SPATIAL CHARACTERISTICS OF TOPOGRAPHY, ENERGY EXCHANGE, AND FOREST COVER IN A CENTRAL APPALACHIAN WATERSHED

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Abstract: Spatial variation of topography, net radiation, evapotranspiration, and forest stand in the central Appalachian watershed is described. The study area is the control watershed 4 (39°20'N,79°49"W) located in the Fernow Experimental Forest at Parsons, West Virginia. The watershed encompasses an area of 39.2 ha, it has a south-east orientation, and the average slope inclination is 14°. The forest cover is ca. 85 years old and consists of upland oak and cove hardwoods. Topographic analysis was based on data for 432 triangular segments with an average area of 360 m^2, covering the whole watershed. Partial areas for defined slope and azimuth ranges and the distribution of both parameters are illustrated. Half of the watershed area has an azimuth between 90 and 150° (east facing slopes), and 65% of the area has slope inclination ranging from 10 to 20°. Net radiation (Rn) was computed for all terrain segments. Its distribution in the watershed is illustrated, and its average yearly sum for the whole watershed was 2.2 GJ m^{-2}. Yearly sum of Rn of southwest facing slopes was 55% (lower sites) to 60% (upper sites) greater than that of east facing slopes. The average yearly precipitation (P) and evapotranspiration (Et) of the watershed are 145.5 cm and 81.7 cm, respectively. A regression formula defines yearly sum of Et as a function of P and Rn of the watershed. Using this formula, average yearly sums of Et of all terrain segments were calculated. The distribution of the yearly average sum of Et in the watershed is illustrated; yearly Et of partial areas varied from ca. 60 to 85 cm. The average air-dry above ground biomass for 112 plots was 320.3 t ha^{-1}. East facing slopes had the highest air-dry biomass (354 t ha^{-1}) and the southwest facing slopes the lowest (224 t ha^{-1}). Thirty-five species were recorded on the plots surveyed. The most frequent species were sugar maple (32.1% of the total number of trees, DBH > 5 cm), red maple (19.3%), American beech (9.7%), northern red oak (7.6%), black cherry (4.1%), sweet birch (3.6%), and chestnut oak (2.4%). Red oak had the highest total biomass (30.2% of the total for all species), followed by sugar maple (13.8%), black cherry (13.0%), red maple (9.9%), chestnut oak (6.9%), yellow-poplar (5.7%), American beech (4.7%), and white oak (4.5%).

INTRODUCTION

On a broad scale, the major plant associations of the central Appalachian region are oak forests and northern hardwoods. The relationship between forest and climate of the region is well established. Regional energy-water relations for a horizontal surface - are defined by Hare [1972 (in Miller, 1977)]. However, on smaller scales, there is a wide variety of vegetation types that, according to Rumney, (1968) is a natural consequence of variations in topography, weather patterns and underlying bedrock. There are numerous descriptions of forests in the region (e.g., Hack and Goodlett, 1960; Trimble, 1973; Burns, 1983). However, for most forest sites, quantitative information on topography related variation in meteorologic, hydrologic, and other parameters is missing. Foresters correlate forest growth in the region with such parameters as slope aspect and inclination, soil depth and fertility, precipitation, and stone content (Trimble and Weitzman, 1956; Yawney, 1964; Yawney and Trimble, 1968; Auchmoody and Smith, 1979). However, Carmean (1975) remarked that "correlations cannot be accepted as evidence of cause and effect relations" and that "features of soil, topography, and climate found to be correlated with site index are indirect indices

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of more basic growth controlling factors and conditions, such as available moisture and nutrients, and microclimatic factors that affect evapotranspiration and tree physiological processes". This calls for the understanding of ecological processes at specific forest sites and is compatible with geophysics of landscapes and with landscape ecology (Armand, 1964; Forman, 1983; Swanson et. al. 1988).

Among many processes that take place in the forest, cycles of water and energy play a key role. Hydrologic studies at the watershed level yield information on average values of the water balance components. The number of such studies is limited, and in addition the water balance components so obtained cannot be related to specific forest sites with varying topography and location in the watershed. Net radiation of the forest is regarded as the main source of energy needed for the processes of growth, etc. But, studies dealing with the distribution of net radiation in forested watersheds are infrequent (Tajchman et al. 1988; Fu et al. 1995).

For this particular study, we have selected a forested watershed (watershed 4) in the Fernow Experimental Forest at Parsons, West Virginia, which has been the subject of hydrologic and meteorologic observations for more than 40 years (Adams et al., 1993). The objectives of the study were to obtain a detailed analysis of a) topography, b) energy and water exchange, and c) forest cover.

STUDY SITE

The study area, the control watershed 4, is shown Fig. 1. The watershed area is 39.2 ha, the average watershed elevation is 804 m with the maximum of 869 m and minimum of 739 m. The watershed has a southeast orientation and ca. 65% of its area has the azimuth ranging from 90° (east facing) to 180° (south facing). Slope inclination ranges from 2 to 29° and the average value is 14°. The predominant soil is Calvin silt loam with considerable stone content. Soil depth to bedrock averages 0.8 m, ranging from 0.56 to 1.2 m. About 95% of the tree roots were found in the upper 0.90 m layer of the soil (Patric, 1973; Kochenderfer et al. 1987).

The area was heavily logged between 1905 and 1910; no surface disturbance has been permitted since that time, except for a road constructed adjacent to its upper boundary in the 1930's. The major forest types in the watershed are upland oaks and cove hardwoods. The upland oak type occurs on drier areas and consists primarily of red oak (*Quercus rubra*), chestnut oak (*Quercus primusprinus)*, and white oak (*Quercus alba*). Cove hardwood type occupies moist sites along the streams and consists mainly of sugar maple (*Acer saccharum*), and black cherry (*Prunus serotina*), frequently including yellow-poplar (*Liriodendron tulipifera*) and scattered American beech (*Fagus grandifolia*).

