative significance of readily measured forest attributes, specifically, forest density and potential direct-beam solar radiation, as they correlate empirically with snowpack accumulations in the ponderosa (*Pinus ponderosa* Laws.) type of Arizona.

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Study Area

Data were obtained from a study area 7 miles south of Alpine, Arizona, on the Apache National Forest. Ponderosa pine, comprising 90 percent of the tree cover, is uneven-aged with different age classes occurring as small, even-aged groups or as two or more intermixed, even-aged groups (Figure 1). Gambel oak (*Quercus gambelii* Nutt.) and quaking aspen (*Populus tremuloides* Michx.) are minor overstory components. The estimated site index is 65 feet at 100 years (*8*).

The area's topography is gently rolling with few slopes exceeding 15 percent. Mean elevation is 8,010 feet with a limited range of 100 feet variation. Soils are volcanic-derived.

Annual precipitation averages 27 inches, almost half of which occurs between October 1 and May 31 (*13*). Precipitation between November 15, 1968, and April 15, 1969, the study sampling period, was 7.6 inches.

Study Method

Forty primary sampling units—clusters of five sample points arranged in a diamond-shaped pattern within a circular 1/5-acre plot—were located in areas representative of forest densities commonly encountered in cutover ponderosa pine stands in Arizona (Table 1).

Measurements of the snowpack water equivalent were made with a federal snow tube and scale at all sample points to characterize (1) a winter accumulation-melt period and (2) peak accumulation prior to spring runoff. Measurements characterizing a winter accumulation-melt period, indicative of the winter snowpack buildup, may suggest management guidelines for increasing the subsequent peak accumulation. The magnitude of snowpack water equivalent at peak accumulation, just prior to the start

Figure 1. Size classes often intermix in Arizona ponderosa pine forests.

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of spring runoff, is a key management criterion because, conceptually, this quality should be one of the better estimators of potential water yields from snow.

Snowpack measurements were assumed to index the combined influence of precipitation quantity and distribution, losses to interception vaporization, and snowpack ablation. The integration of inputs and losses over time results in a distribution of residual snowpack accumulation that should be measurable in terms of water equivalent.

Expressions of forest density were developed from point sampling techniques employing standard mensurational procedures. Using a basal area factor of 25 to select trees, the tally from the five sample points comprising a sampling unit provided a framework for developing forest density variables. Measurements evaluated included basal areas, sum of diameters, number of trees, bole area, and volume.

Basal area is a widely accepted expression of forest density. Although not always indicating different size-class distribution patterns, basal area is an objective measure of forest density which is understood and applied by land managers. Furthermore, basal area is easily determined in the field, is readily converted to other forest density measurements, and is a major input term for existing multiple-use relationships.

Sum of diameters is a measure of forest density similar in rationale to basal area. However, sum of diameters gives more weight to smaller trees relative to larger trees. Consequently, it is not directly correlated with basal area, especially in uneven-aged forest stands of many size classes. The basic structure of ponderosa pine stands in Arizona is uneven-aged; therefore, sum of diameters was considered a possible alternative to basal area in indexing processes that influence snowpack conditions.

A logical measure of forest density is simply a count of the trees occurring on a unit area. Unfortunately, this expression of density may be of little mensuration value unless coupled with some indication of tree size, spacing, or distribution (*2*). However, due to wide usage, number of trees per acre was considered a potential snowpack inventory-prediction variable.

The surface area of the main stem of a tree, termed bole area (*6*), has been suggested as a measure of growing stock density for silvicultural purposes. In this study, bole area was considered a measure of the tree stem surface absorbing short-wave radiation from the sun and re-radiating long-wave radiation onto the snowpack (*9, 12*). Formulas describing the bole area of individual trees as a function of diameter and height were used (*5*).

Forest density must ultimately be expressed in terms of timber volume to develop management guidelines. For flexibility in interpretation of multi-product markets, cubic feet was selected as the unit of volume measurement. Point sampling factors (*10*) which define cubic foot volume per square foot of basal area were used to develop volume estimates.

Potential direct-beam solar radiation (gram-calories/cm²) was obtained from land form characterizations of slope and aspect (*3*) at each sampling unit and for index dates selected to approximate the times of snowpack measurement.

Initially, simple regressions between snowpack accumulations, defined as a percentage of the maximum accumulation measured on the study area, and expressions of forest density were analyzed. Defining snowpack accumulations as a percentage of the maximum observed provided a base for estimating snowpack water equivalents on each sample point independent of annual precipitation.

