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FOREST STAND BASAL AREA AND ITS RELATIONSHIP TO INDIVIDUAL SOIL AND TOPOGRAPHIC FACTORS IN THE SHAWNEE HILLS

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ABSTRACT

The effect of soil and topographic factors on total basal area was studied in 54 undisturbed, fully-stocked, mature forest stands in the Illinois Shawnee Hills. Basal areas were strongly related to effective soil depth (ESD) and soil available water capacity (AWC) but the relationship was curvilinear. Across a range of sites, basal area increased from <2 m^2/ha on extremely thin soil (ESD < 5 cm; AWC < 2 cm) to 32 m^2/ha when ESD = 100 cm and AWC = 25 cm; at higher values basal area fluctuated between 30 and 38 m^2/ha. Transformation of soil data using the natural log changed the relationship to a nearly linear function and resulted in r values between basal area and ESD and AWC of 0.89 and 0.94 (p. <.01), respectively. Moderately strong positive relationships also were found between basal area and transformed aspect (r = 0.72, p <.01) and slope position (r = 0.65, p <.01). The relationship between basal area and percent slope was weak (r = 0.42, p <.05). Sites on shallow soil, on west, southwest, and south slopes, and in high slope positions supported low basal area stands. High basal area stands were on deep soil, on north, northeast and east slopes, and in the deeper coves and valleys.

INTRODUCTION

Since 1920, evaluation of forest land for its potential to produce wood has been based on site index measurements but only in the last 25 years have the problems associated with use of site index been identified. While stem analysis data and polymorphic curves have resolved some problems, others continue including the use of site index in stands that are uneven-aged, of mixed composition, or have received height growth damage (Monserud 1984). Furthermore, stand density or stocking level normally is ignored in site index estimations yet it also may have an effect on height growth (Gaiser and Merz 1951).

A major gap in site evaluation research has been the absence of studies relating site index to stand volume or productivity. The presence of a strong relationship has been assumed although a few studies suggest that research in this area is needed. Assmann and Franz (1963) found that some spruce stands with the same site index had greatly differing volume yields. Assmann (1970) indicated that two sites of the same height growth potential need not to have the same basal area growth potential. Curtis (1972) states that since height is only one component of volume, site index is not synonymous with volume productivity. In view of the possibility that site index may not be reliable in all situations, other stand parameters related to site productivity should be examined more closely.

A possible supplement or alternative to site index data is potential basal area defined here as the maximum basal area a mature, fully-stocked stand will achieve within the limitations imposed by the site environment. The basal area of such stands is a parameter that has not been related to stand volume. However, an examination of any standard volume table shows that for stems over 17 cm, tree volume increases arithmetically with basal area. It follows that if stocking (stem) density is related to site quality a linear relationship between stand volume and total basal area should exist.

The purpose of the reseach reported here was to (1) examine the relationships which exist between the maximum basal area of fully-stocked, undisturbed, mature stands and individual soil and topographic characteristics, and (2) provide a biological explanation of these relationship.

THE STUDY AREA

The research was conducted in the Shawnee Hills region that bisects the southern tip of Illinois. This 240,000 ha extension of the Interior Low Plateau is underlain primarily by consolidated Pennsylvanian and Mississippian sandstone. Topography is gently to moderately rolling but sandstone outcrops and cliffs are relatively common. A few deep, sheltered gorges have been cut by larger streams; relatively small (<3 ha) terraces occur along stream margins.

Bedrock is capped by a loess deposit which varies in thickness from a few centimeters in soil lenses on rock outcrops to over 150 cm on low slopes and stream terraces. On south slopes and ridgetops, a fragipan is located at a depth of 38 to 78 cm. This pan limits root penetration and has a pronounced effect on forest development. The fragipan usually is deeper (50 to 120 cm) on upper north slopes: low north slopes and stream terraces usually have no pan (Fralish *et al.* 1978).

Annual precipitation is 1140 mm with 65 to 70 percent occurring during the 180 to 190 day growing season. The region is located within the prairie-forest border region (Anderson 1983) where summer droughts of three to five weeks may limit tree growth and stand development.

