Throughfall for Summer Thunderstorms in a Juniper and Pinyon Woodland Cibecue Ridge, Arizona

GEOLOGICAL SURVEY PROFESSIONAL PAPER 485-B

Throughfall for Summer Thunderstorms in a Juniper and Pinyon Woodland Cibecue Ridge, Arizona

By M. R. COLLINGS

VEGETATION AND HYDROLOGIC PHENOMENA

GEOLOGICAL SURVEY PROFESSIONAL PAPER 485-B

The relation between throughfall, precipitation, stemflow, and interception is investigated and analyzed

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1966

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 20 cents (paper cover)

CONTENTS

ILLUSTRATIONS

TABLES

THROUGHFALL FOR SUMMER THUNDERSTORMS IN A JUNIPER AND PINYON WOODLAND CIBECUE RIDGE, ARIZONA

By M. R. Collings

ABSTRACT

To determine throughfall for summer thunderstorms in a juniper and pinyon woodland and to gain an understanding of the factors involved, a stratified random sampling experiment was conducted on Cibecue Ridge, Ariz. Forty-eight rain gages were used to measure throughfall. The strata, or variables, investigated were tree type, tree size, and direction and distance of the gage from the tree bole. Equations for curves of precipitation against throughfall were computed for each tree type used. Statistical analyses were used to test the variables investigated, and it was found that: (1) the throughfall for Utah juniper is the same as that for pinyon, (2) the amount of rainfall catch that the gage will receive is a function of the direction in which the gage is located in relation to the tree bole, (3) throughfall is not dependent on tree size (for the sizes tested), (4) the throughfall catch is a function of the distance that the gage is located from the tree bole in three of the five storm groups tested, (5) the combined effect of direction and distance from the tree bole causes a significant difference in throughfall catch for the storm groups tested, and (6) broad-leaved oaks in the study area have less throughfall than juniper and pinyon if precipitation is more than 0.08 inch.

The relation between throughfall (T), precipitation (P), stemflow (S), and interception (I) may be expressed as

$$T=P-S-I.$$

From this relation a curve of precipitation against interception was drawn. Interception increases in the initial stages of a storm, reaches a maximum at 0.50 inch of precipitation, and then becomes constant (assuming constant-intensity storms and excluding wind and evaporation effects).

INTRODUCTION

Cibecue Ridge is on the Fort Apache Indian Reservation in east-central Arizona and is at an altitude of 5,300 to 5,600 feet above mean sea level (fig. 1). The annual precipitation is about 19 inches, of which about 50 percent falls during the major runoff period July through September. In early and middle July, moist airmasses from the Gulf of Mexico are moved into Arizona by the western part of high-pressure systems moving over the southeastern coast of the United States. The moisture in these airmasses is precipitated mainly during convective-type thunderstorms. The

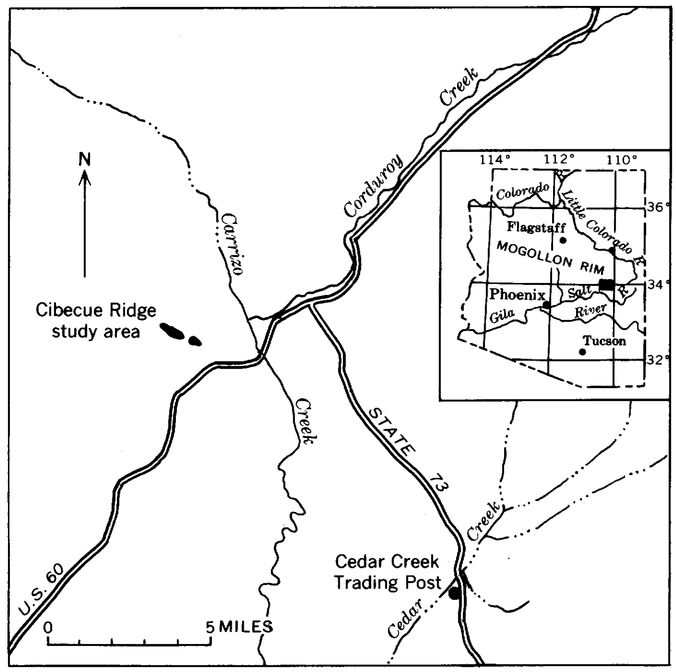

Figure 1.—Location of Cibecue Ridge, Ariz.

cumulonimbus clouds form above the Mogollon Rim, to the north and east of Cibecue Ridge, and then propagate over the area where rainfall occurs. Winter precipitation is received from polar continental and polar Pacific airmasses in the form of frontal-type storms. Winter precipitation is not considered in this report.

The most abundant tree types at this altitude on the reservation are Utah juniper *Juniperus osteosperma* (Torr.) Little and pinyon (*Pinus edulis* Engelm). The crowns of these trees cover about 50 percent of the Cibecue Ridge site.

Two small drainage basins, 63 and 42 acres in area, were selected on Cibecue Ridge for intensive study of the effects of juniper and pinyon removal on runoff. In general, the purpose of this investigation was (1) to study throughfall in a juniper and pinyon woodland on Cibecue Ridge and (2) to further understanding of the factors affecting the physical aspects of throughfall.

ACKNOWLEDGMENTS

F. A. Branson provided the basis for choosing tree species and tree sizes by his vegetation transect measurements. D. R. Dawdy and N. C. Matalas offered many helpful suggestions in their comprehensive reviews. Data were collected with the help of R. M. Myrick, who also critically reviewed the report.

PHYSICAL ASPECTS OF THROUGHFALL

The effect of vegetal cover intercepting and thus reducing the amount of precipitation reaching the ground (throughfall) is significant on Cibecue Ridge. Because interception is satisfied mainly from the first part of a rainstorm and because many storms produce less than 0.25 inch of precipitation—less precipitation than is required to reach the retention capacity of the vegetal cover—interception accounts for a substantial amount of the annual rainfall on Cibecue Ridge.

Interception may be considered a form of storage: raindrops from a storm are intercepted and stored on the surface of the vegetation until retention capacity is reached. When saturation or filling of the leaves has taken place, subsequent interception is close to nil. Wind and evaporation affect interception. Wind tends to keep the vegetation from becoming saturated and because of evaporation more rain is required before the leaves reach their saturation point. The measurement of evaporation during a storm is extremely difficult; however, in this study evaporation was considered to be a negligible factor during a storm event, and any errors introduced by ignoring evaporation are minor.