If simple regressions were significant, potential direct-beam solar radiation, which was considered statistically independent of forest density, was included in multiple regression analyses.

Preliminary analysis suggested a logarithmic model appropriate for basal area, sum of diameters, bole area, and volume. A hyperbolic model was selected for number of trees. A linear function expressed potential direct-beam radiation values.

Results and Discussion

Regardless of how forest density was expressed, snowpack accumulations decreased as density increased, which is consistent with the results of other studies (*4, 7, 11, 14*). This relationship was independent of slope, aspect, and elevation within the range sampled. It was not possible to demonstrate differences in snowpack con-

Table 1. Minimum, mean, and maximum of forest density attributes.

Variable	*Unit of Measure*	*Minimum*	*Mean*	*Maximum*
Basal area	Square feet basal area per acre	5	94	170
Sum of diameters	Inches per acre	57	1,869	8,176
Number of trees	Number per acre	6	340	1,910
Bole area	Square feet bole area per acre	430	11,132	24,560
Volume	Cubic feet per acre (*10*)	64	1,616	4,769

Table 2. Inventory-prediction equations describing snowpack accumulations as functions of forest attributes.

Equations[*]	*Correlation Coefficient*
Winter accumulation-melt period	
$Y_1 = 197 - 28.4 \ln X_1 - 0.195 X_3$	0.73
$Y_1 = 206 - 18.7 \ln X_2 - 0.202 X_3$	0.68
Peak accumulation, prior to runoff	
$Y_2 = 317 - 48.0 \ln X_1 - 0.263 X_4$	0.82
$Y_2 = 306 - 32.5 \ln X_2 - 0.232 X_4$	0.75

[*]Variables: Y_1 is percent of maximum snowpack water equivalent (4.6 inches) for period representing winter accumulation-melt; Y_2 is percent of maximum snowpack water equivalent (5.0 inches) for period representing peak accumulation; $\ln X_1$ is logarithm of basal area in square feet per acre; $\ln X_2$ is logarithm of volume, in cubic feet per acre (*10*); X_3 is potential direct-beam solar radiation (3) received on index date (February 20) representing winter accumulation period, in gram-calories/cm²; X_4 is potential direct-beam solar radiation (3) received on index date (March 21) representing peak accumulation, in gram-calories/cm².

ditions under similar forest density levels comprised of different size classes.

Greater snowpack accumulations were measured on "cool" sites than on "warm" sites (*1, 5, 11*). Cool sites are indicative of low potential direct-beam solar radiation values and warm sites by high values. There was no apparent correlation between forest density and potential direct-beam solar radiation values.

Simple regressions describing snowpack accumulation as a function of basal area, sum of diameters, bole area, and volume were significant ($\alpha = 0.05$) for the snowpack conditions measured. Relationships involving number of trees were not significant; this measure may not adequately reflect possible effects of varying size-class distributions on the snowpack.

Multiple regressions developed for a given snowpack measurement period were not significantly different in terms of correlation coefficients. Consequently, there is no apparent statistical advantage in selecting inventory-prediction equations with any particular expression of forest density. Only equations with basal area and volume are presented (Table 2) because equations with other forest density expressions are not as operational.

Correlation coefficients were slightly higher for multiple regressions developed for peak snowpack accumulation. These differences are considered minor, however, suggesting that the combined indexing values of the forest attributes tested remain essentially unchanged throughout the accumulation period.

Snowpack inventory-prediction relationships are used to predict existing water yield, or changes in water yield resulting from the implementation of a land management system. However, inventory-prediction data alone may not be sufficient to meet these objectives. Estimated snowpack water yield is dependent on two factors: (1) predicted snowpack accumulation on-site and (2) inherent runoff efficiency, which defines the portion of the snowpack that is converted into recoverable water. The inventory-prediction equations developed in this study provide information for predicting snowpack accumulations *in situ*. Determination of runoff efficiency values is a separate problem, and one that is still not predictable.

A land management system that maximizes snowpack accumulation on-site presumably will provide the greatest potential for increasing recoverable water derived from snow. The land manager may have little opportunity to affect runoff efficiency. However, he can develop management systems that will insure that the maximum snowpack water equivalent is available for conversion into recoverable water within constraints dictated by management involving other forest-based products. Snowpack inventory-prediction relationships can provide a basis for the development of these management systems.

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