The Shawnee Hills forest has been highly disturbed by cutting, fire, and grazing; nearly all ridgetops have been cleared for farming. Stands are dominated by five species. *Juniperus virginiana* is found on soil lenses less than 30 cm deep over bedrock and in old fields. On west, southwest, and south slopes, *Q. stellata* or *Q. alba* may dominate stands on soil where the fragipan is less than 78 cm deep. *Quercus stellata* is the major dominant on highly rocky soil (35-60% stone); *Q. alba* dominates on soil of lower stone content (15-40%) and on the somewhat cooler south to southeast slopes. *Quercus rubra* and *Acer saccharum* are restricted to moist northern slopes and lower coves. Stands of *Q. rubra* usually are located in high slope positions while *A. saccharum* dominated stands are found on middle to low slopes and terraces (Fralish 1976; Fralish *et al.* 1978).

METHODS

Stand selection was based on site uniformity and forest community conditions. Within each stand, soil depth, texture, and stoniness, aspect, slope steepness and slope position were uniform. A site with a noticeable variation in any one factor was rejected. Forest communities were free of cutting, grazing, and fire and were older than 100 years. On medium to good sites, the stands were fully-stocked according to the guidelines of Roach and Gingrich (1962, 1968). Selected stands on poor sites where soil depth was less than 50 cm and rock content greater than 40 percent were understocked according to their criteria but were considered fully-stocked for site conditions and used in the study. No stands on ridgetops met the selection criteria because of past farming activity. Stands were selected to include the existing range of forest cover and site types. A total of 54 one to two hectare stands were selected for study.

In each stand, two or three 0.04 ha plots were randomly located with a minimum of 24 m between plot centers and 12 m between the plot center and stand boundary. On each plot, species and diameter to the nearest 0.1 cm at 1.37 m above ground level (breast height) were recorded for stems greater than 9 cm in diameter.

In each stand, one soil pit was opened to a depth of one meter or to bedrock if nearer the surface. Soil samples were taken from each horizon for texture analysis, and data on horizon type, depth, stoniness, and effective soil depth were recorded. Effective soil depth (ESD) coincided with tree root penetration to the top of the fragipan, to bedrock, or to three meters if penetration was unrestricted. Bulk density samples were obtained using a Uhland core sampler or the saran resin method, or both. Volume of stone (particle diameter >2 mm) was estimated using the charts of Yaalon (1966).

Soil texture and bulk density analyses followed the procedure recommended by Wilde *et al.* (1979). Available water capacity (%) was estimated from the model:

$$\text{AWC (Max \%)} = .26\ (\%\text{silt}) + 6.5 \qquad \text{Eq. (1)}$$

developed by Hill (1959) and converted to centimeters of water capacity by horizon using the model of Auclair and Cottam (1971) and Fralish and Loucks (1975):

$$\text{Hor. AWC (cm)} = \text{AWC (\%)} \times \text{BD} \times \text{HW}/100 \qquad \text{Eq. (2)}$$

where BD is bulk density and HW is horizon width in centimeters. Horizon AWC was adjusted by the percentage of stone in the respective horizon since rock fragments were considered to have no water holding capacity:

$$\text{Adj. Hor. AWC (cm)} = \text{Horizon AWC x } (100 \quad \%\ \text{Stone}). \qquad \text{Eq. (3)}$$

Total available water capacity to effective soil depth (AWC) was obtained by summing adjusted horizon AWC for all horizons above the fragipan or bedrock or to 3 meters in soil where there was no restriction to root penetration.

Slope steepness, PSLOP (%) and aspect (degrees azimuth) were recorded on all sites. Aspect was transformed (TASP) according to the model of Beers, Dress, and Wensel (1966): $A^1 = \cos (45 - A) + 1$, where A^1 is the coded value and A is the slope aspect in degrees azimuth clockwise from north. This model assigns a value of 0.00 to an azimuth of 225 degrees (southwest) and a maximum value of 2.00 to an azimuth of 45 degrees (northeast) with intermediate values assigned to other azimuths. A transformed value of 1.00 was assigned to rock outcrops and alluvial sites since the amount of solar radiation striking these horizontal land surfaces was considered to be at an intermediate level between southwest and northeast slopes.