The growing season is May through September, and average frost-free season is 145 days (Patric, 1973). Precipitation is evenly distributed throughout the year, and the yearly average is 145.5 cm. About 44% (64.1 cm) of total precipitation occurs during the growing season. The months of June and July have the greatest average precipitation, 14.4 and 13.6 cm, respectively. September and October are the driest months, with average precipitation of 10.3 cm and 9.7 cm, respectively. The yearly average temperature in the study area is 8.8°C. July and August have the highest average monthly temperatures of 19.3 and 18.7°C, respectively. January has the lowest monthly average temperature of -3.1°C.

METHODS

Topography

For spatial analysis of the watershed, its photogrammetric map (Greenhorne and O'Mara, Inc.) in scale 1:2,500 was considered in the three dimensional coordinate system with x-axis directed toward east, y-axis directed toward north, and z-axis directed toward zenith. The watershed area was divided into 432 triangular segments with an average area of 360 m^2. Using the Summagraphics Microgrid II digitizer, the x and y coordinates of the corners of all triangles

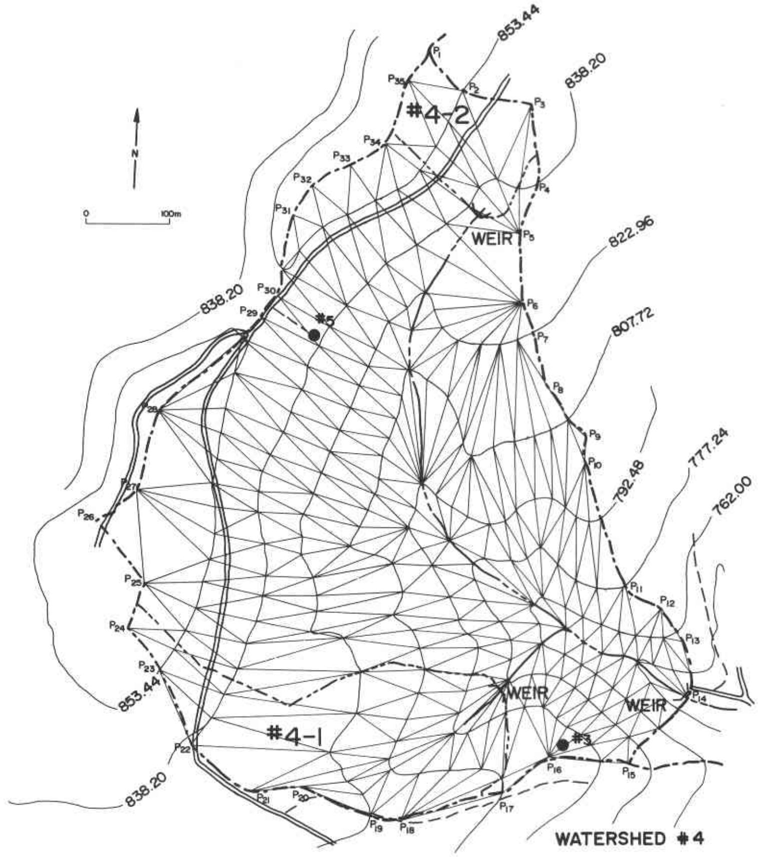

Figure 1. Topographic map and triangulated network of Watershed 4 (Fu et al., 1995).

were determined; the elevation marked on contour lines was accepted for the z-coordinate. The x,y,z coordinates of the corners of triangles were used to compute their azimuth, inclination, and area (Tajchman, 1975).

Water and Energy Balances

The following formula defines the water balance of a watershed

$$P = Et + R + \Delta W, \tag{1}$$

where P is precipitation of the watershed averaged over its area, Et is evapotranspiration of the watershed, R is runoff, and ΔW represents the change of the soil water content in the watershed during the period of observation. For periods starting and ending with the same soil water content $\Delta W = O$ and the water balance of the watershed is given by

$$P = Et + R. \tag{2}$$

The parameters P and R are known from observation and Et can be obtained from Eq. (2).

The energy balance of the watershed, after neglecting the relatively small amounts of energy used in photosynthesis and energy stored in the soil, is given by

$$Rn = L\,Et + H, \qquad (3)$$

where Rn is net radiation of the watershed, L is the latent heat of evaporation of water, and H is the heat exchange between the watershed and the atmosphere. In calculating the yearly energy balance of the watershed, the latent heat of Et obtained from Eq. (2) can be applied. Calculations were carried out for 39 hydrologic years (1951-1990) which start on May 1 of a calendar year and ends on April 30 of the next calendar year.

The net radiation of the watershed is given by

$$Rn = G\,(1 - r) + Rl, \qquad (4)$$

where G is global radiation, r is the reflectivity of the forest for solar radiation and Rl is the longwave radiation balance. The average r values of 0.17 and 0.20 were accepted for the growing season and for the dormant season, respectively (DeWalle and McGuire, 1973; Lee and Sypolt, 1974). The term G (1 - r) represents the amount of solar radiation absorbed by the forest. Net radiation data for the watershed are not available from direct observation. However, they can be calculated for all terrain segments and then for the whole watershed area if the following parameters are known:

a) Monthly sums of global radiation at a horizontal surface in the study area,
b) Climatological data on air temperature, humidity, and sky cover,
c) Topographic parameters of terrain segments including azimuth, inclination, and the view factor,
d) The times of sunrise and sunset of all terrain segments.

Using monthly sums of global radiation (horizontal surface) for Parsons (1965-1977) and the monthly average sky cover data for Elkins, ca. 24 km south-east of Parsons, the following regression formula was obtained

$$G = Go\,(0.82 - \alpha\,C),\ R^2 = 0.87, \qquad (5)$$

where Go is the monthly sum of extraterrestrial radiation, and C is average monthly sky cover in fractions of unity. Monthly values of the coefficient α are listed in Table 1. Eq. (5) was used to calculate the missing data on global radiation at Parsons during the period 1951-1990.

Table 1. Monthly values of α (Eq. 5) at Parsons, W.Va.