EXPERIMENTAL PROCEDURE

In the spring of 1963 a sampling experiment was devised to measure precipitation throughfall in a juniper and pinyon woodland. The experimental procedure consisted of stratified random sampling (table 1); the strata used were as follows:

- Tree types:
  - Utah juniper
  - Pinyon
  - Others[1]
- Tree sizes (diameter of bole, in inches):
  - 1–3
  - 3–10
  - >10
- Fraction of the distance of gage from tree bole to edge of crown cover:
  - ⅓ (distance A)
  - ⅔ (distance B)
  - ³⁄₃ (distance C)
  - ⁴⁄₃ (distance G; considered within throughfall area because of shadow effect of a tree (Penman, 1963, p. 9))
- Direction of gage in relation to tree bole:
  - North
  - East
  - South
  - West

[1] Trees other than juniper and pinyon were sampled (table 1) but were not included in the main part of the analysis because of their small percentage of areal cover.

The dominant tree type, the dominant size, and the percentage of areal cover occupied by each type were determined from 15 vegetation transects by F. A. Branson for the 63-acre drainage basin on Cibicue Ridge. From the vegetation transects a study was

TABLE 1.—*Location and arrangement of rain gages used to measure throughfall in the Cibecue Ridge area*

[Distance: A, ⅓ the distance from the tree bole to the edge of the crown cover; B, ⅔ the distance from the tree bole to the edge of the crown cover; C, at the edge of the crown cover; G, ¾, or ⅓, beyond the edge of cover. Direction: N, north; S, south; E, east; W, west]

Gage	Tree		Relation of gage to tree bole	
	Type	Size class (inches)	Direction	Distance
1	Juniper	>10	E	C
2	Arizona white oak	1–3	N	A
3	Juniper	1–3	E	A
4	Pinyon	1–3	W	G
5	Scrub oak	[1] Large	N	G
6	Juniper	1–3	N	G
7	do	1–3	N	C
8	Pinyon	1–3	W	C
9	do	1–3	S	G
10	Juniper	>10	N	B
11	Pinyon	1–3	S	A
12	do	1–3,	S	B
13	Scrub oak	[1] Large	N	A
14	Juniper	3–10	E	B
15	do	3–10	E	G
16	do	<1	E	B
17	do	3–10	N	G
18	Pinyon	1–3	E	C
19	Juniper	1–3	N	A
20	do	3–10	W	B
21	do	3–10	S	G
22	Manzanita		W	C
23	Pinyon	1–3	E	B
24	Arizona white oak	3–10	S	A
25	Manzanita		N	A
26	do		E	B
27	Juniper	3–10	W	G
28	do	3–10	S	B
29	do	1–3	S	C
30	Pinyon	<1	N	A
31	Arizona white oak	1–3	S	C
32	Juniper	>10	S	G
33	do	3–10	E	A
34	Pinyon	3–10	S	A
35	do	3–10	W	C
36	Juniper	3–10	W	A
37	do	3–10	N	A
38	Arizona white oak	3–10	W	B
39	Pinyon	1–3	W	A
40	do	3–10	N	B
41	do	1–3	E	G
42	do	1–3	N	B
43	do	3–10	E	C
44	do	>10	W	A
45	Scrub oak	[1] Medium	W	C
46	Juniper	1–3	W	B
47	do	3–10	S	C
48	Pinyon	3–10	N	C

[1] A large oak is >6 in. in diameter; a medium oak is 1 to 6 in. in diameter.

made of tree height, areal extent of crown cover, and tree volume in relation to the bole diameter of given types. The findings show that the bole diameters of the trees studied have nearly the same percentage relation to dominance within a given tree type with respect to the magnitude of tree height and volume and to percentage of areal cover. Therefore, tree diameters were used to place rain gages at localities where the most abundant size class occurred within a type group. On the basis of percentage of areal cover, an allotted number of rain gages was assigned each tree size within that type (table 1). The trees were picked at random within a predetermined 15-acre area of the 63-acre drainage basin.

Wedge-type rain gages were used to measure the throughfall. Two 8-inch standard rain gages were used to measure the total precipitation in the open, and a weighing-type recording gage was used to distinguish between the different storms by giving the storm time. Table 1 shows the number and relative location of the rain gages used to measure throughfall.

Storm events were recorded from July through September. Many small storm events were not used in the study because of inaccuracies introduced in measuring very small amounts of precipitation. All storms with throughfalls of zero or a trace of precipitation were omitted. Immediately after or very soon after a storm, the gages were read and emptied to minimize the error caused by evaporation and to insure that data were related to individual storm events. Olive oil was used in the gages to suppress evaporation. Storm intensities were not measured. The storms analyzed were all high-intensity summer thunderstorms.

DEFINITIONS AND ASSUMPTIONS

In this investigation all the analyses used to study throughfall are based on the assumption that the data are normally distributed. Common logarithmic transformations were used in parts of the analysis to reduce interactions or to more closely approximate the normal distribution and to stabilize the variance (Cramer, 1946, p. 397). The assumption of normality was tested by plotting on normal probability paper the cumulative probability distributions of the (1) log of juniper throughfall, (2) log of pinyon throughfall, and (3) log of total precipitation and the throughfall (not transformed) of juniper and pinyon trees combined for one storm group. The plotting position used was $(M-\frac{1}{2})/N$ (Hazen formula) where M is the order of magnitude and N is the number of events. On normal probability paper a normal distribution plots as a straight line. The normal distribution fits the data fairly well in the cases tested.

The data for individual storm groups were studied (table 3), and each group, when the data were plotted on probability distribution paper, approximated a normal distribution without the use of transformations. To evaluate interaction between variables, storms of about equal total precipitation (within measurable error) were grouped. Interaction is an estimate of variance used to test the differences between means that cannot be accounted for by shifts in, say for example, the means of tree size, direction, and distance. Zero interaction would be indicative of an additive model—that is, the effect of any one factor, say tree size, on throughfall is not related to magnitude of any other factor, say direction. However, additivity was accepted only because interaction was ruled out by the appropriate F test, both the F test and the assumption of additivity are invalid if significant interaction does exist. Thus, if interaction does exist and is not evaluated, it is treated as part of the error (within group) component, in which case the mean square ratios of the variables do not follow the F distribution used to test the variables (Brownlee, 1960, p. 373; Dixon and Massey, 1957, p. 166; Scheffe, 1961, p. 124).