Slope position, SLOPOS, was assigned a value based on the percentage of the distance between the ridge (1) and the nearest permanent stream (10). Distances were measured from the site or obtained from topographic maps for large hills and wide valleys and in complex topography.

Plot basal area was calculated by converting stem diameter to basal area and summing for all trees in a plot. Stand basal area was obtained by averaging basal area values for all plots in a stand. Stand basal area was related to site factors using simple regression analysis.

RESULTS

Stand basal area was most strongly correlated with soil variables ESD and AWC although the relationship was curvilinear (Figs. 1a and 2a). Transformation of ESD and AWC data to a natural log (ln) base changed the relationship to a nearly linear function (Figs. 1b and 2b) that increased the correlation coefficient (r) between basal area and ESD from 0.81 to 0.89 and between basal area and AWC from 0.82 to 0.94 ($p < .01$, $n = 54$).

Correlation coefficients between stand basal area and the various percentages of sand, silt, clay and stone and bulk density were not significant ($r < 0.29$, $p > .05$, $n = 54$). The loessal soils of the region vary from about 38 to 66 percent silt (B2 horizon), a range that is not sufficient to greatly affect stand growth and development. These medium loam to silt loam soils have good to excellent soil moisture retention properties on a per unit basis. Using Eqs. 1 and 2 above, it can be shown that soils which have 38 to 66 percent silt in the B2 horizon (bulk density = 1.3 g/cc) hold 2.1 and 3.1 cm of water, respectively, per 10 cm of soil depth. As a result, tree growth primarily becomes a function of rooting depth (effective soil depth) which largely determines the amount of available water.

A moderately strong positive relationship ($r = 0.72$, $p < .01$, $n = 54$) was found between basal area and TASP (Fig. 3). Stands on north, northeast, and east slopes (TASP >1.4) had basal areas greater than 23 m^2/ha while southeast, south, and southwest slopes (TASP <0.6) supported stands with less than 25 m^2/ha. The wide range of stand basal area values plotted above a TASP of 1.0 resulted from applying this mid-point value to stands on horizontal land surfaces. Included here were low basal area *Juniperus virginiana* stands on thin soil lenses and high basal area *Acer saccharum* stands on stream terraces. Soil is the limiting factor in *Juniperus* stands regardless of slope position (SLOPOS 3 to 7) while the deep soil and low slope position favor a high basal area in *Acer* stands on stream terraces. On both sites, aspect apparently has had little effect on stand development. An analysis of the data excluding these two site types substantially increased the correlation coefficient ($r = 0.84$, $p < .01$, $n = 41$).

Basal area also was moderately strongly related to slope position ($r = 0.65$, < 0.01, $n = 54$) as stand basal area increased from sites directly below the ridgetop to middle slopes to stream terraces (Fig. 4). Stands located on side slopes (SLOPOS = 2 to 8) had a relatively large range in basal area for a given slope position. Much of this variation was due to the extremely low basal area (< 10 m^2/ha) of *Juniperus* stands whose development apparently was limited by soil conditions. However, an additional analysis excluding the data for these stands did not appreciably increase the correlation coefficient ($r = 0.68$, $p < .05$, $n = 44$). All stands on slope-terrace interfaces (SLOPOS = 9) and stream terraces (SLOPOS = 10) had high basal areas (>24 m^2/ha).

The correlation coefficient between basal area and PSLOP was not significant ($p > .05$) when the complete data set was used in the analysis. However, with data from stands on nearly level sites (i.e., low BA *Juniperus* stands on soil lenses and high BA *Acer* stands on stream terraces) excluded, the correlation coefficient of -0.42 was significant ($p < .05$, $n = 41$). Generally as slope steepness increases, stand basal area decreases (Fig. 5).

DISCUSSION

Stand basal area was most strongly correlated with effective soil depth and available water capacity. Effective soil depth is a site variable that can easily be measured by a forest manager, but it is not a direct measure of available soil water although the two are strongly correlated ($r = 0.93$). The single most important requirement for tree growth and development is water (White 1958; Kramer 1983) and thus, it was felt that a quantitative measure of soil water provided the best opportunity to examine forest response in a possible cause-and-effect relationship.