Month	α	Month	α
January	0.598	July	0.514
February	0.562	August	0.516
March	0.546	September	0.534
April	0.576	October	0.613
May	0.537	November	0.639
June	0.500	December	0.622

The following regression formula describes yearly sums of Et as functions of the corresponding P and Rn.

$$Et = 0.2052\,P + 5841\,(Rn/L),\ R^2 = 0.82, \qquad (6)$$

where Et and P are in cm, Rn in kJ m^{-2}, and L is the latent heat of evaporation of water. Assuming that the same relationship exists between long term average monthly sums of Et, P, and Rn, Eq. (6) was used to calculate 39 years average monthly values of Et of all terrain segments. Then, yearly sums of Et were obtained. The standard deviation of the difference between measured and calculated yearly sums of Et was 1.85 cm, and the relative error ranged from 0 to 7.8% (average = 2.8%). For more details see Fu (1992).

Above Ground Biomass and Species Composition

Data on DBH and species composition were collected during the summer of 1993 on eighty seven 804 m^2 (93 x 93 ft.) plots randomly distributed in the watershed. All trees with DBH > 5 cm were recorded. Additional data on DBH and species composition in the watershed, collected in 1990 at 25 809 m^2 (0.2 acre) plots randomly distributed in the watershed, were included in the study.

The location of the plots is seen in Fig. 2. The above ground air-dry biomass of single trees at each plot was obtained using the relationships reported by Brenneman et al. (1978).

RESULTS AND DISCUSSION

Topographic parameters were computed for all terrain segments and were used to obtain a) partial areas of the watershed with definite ranges of inclination and azimuth, and b) maps showing the distribution of inclination and azimuth in the watershed.

Figures 3 and 4 show partial areas of the watershed in percent of its total area within different intervals of inclination and azimuth. As shown in Fig. 3, slopes with the inclination ranging from 10 to 15° occupy 42% and those with inclination ranging from 25 to 30° occupy only 3% of the total watershed area. Fig. 4 shows, e.g., that, east and south-east facing slopes with the azimuth ranging from 90 to 150° occupy about 50% of the watershed area, and the north facing slopes with the azimuth ranging from 330 to 30° occupy about 7% of the total watershed area. Since site quality is related to aspect, knowing of the relative amount of area in each aspect can be useful in the preliminary evaluation of forest land in the study area.

The distribution of slope inclination and azimuth in the watershed is seen in Figs. 5 and 6, respectively. The western half of the watershed contains more or less topographically uniform areas with inclination ranging from 8 to 12° (Fig. 5), and with azimuth ranging from 100 to 140° (Fig. 6). The eastern half of the watershed is characterized by a more complex topography with inclination of partial areas ranging from 6° in the north-eastern part of the watershed to 26° in the south-eastern part of the watershed. The prevailing aspect in this part of the watershed is south and south-west.

Topography affects the radiation exchange in complex terrain. This is seen in Fig. 7 where the distribution of the average yearly sums of net radiation in the watershed is marked by isolines. In the western half of the watershed the net radiation is more or less uniformly distributed, and in the eastern half a variation is substantial. In the western half of the watershed the yearly sum of net radiation amounts to approximately 2.20 GJ m^2, and in the eastern part it varies from approximately 1.60 GJ m^{-2} to 2.20 GJ m^{-2}. The yearly average net radiation of the whole watershed is 2.20 GJ m^{-2}.

The evapotranspiration of the watershed is a component of its water and energy balances (Eqs. 1 and 3). Its average value for the period 1951-1990 was 81.7 cm, and the equivalent latent heat amounted to 2.02 GJ m^{-2}. One can determine from Eq. (3), that the yearly average sum of the sensible heat transferred from the watershed to the atmosphere amounted to 0.18 GJ m^{-2} or 8.2% of Rn.

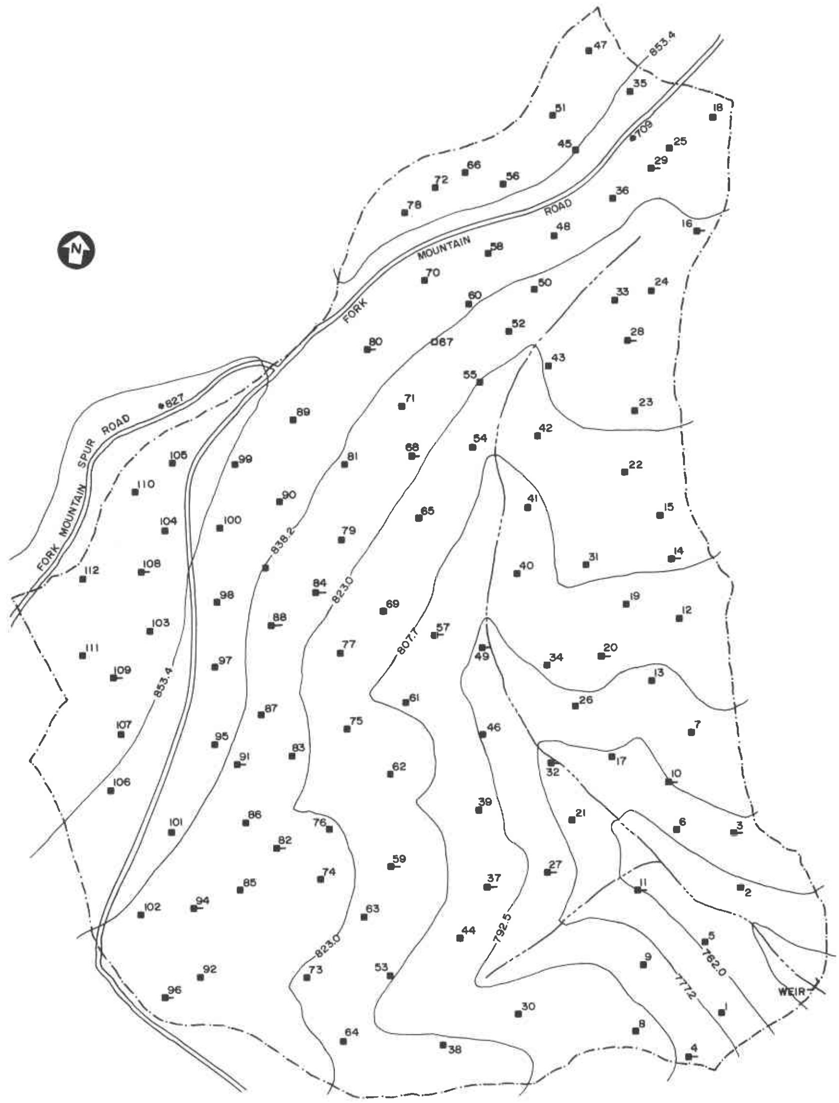

Figure 2. Location of sampling plots. Squares with a dash represent permanent plots of the U.S. Forest Service.