ANALYSIS

Throughfall was related to storm precipitation for both juniper and pinyon, and the results are shown in figures 2 and 3. The equations for the curves in figures 2 and 3 are similar. A regression equation of the relation of juniper throughfall to pinyon throughfall was computed as

$$T_j=0.99\,T_p^{1.02}.$$

Neither the slope nor the intercept is significantly different from 1.0. Statistical analysis indicates no significant difference between juniper and pinyon throughfalls (table 2); one curve may best be used to describe the precipitation-throughfall relation for both tree types. The plot of total precipitation versus the throughfall for juniper and pinyon is shown in figure 4. The equation of the curve is

$$T=0.873P^{1.156}.$$

The standard error of estimate is +12.2 percent and −11.0 percent (0.049 log units) with a coefficient of correlation of 0.994. For a 1-inch rainfall, this standard error would give a range in throughfall from 0.78 to 0.98 inch.

The throughfall data (table 3) for both juniper and pinyon are used in an analysis to determine the effect of: (1) the storm event (the storms were grouped into size classes, each class having several throughfall events with the same total precipitation, as in table 3), (2) direction of gage from tree (table 1), (3) tree type (this

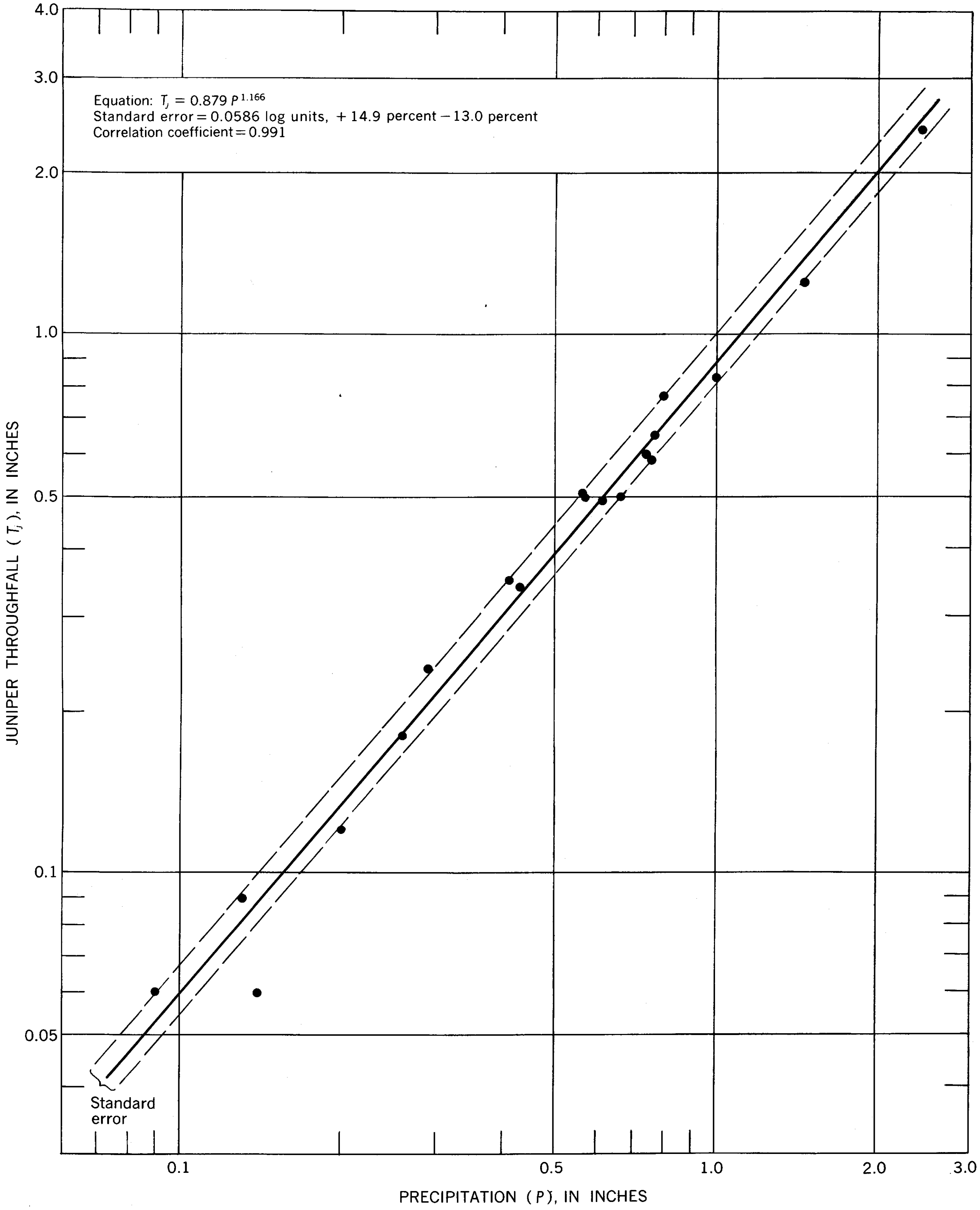

FIGURE 2.—Precipitation-throughfall relation for juniper.