In this study, an accurate estimate of available soil water was obtained by converting percent silt, effective soil depth, bulk density and percent stone to centimeters of water within the rooting zone. Downs (1976) reported that the estimate of AWC (%) from Hill's model (Eq. 1) developed for New England soil closely corresponded to pressure plate values for silt loam soil in the Shawnee Hills so that application of the model to this ecosystem is acceptable. Use of Eqs. (1) and (2) simplified the process of obtaining reliable data on soil water capacity and provided a parameter to which trees apparently respond.

The relationship of basal area to soil factors is consistent with existing biological theory. The curvilinear relationship between basal area and ESD or AWC is a practical example of the general principle of limiting factors as defined by Odum (1971). Large increases in basal area occur with relatively small changes in soil volume until ESD and AWC exceed 100 cm and 25 cm, respectively. Thereafter, the curve is nearly asymptotic as increases in these variables have little effect on the basal area level and stand development. This relationship is supported by Pienaar and Turnbull (1973) who state that there is a limit to the amount of live matter than can be sustained by a given site and that stand basal area will approach an asymptotic level that is determined by the productive capacity of the site. A maximum basal area of 35 to 38 m^2/ha in stands on the best low north slopes and terrace sites slightly exceeds the average of 30 m^2/ha (maximum 32 m^2/ha) reported by Held and Winstead (1975) for old-growth stands on mesic sites in eastern United States. It is comparable to basal area noted by Whittaker (1966) for stands in the Great Smoky Mountains.

Soil water capacity is an estimate of the maximum available water that can be stored while the actual amount of water stored at a given time varies. The rate of loss from the soil water reserve depends on the extent that topography modifies microclimate. On north, northeast, and east slopes, the impact of solar radiation is ameliorated. The resulting cool temperatures reduce evapotranspiration loss and soils retain water for tree growth even through extended drought periods (Downs 1976). The surface of west, southwest, and south slopes are oriented nearly perpendicular to incoming solar radiation for much of the growing season and have a higher evapotranspiration loss. They dry more quickly and may have several periods where soil water is below permanent wilting point (15 bars) at all levels of the rooting zone (Downs 1976); on these slopes, tree growth is substantially reduced.

Slope position has a similar effect on microclimate. Sites in high to mid-slope positions (SLOPOS = 1 to 5) have a higher wind velocity and temperature than lower slopes (Fralish and Downs, Unpublished data). Both factors contribute to increased evapotranspiration and a higher probability of soil drought. Cool air flows on to middle and low slope positions (SLOPOS = 6 to 10) thereby reducing evapotranspiration loss and making these sites more moist and productive.

CONCLUSIONS

In the Shawnee Hills, the basal area of undisturbed, fully-stocked, mature stands is strongly related to effective soil (rooting) depth, aspect, and slope position. These factors determine the amount of soil available water, rate of water loss through evapotranspiration, and ultimately, site productivity. Stand basal area is not related to soil texture estimates that have been used in many forest site evaluation and ecology studies. Basal area appears to be more closely related to site factors than is site index; therefore, it is suggested that in the Shawnee Hills, evaluation of upland site productivity may be improved by supplementing site index data with basal area estimates taken from mature or old-growth stands on comparable sites.