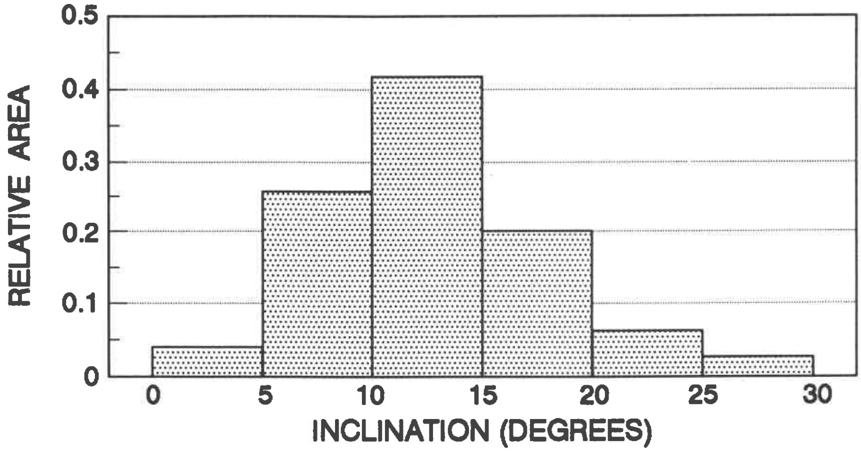

Figure 3. Ranges of slope inclination and the corresponding partial areas (%) of the watershed.

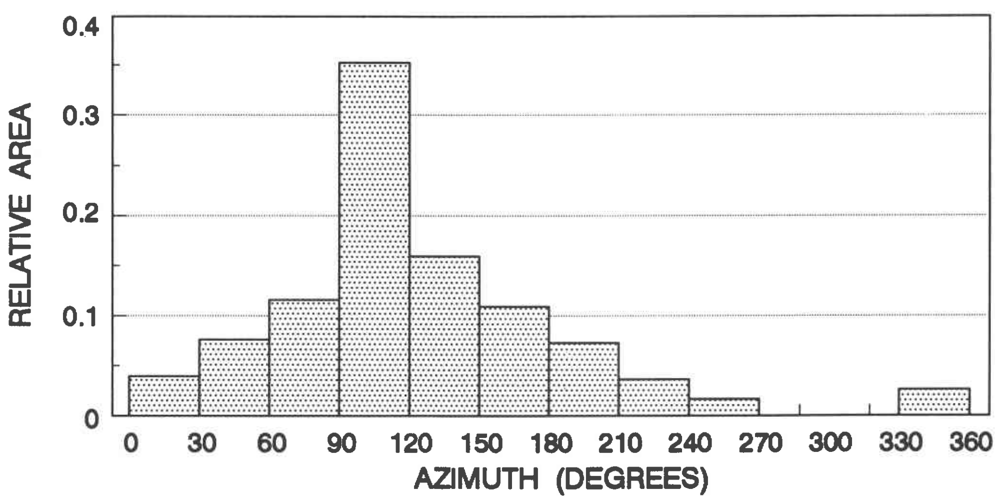

Figure 4. Ranges of slope azimuth and the corresponding partial areas (%) of the watershed.