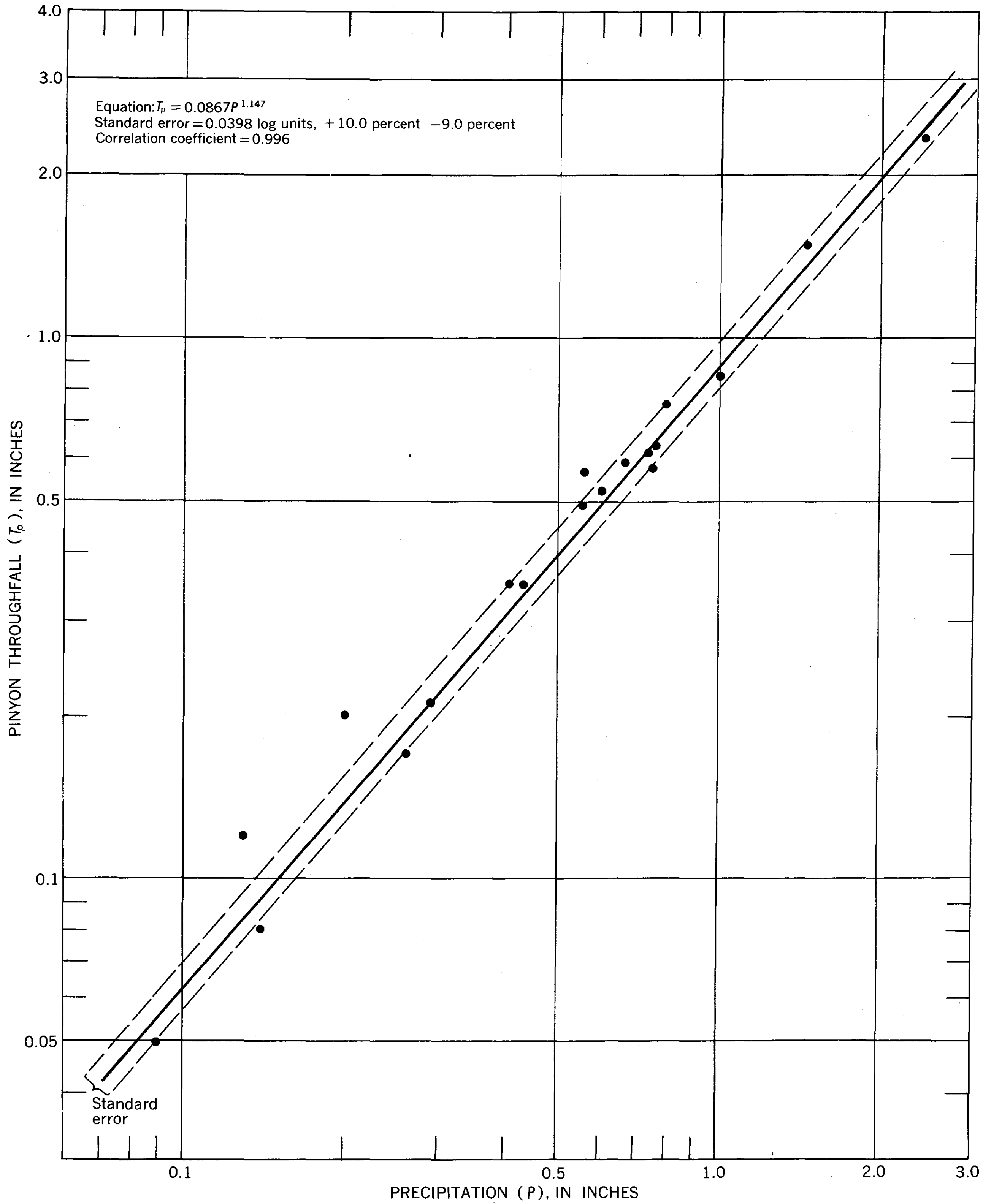

FIGURE 3.—Precipitation-throughfall relation for pinyon.

791-599 O—66——2

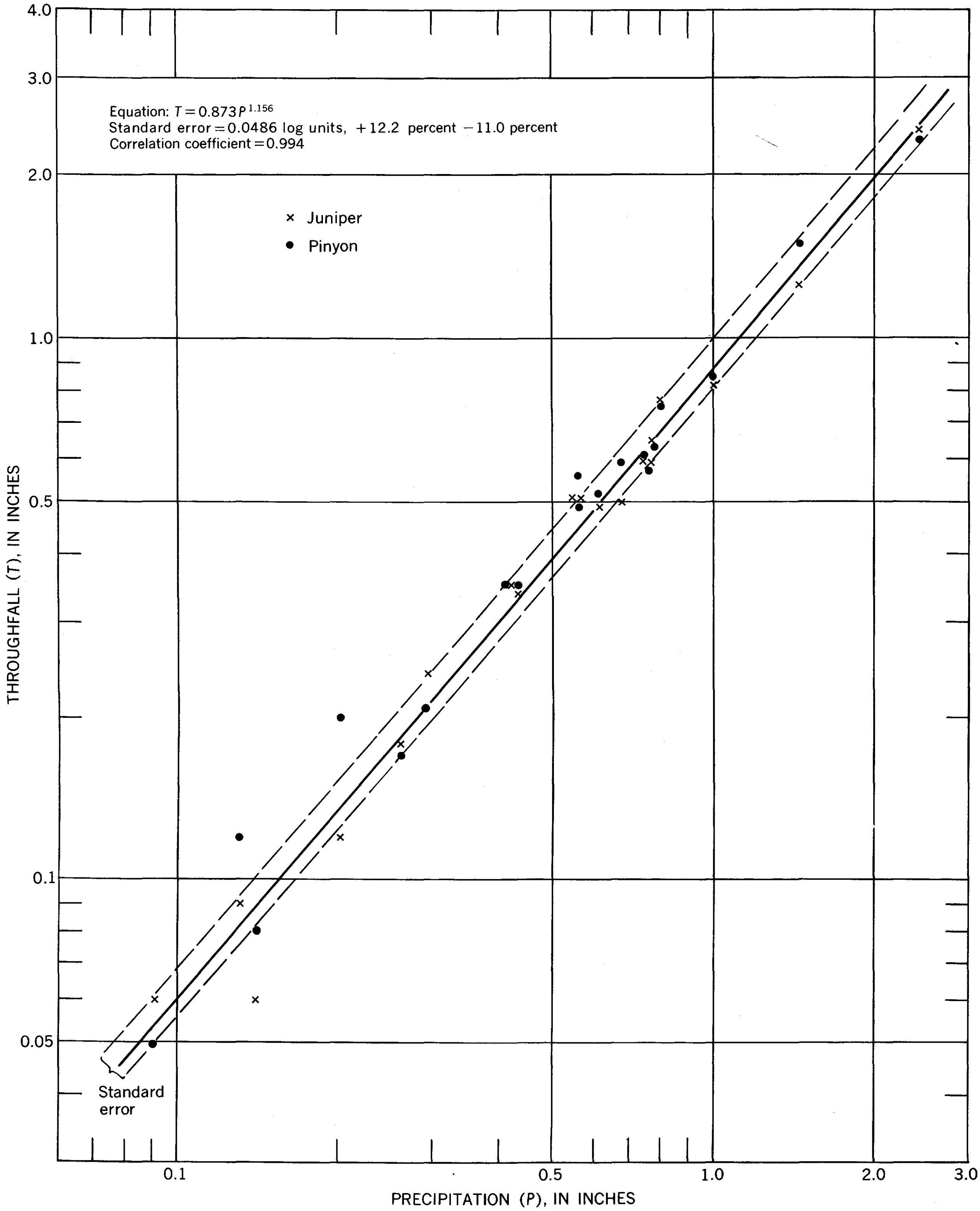

FIGURE 4.—Precipitation-throughfall relation for juniper and pinyon.

TABLE 2.—*Covariance analysis, test of the regressions of precipitation versus throughfall of juniper trees and of pinyon trees*

[P, precipitation; T, throughfall]

Source of variance	ΣP^2	ΣPT	ΣT^2	Sum of squares about regression line
Within each group:				
Juniper	2.44231	2.84778	3.37878	0.05822
Pinyon	2.44231	2.80069	3.23838	.02672
Among means	0	0	−.00010	−.00010
Within	4.88462	5.64847	6.61716	.08539
Total	4.88462	5.64847	6.61706	.08529

NOTE.—Tests:
For difference in means, $F=-0.04$ (not significant).
Whether one regression line can be used for all observations, $F=-0.07$ (not significant).

is another test to see if juniper and pinyon throughfall are different), (4) tree size (trees with boles 1–3 and 3–10 in. in diameter were tested), and (5) the distance that the rain gage is located from the tree bole (table 1).