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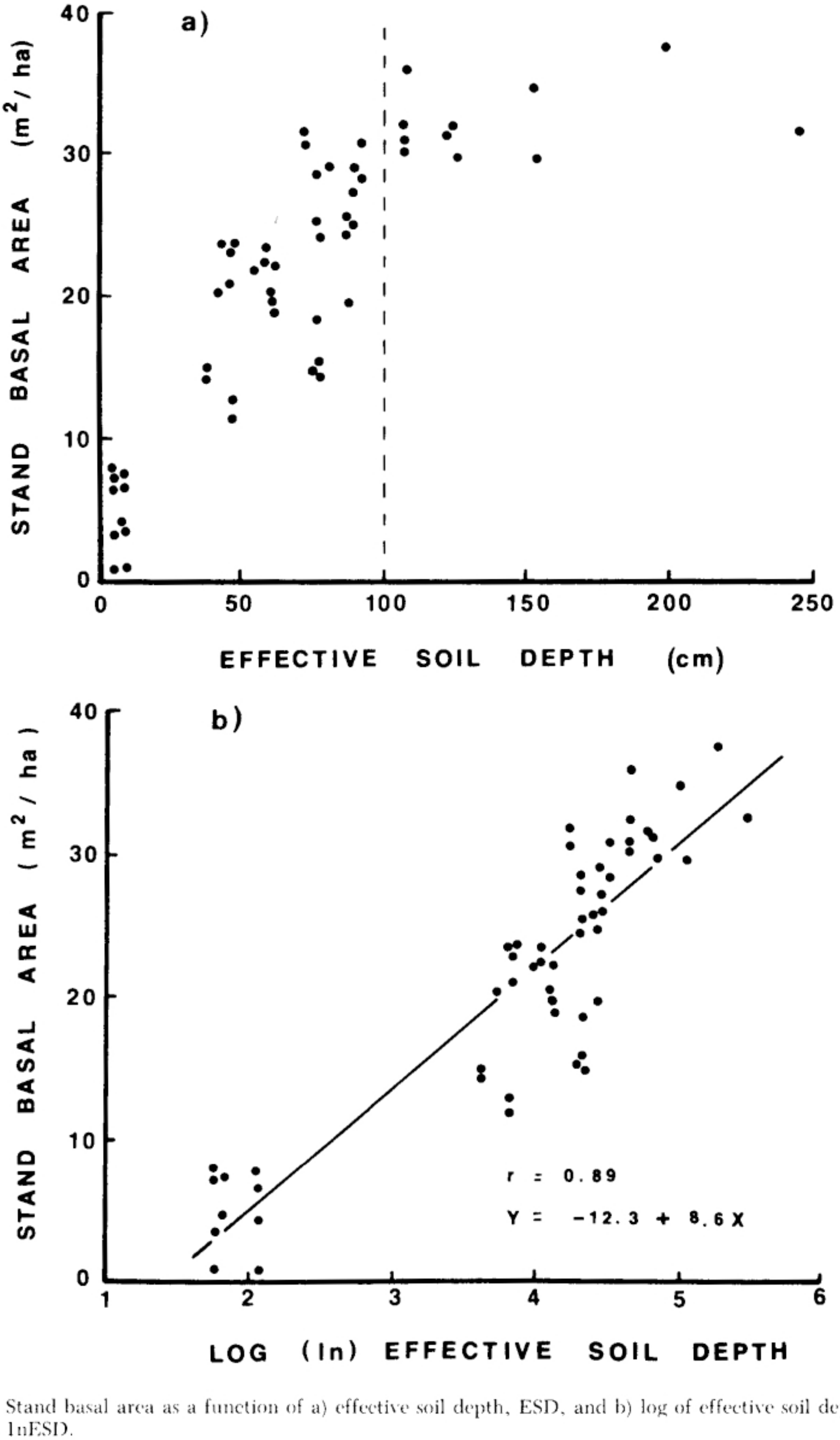