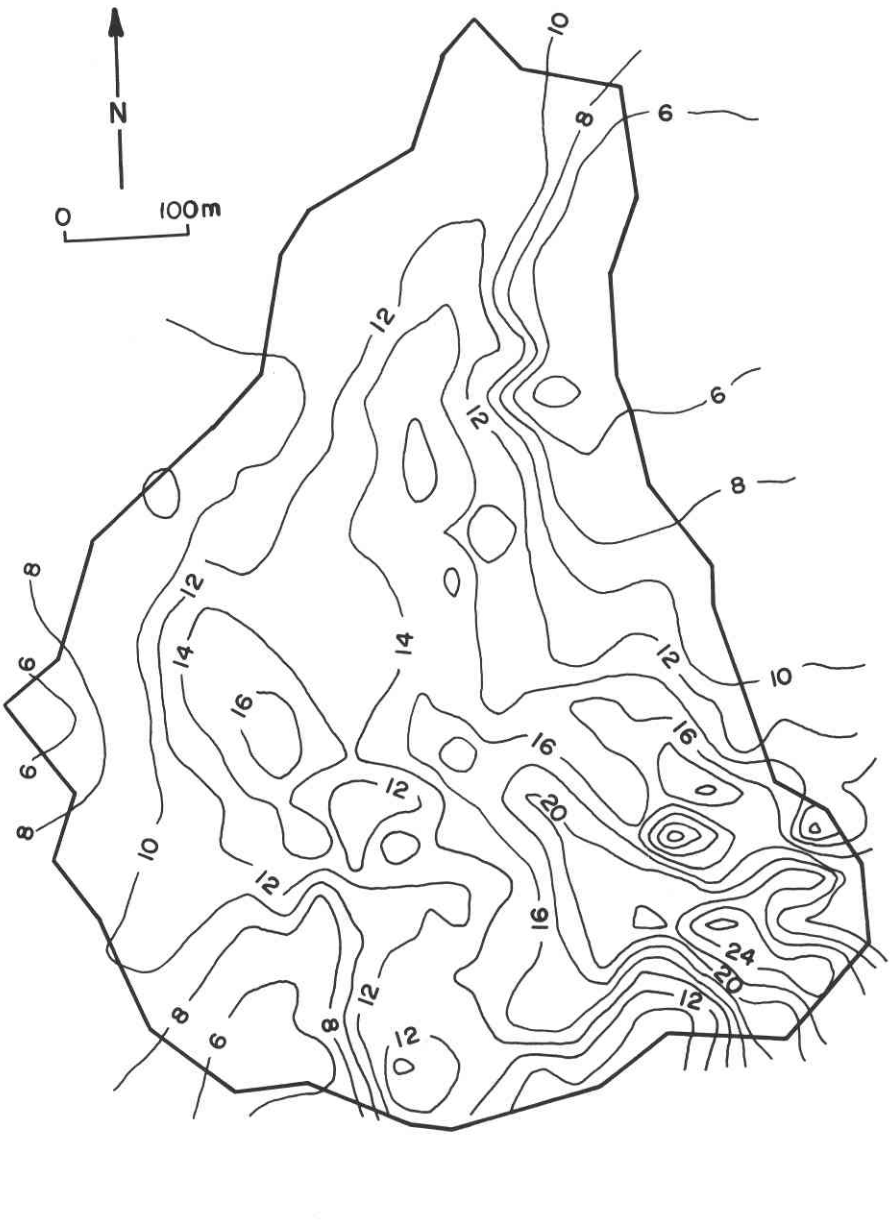

Figure 5. Distribution of slope inclination (degrees) in Watershed 4 (Fu et al., 1995).

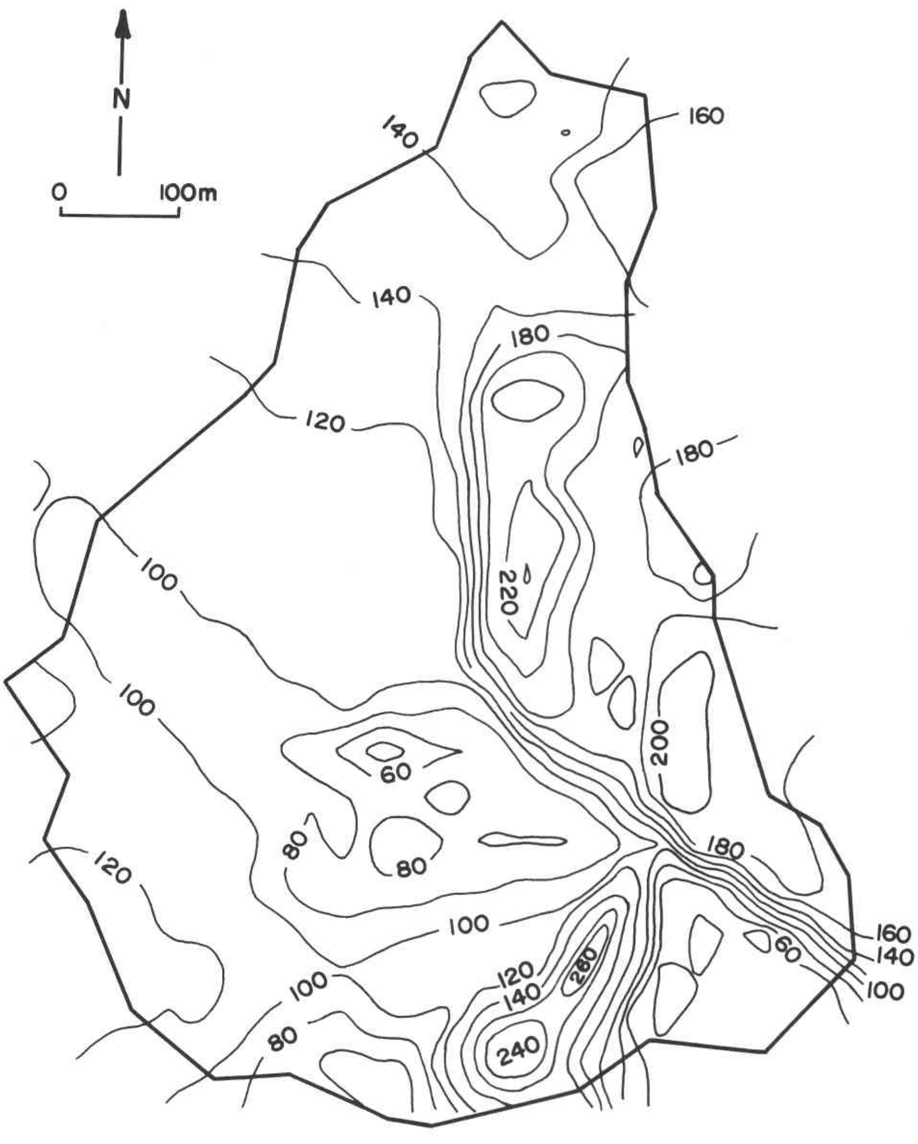

Figure 6. Distribution of slope azimuth (degrees) in Watershed 4 (Fu et al., 1995).