Five groups of events (the 0.76-, 0.60-, 0.42-, 0.28-, and 0.12-in. storm groups) with replications were analyzed using a three-way analysis of variance (table 4). The mathematical model underlying the first three-way analysis of variance is

$$T_{ijkv}=\mu+E_i+D_j+t_k+(ED)_{ij}+(Et)_{ik}+(Dt)_{jk}+(EDt)_{ijk}+\epsilon_{ijkv}$$

where

T_{ijkv}=an individual throughfall measurement,
μ=a fixed value representing the general mean of the throughfall,
E_i=the random effect associated with storm event,
D_j=the fixed effect due to gage direction,
t_k=the fixed effect of tree type,
$(ED)_{ij}$, $(Et)_{ik}$, and $(Dt)_{jk}$=two-way interactions of indicated variables,
$(EDt)_{ijk}$=three-way interaction of indicated variables, and
ϵ_{ijkv}=random component or error term.

The analyses of the five storm groups are summarized in the upper part of table 4. Because E is a random effect and D and t are fixed effects, the F ratio was obtained by testing E, ED, Et, and EDt against the within-group mean square, D and t against ED and Et respectively, and Dt against interaction EDt (Scheffe, 1961, p. 274).

E was found to differ for small-storm groups but not enough to warrant concern. The errors introduced in measuring small storms become rather great percentagewise; for example, the component of variance ($\sigma_E{}^2$) was calculated for both the 0.28- and 0.12-inch storm events as 0.0009 and 0.0004 inch, respectively.

Because the analysis indicated that the events do not differ within the storm group, it may be assumed that the classification of storms into groups provides replication (more than one throughfall measurement for a given size storm) which may be used to define the sampling error for testing the other variables. This analysis showed further that the tree types did not differ more than would be expected by chance, and thus further indicated that the throughfall for juniper and pinyon trees is the same.

To investigate other variables and test the direction (D) by a more sensitive method, a second three-way analysis of variance was made on the five storm groups used in the upper part of table 4. The mathematical model used was

$$T_{ijkv}=\mu+D_i+Sd_{jk}+(DS)_{ij}+(Dd)_{ik}+(Sd)_{jk}+(DSd)_{ijk}+\epsilon_{ijkv}$$

where

T_{ijkv}=an individual throughfall measurement,
μ=a fixed value representing the general mean of the throughfall,
D_i=a fixed effect due to gage direction,
S_j=a fixed effect representing throughfall for different tree-bole diameters,
d_k=a fixed effect due to rain-gage distance from the tree bole,
$(DS)_{ij}$, $(Dd)_{ik}$, and $(Sd)_{jk}$=two-way interaction of variables,
$(DSd)_{ijk}$=three-way interaction of the variables, and
ϵ_{ijkv}=random component or error term.

The analyses for the 0.76-, 0.60-, 0.42-, 0.28, and 0.12-inch storm groups—using D, S, and d as variables—are summarized in the lower part of table 4. The three variables are fixed values and, therefore, were all tested using the error or within-groups mean square.

Statistical tests showed that (1) the amount of throughfall a gage catches is a function of the direction of the gage in relation to the tree bole, (2) the size of the tree bole (1–3 and 3–10 in. in diameter) was found not to affect the amount of throughfall from a given size storm, (3) the distance that the gage is located from the tree bole did not vary the throughfall catch more than would be expected by chance for the 0.76-inch storm group but did more strongly affect throughfall for the 0.60-, 0.28-, and 0.12-inch storm groups, and (4) the combined effect of direction and distance was

TABLE 3.—*Precipitation and throughfall data, in inches, for equal-size storm groups*

Precipitation over area		Throughfall at gages placed at tree type indicated											
		Juniper											
Group average	Total for individual storm	1	3	6	7	10	14	15	16	17	19	20	21
	0.74	0.43	0.54	0.62	0.60	0.64	0.85	0.77	0.50	0.75	0.66	0.40	0.72
0.76	.77	.78	.76	.86	.70	.79	.79	.15	.34	.76	.66	.56	.70
	.76	.36	.49	.50	.67	.56	1.18	.60	1.21	.78	.40	.25	.69
.60	.56	.39	.37	.48	.59	.50	.47	.60	.55	.63	.49	.47	.60
	.61	.36	.29	.47	.58	.62	.85	.53	.49	.61	.44	.34	.58
.42	.41	.38	.32	.38	.42	.40	.48	.37	.30	.42	.37	.20	.38
	.43	.20	.20	.26	.42	.34	.51	.39	.48	.45	.24	.15	.43
.28	.29	.14	.09	.26	.28	.21	.54	.24	.65	.29	.14	.04	.29
	.26	.11	.09	.20	.25	.17	.35	.21	.33	.25	.11	.04	.27
	.13	.07	.05	.14	.12	.08	.15	.08	.16	.15	.03	.03	.14
.12	.09	.03	.03	.06	.08	.05	.11	.06	.14	.09	.05	.03	.11
	.14	.03	.05	.07	.12	.07	.11	.10	.08	.13	.05	.01	.12
----------	2.42	1.98	1.75	1.85	1.77	2.05	1.86	2.19	3.06	2.49	3.01	3.35	2.10
----------	1.46	1.07	.88	1.25	1.35	1.43	1.28	1.37	1.07	1.52	1.12	1.05	1.47
----------	1.00	.59	.53	.81	.79	1.02	1.07	.76	.73	.95	.51	.68	.93
----------	.80	.60	.52	.70	.62	.82	1.14	.73	1.27	.86	.88	.80	.75
----------	.67	.34	.32	.48	.55	.49	.84	.50	.68	.70	.25	.30	.64
----------	.56	.39	.28	.38	.36	.40	.56	.54	.62	.54	.58	.66	.58
----------	.20	.06	.08	.14	.18	.11	.22	.16	.16	.22	.07	.04	.22