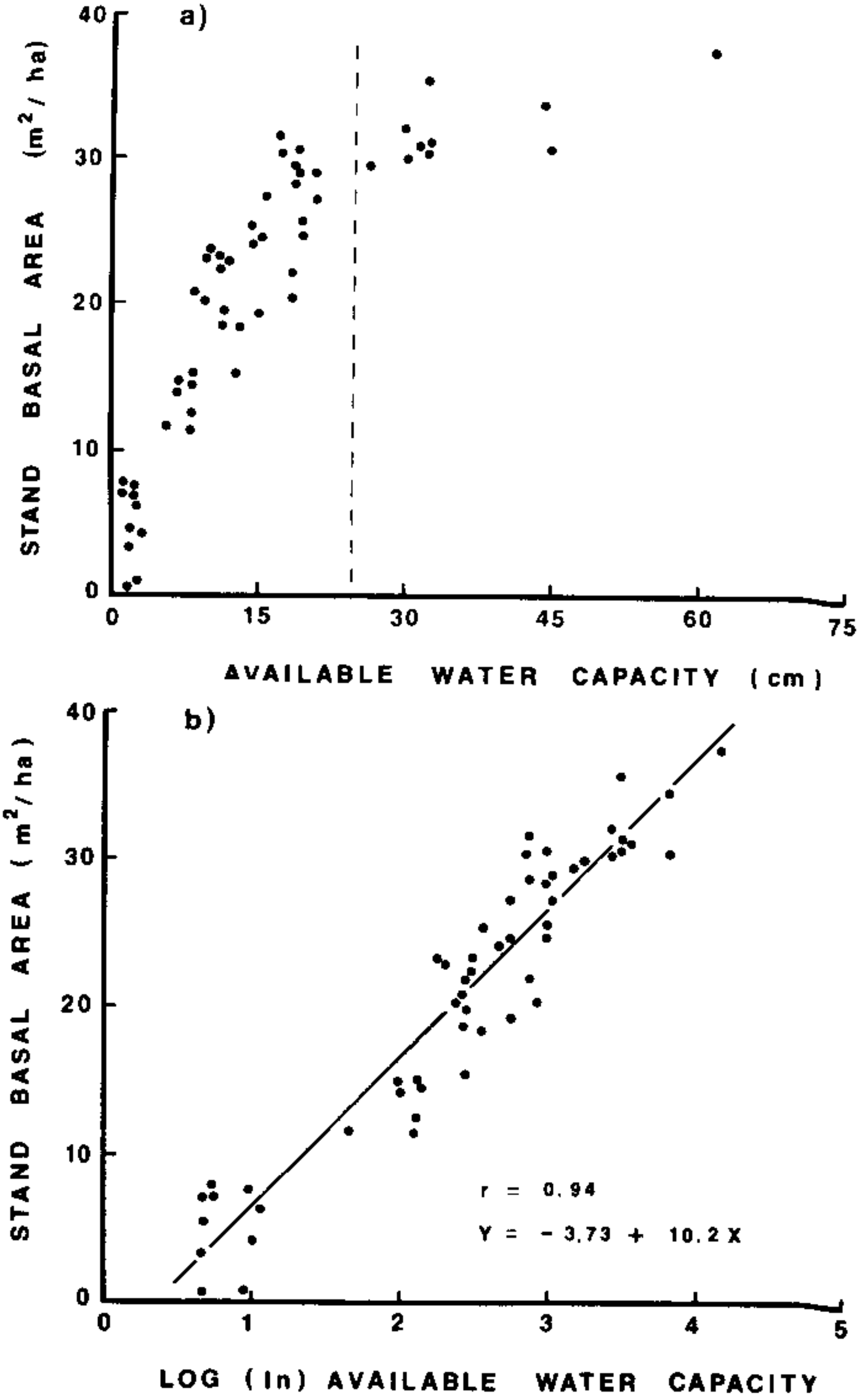
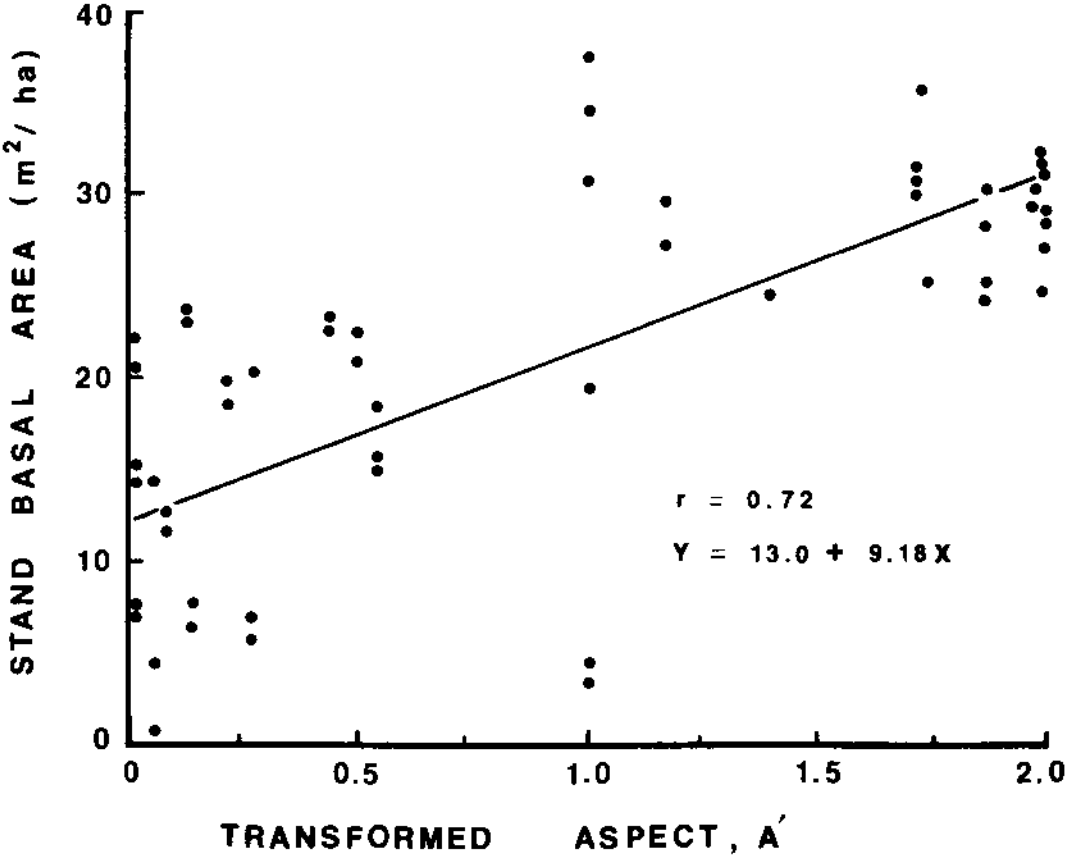