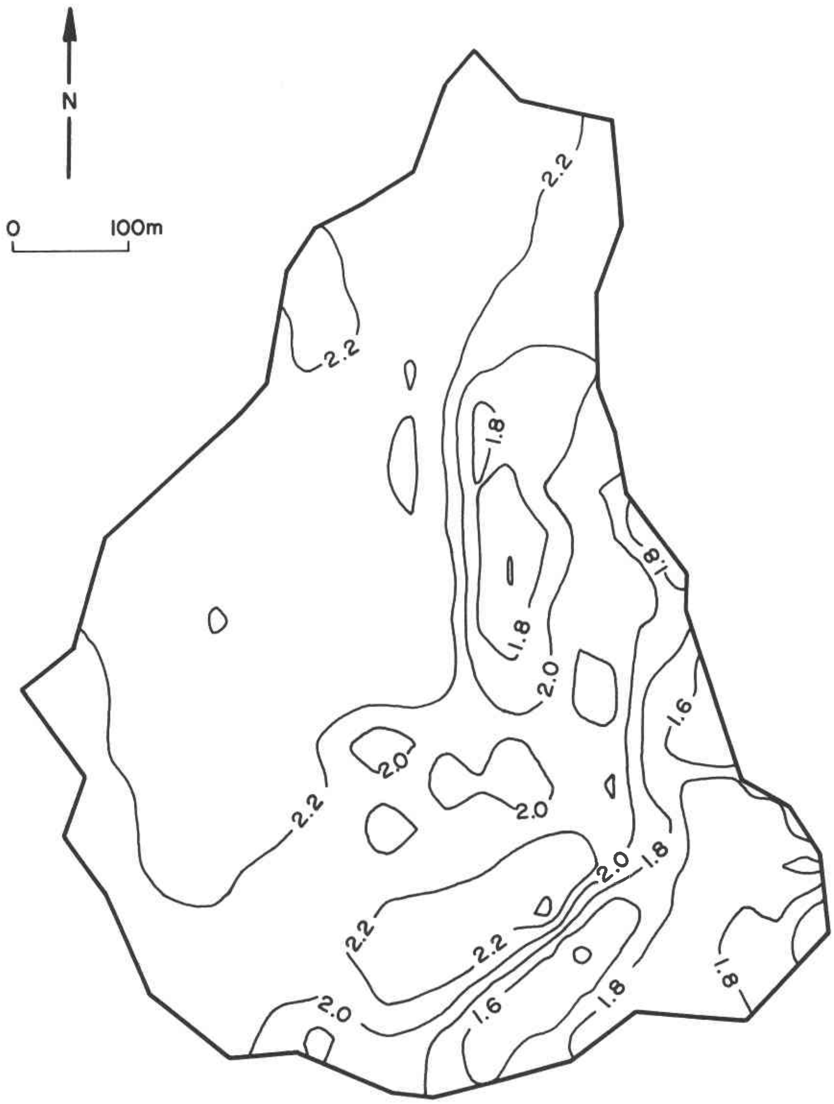

Figure 7. Distribution of the yearly sums of net radiation (G J m^{-2}) (Fu et al., 1995).

Applying Eq. (6) to all terrain segments, their Et values were obtained. A linear interpolation was applied to obtain the distribution of Et values in the watershed, represented by isolines on the map of the watershed (Fig. 8). In the western half of the watershed, Et varies from 82 to 85 cm per year and is uniformly distributed. In the eastern half of the watershed, the yearly average sum of Et varies from 60 to 82 cm, and its distribution is complex.

Figure 9 shows the location of plots where trees were sampled, and the numbers at each plot express the above ground air dry biomass in tons per hectare. A total of 35 species were found on the plots (Table 2). The average biomass for 112 plots is 320.3 t ha^{-1} . The difference between the maximum and minimum biomass of single plots is equivalent to 152% of the average value. The coefficient of variation of single plot biomass decreases when the number of plots (n) increases, and reaches a more or less steady value when $n \geq 20$.

Plot biomass values were compared to those of Rn and Et, and the possible relationship between the biomass and two other parameters was examined. In the eastern part of the watershed with a more complex topography, the coefficient of variation of the plot biomass is 29.9%; the corresponding coefficients of variation for Rn and Et are 8.9% and 6.4%, respectively. In the western part of the watershed, with more uniform topography, the coefficient of variation for plot biomass is 25.3%, and those for Rn and Et are 3.1 and 2.4%, respectively. The correlation between the above ground biomass and Rn and Et is illustrated in Table 3.

The above data (Table 3) show a poor correlation between biomass and the two other parameters for single plots. However, the correlation coefficient increases with number of plots averaged, and it exceeds 0.8 for $n \geq 15$.

The average biomass for different ranges of azimuth is given in Table 4.

For the azimuth ranges 0 - 30°, 210 - 240°, and 240 - 270° only 3, 5, and 2 plots are available, respectively. Data for these azimuth ranges should not be regarded as representative. Sites with azimuth ranging from 90 to 120° have the highest average above ground biomass. For the azimuth values decreasing or increasing from this azimuth range the average above ground biomass decreases (Table 4).

Species found on the plots surveyed are listed in Table 5 together with the number of trees and air dry biomass for each species and the corresponding percentages of the totals. According to Table V, the most prevalent species in the watershed based on number of trees are Sugar maple (32.1%), Red maple (19.3%), American beech (9.7%), Northern red oak (7.6%), Black cherry (4.1%), Sweet birch (3.6%), Chestnut oak (2.4%), Downy serviceberry (2.4%), and Yellow-poplar (1.8%). Each of the remaining species accounts for less than 1.5% of the total. The following eight species account for 88.7% of the total biomass: northern red oak (30.2%), sugar maple (13.8%), black cherry (13.0%), red maple (9.9%), chestnut oak (6.9%), yellow-poplar (5.7%), American beech (4.7%), and white oak (4.5%).

Species frequency and stand composition vary with site azimuth. Some typical examples are listed in Table 6.

CONCLUSIONS

Future improvement in ecological forest management will depend on progress in understanding processes and interactions which take place in the forest. This particular study shows results of a three-dimensional analysis of topography, radiation exchange, and evapotranspiration in a forested watershed. This is probably the first attempt to calculate the distribution of evapotranspiration in a forested watershed. However, our results on Et should be verified in independent research, e.g., on isolated plots in the watershed. The distribution of the 39-year average yearly sum of Et was obtained under the assumption that for an "average year" Eq. (6) applies to all terrain segments, and that soil conditions and forest cover are uniform. Data on spatial distribution of soil horizon thicknesses, stoniness, organic matter content, and stand density (which could be described in the x, y, z - coordinate system) would allow modifications to Eq. (6) for specific terrain segments.