Precipitation over area		Throughfall at gages placed at tree type indicated														
		Juniper									Pinyon					
Group average	Total for individual storm	27	28	29	32	33	36	37	46	47	4	8	9	11	12	18
	0.74	0.45	0.68	0.51	0.50	0.55	0.73	0.75	0.57	0.46	0.33	0.55	0.73	0.39	0.49	0.90
0.76	.77	.38	.39	.51	1.35	.62	.75	.90	.61	.36	.32	.60	.68	.35	.44	.78
	.76	.38	.59	.85	.28	.32	.72	.65	.38	.47	.30	.48	.79	.53	.62	.55
.60	.56	.40	.52	.62	.60	.42	.55	.61	.46	.44	.35	.57	.59	.45	.43	.59
	.61	.34	.46	.54	.30	.27	.60	.68	.47	.39	.32	.45	.59	.39	.45	.72
.42	.41	.28	.20	.24	.37	.25	.41	.58	.36	.18	.20	.38	.40	.26	.23	.38
	.43	.27	.42	.47	.19	.22	.42	.56	.24	.32	.21	.34	.41	.38	.35	.44
.28	.29	.16	.22	.35	.08	.14	.26	.26	.13	.23	.15	.20	.29	.19	.21	.34
	.26	.16	.12	.15	.07	.11	.22	.22	.13	.17	.15	.16	.23	.16	.17	.27
	.13	.05	.08	.09	.01	.04	.14	.18	.10	.08	.11	.14	.14	.11	.10	.02
.12	.09	.03	.06	.06	.04	.03	.09	.06	.03	.04	.03	.03	.09	.06	.04	.05
	.14	.03	.02	.04	.01	.01	.14	.07	.06	.02	.05	.03	.15	.04	.08	.04
----------	2.42	2.15	2.77	3.00	3.44	2.71	1.91	3.10	1.51	2.36	1.75	2.30	2.11	2.18	2.00	3.26
----------	1.46	1.10	1.22	1.22	1.45	.94	1.46	1.92	1.16	.97	.74	1.40	1.35	.87	1.03	1.41
----------	1.00	.80	1.06	1.13	.35	.46	.96	1.48	.96	.90	.71	1.14	1.01	.75	.72	.93
----------	.80	.52	.69	.70	.74	.58	.82	1.08	.66	.70	.42	.78	.88	.60	.58	.87
----------	.67	.42	.52	.66	.20	.25	.67	.84	.49	.48	.50	.63	.70	.48	.62	.56
----------	.56	.44	.75	.70	.63	.54	.42	.64	.27	.44	.22	.40	.42	.39	.33	.78
----------	.20	.09	.12	.18	.04	.02	.21	.15	.10	.05	.18	.10	.21	.15	.16	.09

Precipitation over area		Throughfall at gages placed at tree type indicated										
		Pinyon										
Group average	Total for individual storm	23	30	34	35	39	40	41	42	43	44	48
	0.74	0.79	0.52	0.81	0.60	0.37	0.63	0.88	0.61	0.73	0.32	0.78
0.76	.77	.98	.37	.70	.51	.39	.62	1.27	.82	.76	.24	.83
	.76	.64	.44	.38	.65	.69	.71	.68	.59	.74	.25	.72
.60	.56	.59	.39	.54	.45	.31	.50	.63	.49	.53	.37	.54
	.61	.57	.45	.40	.62	.55	.61	.62	.54	.64	.21	.64
.42	.41	.36	.28	.26	.32	.24	.44	.63	.48	.47	.08	.51
	.43	.39	.29	.39	.40	.32	.43	.39	.26	.38	.16	.35
.28	.29	.26	.17	.11	.26	.19	.27	.25	.14	.26	.10	.23
	.26	.20	.16	.13	.24	.21	.16	.20	.11	.13	.10	.16
	.13	.08	.03	.02	.15	.07	.15	.18	.08	.18	.01	.09
.12	.09	.04	.03	.01	.08	.05	.07	.05	.05	.07	.01	.08
	.14	.20	.03	.01	.12	.07	.11	.09	.06	.11	.01	.10
----------	2.42	3.44	1.94	3.08	1.65	1.64	1.66	([1])	2.60	2.52	2.11	2.86
----------	1.46	1.42	1.16	1.32	1.34	1.14	1.24	1.50	1.13	1.30	.52	1.34
----------	1.00	.88	.70	.88	.95	.75	.93	1.20	.73	.97	.54	.71
----------	.80	1.06	.49	.93	.52	.57	.82	1.06	.86	.90	.40	.95
----------	.67	.61	.44	.85	.70	.56	.69	.72	.41	.68	.38	.50
----------	.56	.79	.38	.71	.31	.28	.31	.40	.43	.37	.22	.55
----------	.20	.11	.07	.04	.18	.12	.21	.13	.13	.18	.04	.14

Precipitation over area		Throughfall at gages placed at tree type indicated										Mean of throughfall			
		Oak							Manzanita bush						
		Arizona white				Scrub									
Group average	Total for individual storm	2	24	31	38	5	13	45	22	25	26	Juniper	Pinyon	Oak	Manzanita bush
	0.74	0.42	0.22	0.70	0.75	0.66	0.46	0.42	0.70	0.80	0.69	0.60	0.61	0.52	0.73
0.76	.77	.55	.20	.64	.90	.86	.54	.34	.74	.72	.47	.65	.63	.55	.64
	.76	.46	.22	.65	.66	.79	.39	.70	.65	.71	.64	.59	.57	.55	.67
.60	.56	.44	.30	.51	.45	.51	.31	.32	.60	.61	.51	.51	.49	.40	.57
	.61	.58	.21	.54	.60	.60	.44	.44	.54	.57	.50	.49	.52	.49	.54
.42	.41	.51	.11	.36	.50	.42	.30	.12	.40	.34	.26	.35	.35	.33	.33
	.43	.20	.26	.45	.32	.38	.22	.35	.22	.42	.45	.34	.35	.31	.42
.28	.29	.17	.07	.26	.20	.27	.08	.29	.23	.30	.24	.24	.21	.19	.26
	.26	.13	.08	.28	.17	.22	.12	.18	.30	.30	.26	.18	.17	.17	.27
	.13	.06	.04	.15	.06	.17	.05	.12	.15	.10	.11	.09	.10	.09	.12
.12	.09	.02	.05	.08	.07	.07	.04	.08	.09	11	.10	.06	.05	.06	.10
	.14	.05	.01	.11	.08	.12	.05	.09	.12	.13	.11	.06	.08	.07	.12
----------	2.42	2.03	1.09	1.72	2.00	1.85	1.74	1.70	2.07	2.10	2.00	2.40	2.32	1.71	2.06
----------	1.46	1.34	.58	1.38	1.18	1.44	1.06	.78	1.48	1.71	1.40	1.25	1.19	1.11	1.53
----------	1.00	.82	.39	.94	.83	.93	.64	.86	.97	.90	.86	.83	.85	.77	.91
----------	.80	.60	.47	.59	.93	.82	.50	.66	.70	.72	.73	.77	.75	.65	.72
----------	.67	.32	.28	.69	.50	.68	.38	.60	.66	.65	.64	.50	.59	.51	.65
----------	.56	.28	.30	.44	.48	.38	.30	.31	.54	.56	.50	.51	.43	.35	.53
----------	.20	.07	.06	.19	.12	.21	.08	.20	.20	.21	.20	.12	.13	.13	.20

[1] Gage washed out.