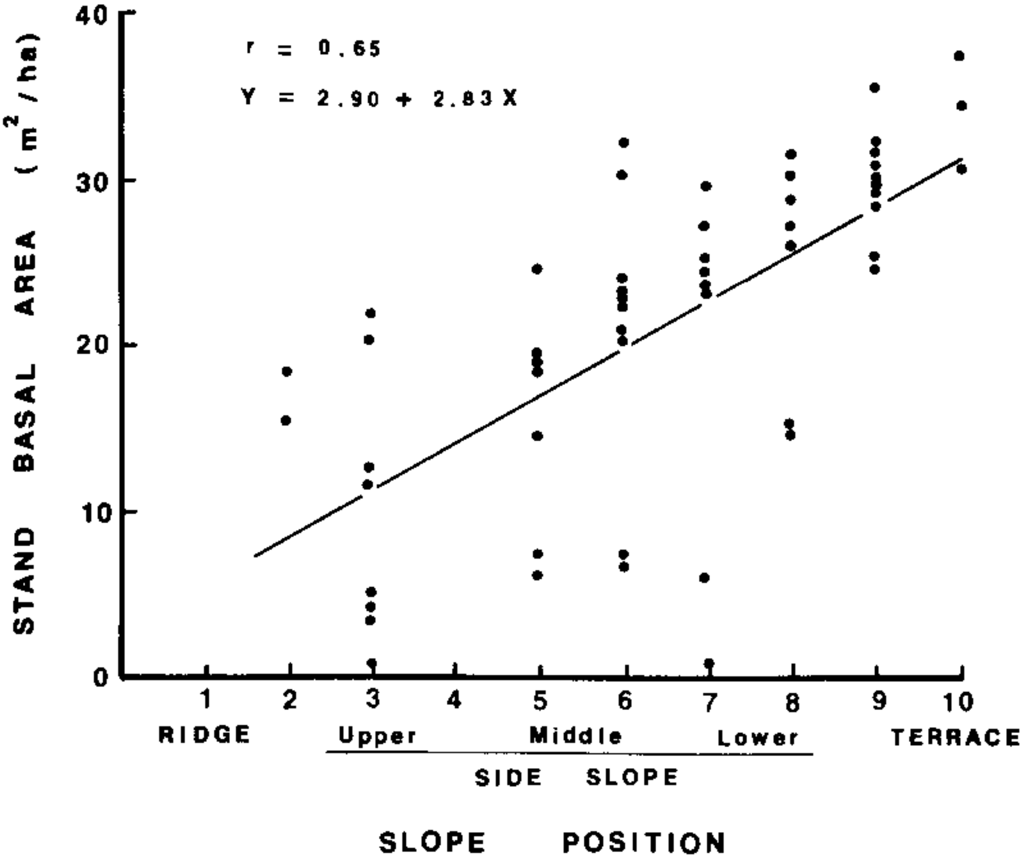
1. Stand basal area as a function of a) effective soil depth, ESD, and b) log of effective soil depth, lnESD.