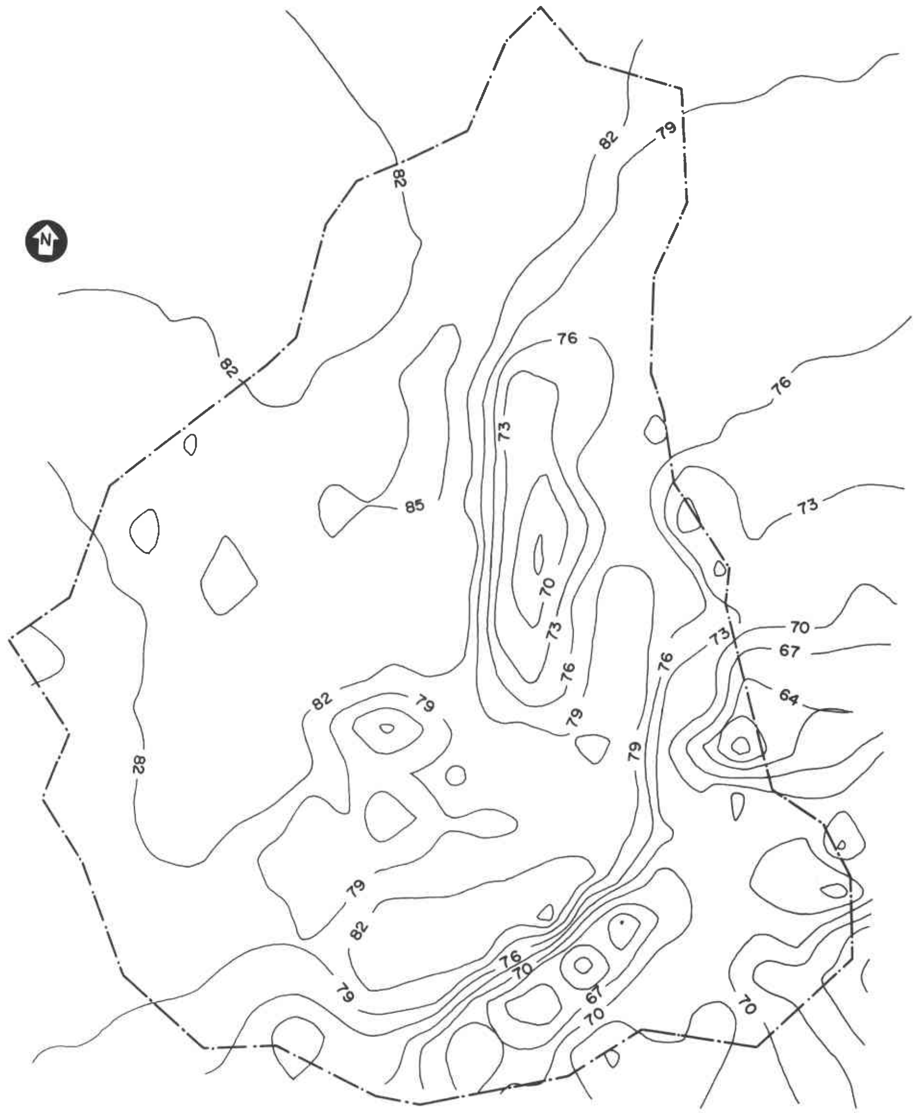

Figure 8. Distribution of the yearly sums of evapotranspiration (cm) (Fu, 1992).

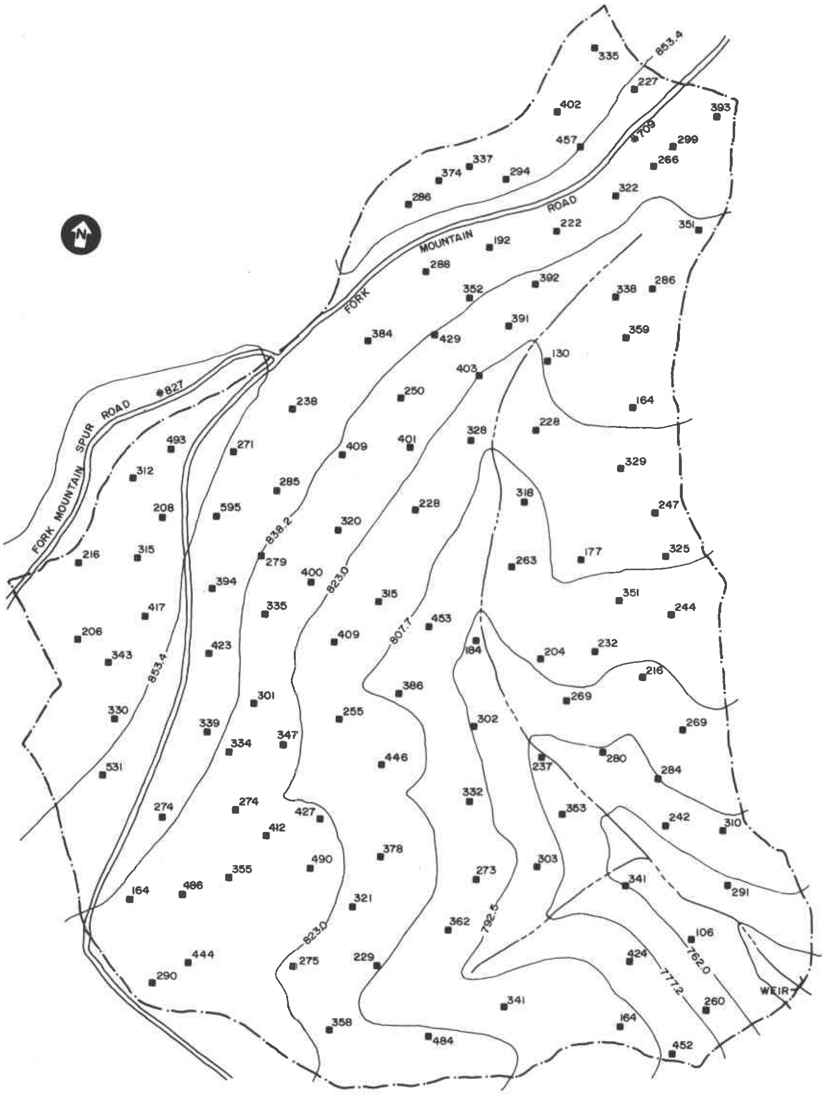

Figure 9. Above ground air-dry biomass at sampling plots.

Table 2. Species found in Watershed 4.