TABLE 4.—*Three-way analysis of variance*

[Asterisk indicates result is significant]

Source of variance	Sum of square for indicated storm groups					Degrees of freedom for indicated storm groups			Mean square for indicated storm groups					*F* ratio for indicated storm groups				
	0.76 in.	0.60 in.	0.42 in.	0.28 in.	0.12 in.	0.76 in.	0.60, 0.42 and 0.28 in.	0.12 in.	0.76 in.	0.60 in.	0.42 in.	0.28 in.	0.12 in.	0.76 in.	0.60 in.	0.42 in.	0.28 in.	0.12 in.
Variables: storm event (*E*), direction of gage (*D*), and tree type (*t*)																		
E	0.04089	0.00191	0.00002	0.03563	0.03063	2	1	2	0.02044	0.00191	0.00002	[1] 0.03563	[2] 0.01532	0.66	0.16	≈0	*5.46	*7.74
D	.66184	.07765	.10002	.03093	.00225	3	3	3	.22061	.02588	.03334	.01031	.00075	*9.20	3.82	1.01	3.68	1.50
t	.01870	.00544	.00620	.00008	.00107	1	1	1	.01870	.00544	.00620	.00008	.00107	10.05	.46	8.98	.23	.96
E × *D*	.14391	.02031	.09875	.00840	.00300	6	3	6	.02398	.00677	.03292	.00280	.00050	.77	.56	*3.57	.43	.25
E × *t*	.00373	.01183	.00069	.00035	.00222	2	1	2	.00186	.01183	.00069	.00035	.00111	.06	.98	.07	.05	.56
D × *t*	.17245	.07686	.02718	.02458	.00488	3	3	3	.05748	.02562	.00906	.00819	.00163	1.50	*14.81	2.44	5.28	2.33
E × *D* × *t*	.23049	.00519	.01115	.00465	.00420	6	3	6	.03842	.00173	.00372	.00155	.00070	1.24	.14	.40	.24	.35
Within (error)	2.23585	.58222	.44272	.31308	.14295	72	48	72	.03105	.01213	.00922	.00652	.00198					
Total	3.50786	.78141	.68671	.41770	.19120	95	63	95										
Variables: direction of gage (*D*), size of tree (*S*), and distance of gage from tree bole (*d*)																		
D	0.76464	0.10742	0.12833	0.03097	0.00714	3	3	3	0.25488	0.03581	0.04278	0.02032	0.00238	*11.82	*5.61	*6.94	*4.32	1.86
S	.00735	.01155	.01182	.00360	.00150	1	1	1	.00735	.01155	.01182	.00360	.00150	.34	1.81	1.92	1.51	1.17
d	.03791	.07952	.01560	.04484	.01324	3	3	3	.01264	.02651	.00520	.01495	.00441	.59	*4.16	.84	*6.25	*3.44
D × *S*	.13780	.03212	.01823	.01193	.00962	3	3	3	.04593	.01071	.00608	.00398	.00321	2.13	1.68	.99	1.66	2.51
D × *d*	.68044	.27595	.12946	.16257	.04841	9	9	9	.07560	.03066	.01438	.01806	.00538	*3.51	*4.80	*2.33	*7.56	*4.20
S × *d*	.13563	.04212	.02824	.01809	.00327	3	3	3	.04521	.01404	.00941	.00603	.01109	2.10	2.20	1.53	2.52	.85
D × *S* × *d*	.32762	.04346	.16184	.07478	.02715	9	9	9	.03640	.00483	.01798	.00831	.00302	1.69	.76	*2.92	*3.48	*2.36
Within (error)	1.37967	.20430	.19715	.07640	.08213	64	32	64	.02156	.00638	.00616	.00239	.00128					
Total	3.47106	.79644	.69067	.42318	.19246	95	63	95										

[1] An estimate of the mean square for *E* component of variance is $\sigma^2+4\cdot4\cdot2\sigma^2_E$, or $\sigma^2_E=0.00091$ and $\sigma_E=0.0302$.

[2] An estimate of the mean square for *E* component of variance is $\sigma^2+4\cdot4\cdot2\sigma^2_E$ or $\sigma^2_E=0.00042$ and $\sigma_E=0.0205$.

found to cause a significant variation of throughfall in the five storm groups tested.

The effect of direction on throughfall in the Cibecue Ridge area may be explained as follows: (1) the summer-thunderstorm clouds have a tendency to form above the Mogollon Rim, to the north and east of Cibecue Ridge, and to propagate over the area where rainfall occurs and (2) the tree foliage may be thicker in one direction than in the others. Local areas of throughfall concentration were attributed by Horton (1919) to the variation in density of the foliage.

Having determined that direction, distance, and the combined effect of direction and distance have a significant effect on throughfall, the next step is to compare and test for the elements of direction and of distance that are causing the difference in the catch of throughfall gages. This is accomplished by using appropriate orthogonal (independent) contrasts and statistical tests. All contrasts were tested against the error or the within-group mean square of the three-way analysis of variance used for a particular storm group. The coefficients of each set of contrasts define orthogonal contrasts because the sum of each contrast is equal to zero and the sum of the products of the three contrasts is equal to zero. The sum of squares for each contrast in any storm group added together equals the unpartitioned sum of squares for the variable used in the three-way analysis of variance (table 4, lower part). Thus, the error in mean square for a given storm group may be used for the F test.

Three contrasts for each of four storm groups using direction as the significant variable and for each of three storm groups using distance as the significant variable were considered. (See table 5.) The direction contrasts (table 5, upper part) indicate that: (1) the north side of the tree does not have more variance in throughfall than the east side, (2) the south side has significantly less throughfall than the north and east sides of the tree for the 0.42-inch storm group, but not for the 0.76-, 0.60-, and 0.28-inch storm groups, and (3) the west side has throughfall significantly different from that of the north, east, and south sides. The distance contrasts (table 5, lower part) indicate that: (1) the two gages nearest the tree bole do not have significantly different throughfall, (2) the gage at the edge of the tree receives throughfall which is significantly different for the 0.60-inch and 0.28-inch storm groups and not significantly different for the 0.12-inch storm group when compared with the throughfall received by the two gages nearest the tree bole, and (3) the gage at G distance has a greater difference in throughfall than would be expected for the 0.28- and 0.12-inch storm groups when compared with throughfall at the A, B, and C distances.