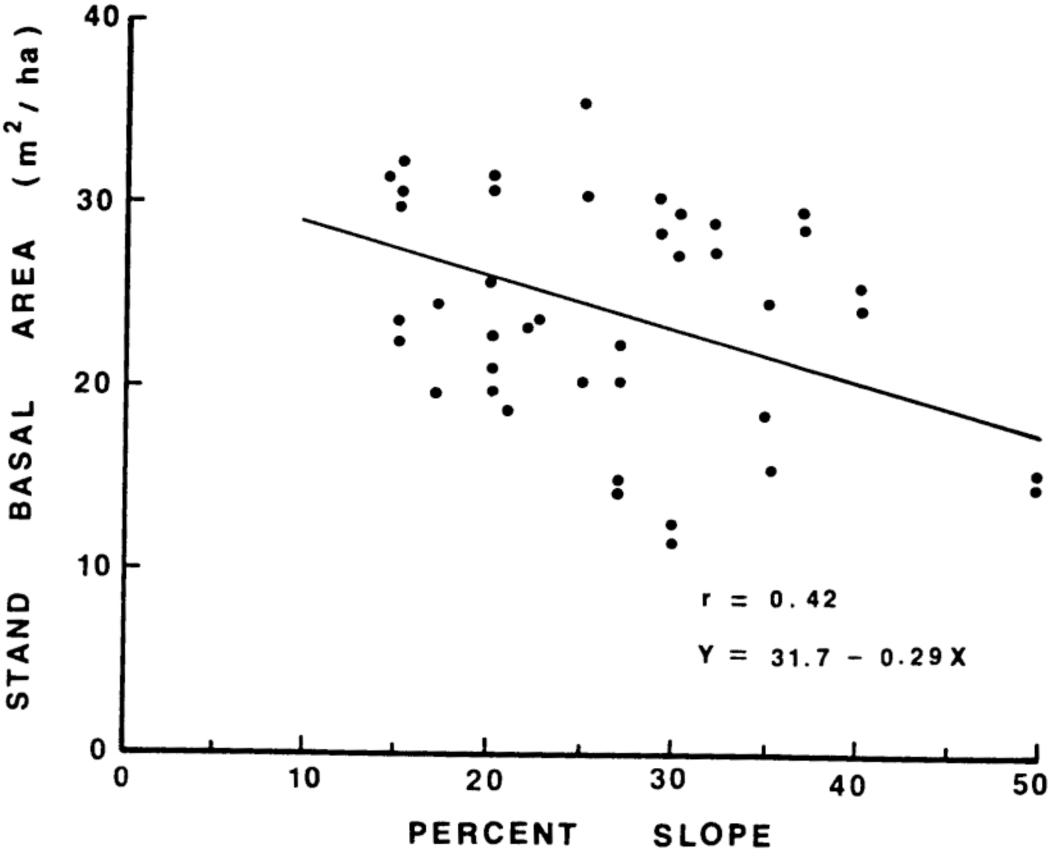
2. Stand basal areas as a function of a) soil available water capacity, AWC, and b) log of soil available water capacity, lnAWC.



3. Stand basal area as function of transformed aspect, TASP.



4. Stand basal area as a function of slope position, SLOPOS.



5. Stand basal area as a function of percent slope, PSLOP.