Common Name	Scientitic Name
Ailanthus	*Ailanthus Altissma* (Mill.) Swingle
American basswood	*Tilia Americana* L.
American beech	*Fagus grandifolia* Ehrh.
American chestnut	*Castanea dentata* (Marsh.) Borkh.
Bigtooth aspen	*Populus gradidentata* Michx.
Blackgum	*Nyssa sylvatica* Marsh.
Black locust	*Robinia Psudoacacia* L.
Cherry	
Black	*Prunus serotina* Ehrh.
Pin	*Prunus pensylvanica* L.f.
Cucumbertree	*Magnolia acuminata* L
Deciduous holly	*Ilex decidua* Walt.
Downy serviceberry	*Amelanchier arborea* (Michx. f.)Fern.
Flowering dogwood	*Cornus florida* L.
Fraser magnolia	*Magnolia fraseri* Walt.
Grapevine	*Vitis* L.
Hawthorn	*Crataegus* L.
Hickory	
Bitternut	*Carya cordiformis* (Wangenh.) K. Koch
Shagbark	*Cary ovata* (Mill.) K. Koch
Eastern hophornbeam	*Ostrya virginiana* (Mill.) K. Koch
Maple	
Mountain	*Acer spicatum* Lam.
Red	*Acer rubrum* L.
Striped	*Acer pensylvanicum* L.
Sugar	*Acer saccharum* Marsh.
Oak	
Black	*Quercus velutina* Lam.
Chestnut	*Quercus prinus* L.
Northern red	*Quercus rubra* L.
Scarlet	*Quercus coccinea* Muenchh.
White	*Quercus Alba* L.
Sassafras	*Sassafras albidum* (Nutt.) Nees.
Sourwood	*Oxydendron arboreum* (L.) DC.
Sweet birch	*Betula lenta* L.
White ash	*Fraxinus americana* L.
Witch hazel	*Hamamilis virginiana* L.
Yellow-poplar	*Liriodendron tulipifera* L.

Table 3. The correlation coefficient for above ground biomass, net radiation (Rn) and evapotranspiration (Et) for single plots and for different numbers of plots averaged.

	Biomass					
	Single plots	Number of plots averaged (n)				
		5	10	15	18	28
Rn	0.21	0.54	0.78	0.86	0.89	0.92
EIT	0.18	0.57	0.75	0.83	0.82	0.89

Table 4. Average above ground biomass in watershed 4 for azimuth ranges.

Azimuth (degrees)	Number of plots	Average biomass (t ha)
0 - 30	3	263.0
30 - 60	10	312.3
60 - 90	14	335.8
90 - 120	33	353.7
120 - 150	22	327.4
150 - 180	14	294.3
180 - 210	9	285.1
210 - 240	5	223.9
240 - 270	2	290.6

Table 6. Azimuth of maximum frequency for different species in watershed 4.

Northeast facing	East facing	South facing	Southwest facing
American beech	American basswood	Black gum	
Striped maple	Black cherry	Chestnut oak	
	Black locust	Downy serviceberry	
	Eastern hophornbean		
	Mountain maple		
	N. red oak		
	Sugar maple		Cucumber tree
	Sweet birch		Fraser magnolia
	White ash		White oak
	Witch hazel		
	Yellow-poplar		

Red maple has a relatively high frequency within the azimuth range of 80 - 200° .

Table 5. Species, number of trees with DBH > 5 cm, and the above ground air-dry biomass for 112 plots in watershed 4.

Species	Number of trees	Percent of total number of trees	Biomass t	Percent of total biomass
Bigtooth aspen	1	0.01	0.22	0.01
Bitternut hick.	6	0.09	2.44	0.08
Shagbark hick.	22	0.32	14.58	0.51
American hornbeam	5	0.07	0.05	0.00
East. hophornbeam	46	0.67	1.48	0.05
Sweet birch	246	3.59	72.56	2.50
American beech	662	9.67	135.73	4.67
American chestnut	11	0.16	0.76	0.03
White oak	70	1.02	131.96	4.54
Chestnut oak	165	2.41	200.40	6.90
North. red oak	518	7.56	876.92	30.19
Scarlet oak	10	0.15	13.18	0.45
Black oak	10	0.15	10.51	0.36
Cucumbertree	90	1.31	17.62	0.61
Fraser magolia	51	0.74	2.45	0.08
Yellow poplar	122	1.78	165.13	5.68
Sassafras	22	0.32	3.45	0.12
Downy serviceberry	164	2.39	4.22	0.14
Fire of pin cherry	2	0.03	0.58	0.02
Black cherry	283	4.13	376.77	12.97
Black locust	46	0.67	28.66	0.99
Ailanthus	1	0.01	0.03	0.00
Sugar maple	2200	32.13	399.62	13.76
Striped maple	231	3.37	1.39	0.05
Red maple	1319	19.26	287.31	9.89
Mountain maple	87	1.27	0.76	0.03
American basswood	79	1.15	18.85	0.65
Blackgum	98	1.43	33.41	1.15
Flowering dogwood	16	0.23	0.13	0.01
Sourwood	53	0.77	8.79	0.30
White ash	108	1.58	94.10	3.24
Grapevine	26	0.38	Not counted	
Hawthorn	1	0.01	0.01	0.00
Deciduous holly	8	0.12	0.01	0.00
Witch hazel	68	0.99	0.32	0.01
Total (All plots)	6848	100	2904	100

Results of this study suggest that at least 20 800 m^2 sampling plots are needed to obtain the average above ground biomass, representative for a large partial area of the watershed. The correlation between the above ground biomass, and Rn and Et is poor ($r \approx 0.2$) for single plots, increasing with the number of plots averaged, and for 18 plots it amounts to 0.89 for Rn and 0.82 for Et. Better correlations with the averaged plots area may be related to plot to plot variation in soil parameters (stoniness, thickness of A- and B-horizon) and in stand density (leaf area index).

The list of species identified in watershed 4 is similar to that for the Fernow Experimental Forest reported by Trimble (1973). Topography related variations of species frequency and above ground biomass in watershed 4 correspond more or less to those found in the Little Laurel Run catchment, West Virginia University Forest, near Coopers Rock, and elsewhere (Knight, 1980; Tajchman and Wiant, 1983; unpublished data). Because of the differences in sampling and reporting procedures and lack of information on stand development, a quantitative comparison of results from different reports would be difficult and would exceed the objectives of our study.

ACKNOWLEDGMENTS

This study was supported by McIntire-Stennis funds (P.L. 87-788) and by the Northeastern Forest Experiment Station at Parsons, West Virginia. Prof. C. Yuil gave assistance in digitizing the topographic data. Thanks are owed to Mrs. Gloria Nestor for preparation of diagrams and to Mr. John Campbell for his assistance in the field work.

This report was approved by the Director of the West Virginia Agricultural and Forestry Experiment Station as Scientific Paper No. 2483.

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