The distance contrasts indicate that the amount of

TABLE 5.—*Orthogonal contrasts of significant variables*
[× indicates significant result]

Situation described in text	Contrasts for indicated direction of gage				Result of $F_{0.95}$ test on indicated storm group, in inches			
	North	East	South	West	0.76	0.60	0.42	0.28
1	1	−1	0	0	--------	--------	--------	--------
2	1	1	−2	0	×	×	×	--------
3	1	1	1	−3	×	×	×	×
	Contrasts for indicated distance from tree bole							
	A	B	C	G	0.60	0.28	0.12	
1	1	−1	0	0	--------	--------	--------	
2	1	1	−2	0	×	×	--------	
3	1	1	1	−3	--------	×	×	

throughfall received by a gage at distance C is significantly different from that received by gages at distances A and B for the larger storm groups tested. It may be that during the 0.12-inch storms a gage at distance C received a drip that did not cause a significant variation in throughfall; however, during the 0.28- and 0.60-inch storms the leaf capacity was filled and drip added a significant amount of throughfall. A gage at G distance would be subjected to greater wind currents; if wind currents increase catch, then the smaller storms, which would logically occur over a shorter time period (assuming that all summer storms have fairly uniform intensities), would have more chance for significantly different throughfall.

The same contrasts used to compare the elements of direction and distance were used to compare the elements of the two-way interaction, direction times distance. The 0.76-inch storm group was investigated by partitioning of the sum of squares for the inter-action into orthogonal contrasts for the given storm group.

The orthogonal contrasts of the combined effect of direction and distance indicate that the gage nearest to the tree bole on the east side and the gage at distance G on the north side receive throughfall amounts that are significantly different from those received at gages located at other combinations of distance and direction.

The effects of direction and distance on throughfall are confirmed by Stout and McMahon (1961) who found that there is a significant difference in throughfall with respect to distance and direction from the tree bole and by Beall (1934) who noted that throughfall is less near the bole than near the edge of the crown cover.

Woody plants other than Utah juniper and pinyon were sampled (table 1) for amount of throughfall received. Curves showing the relation of precipitation to throughfall for oak tree and manzanita bush are shown in figure 5. The equation for the precipitation (P) versus oak-tree throughfall (T_o) is

$$T_o = 0.744P^{1.072}$$

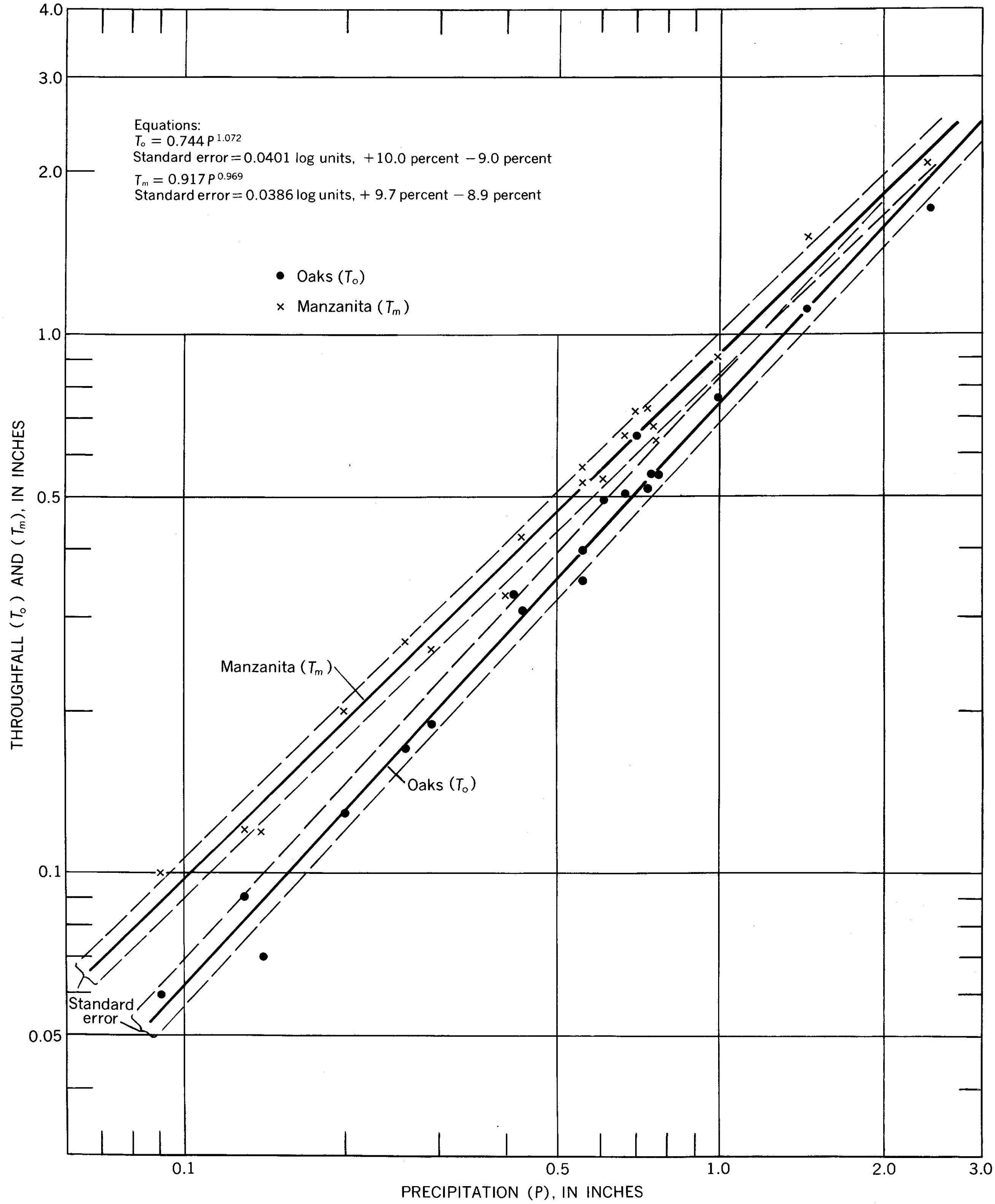

FIGURE 5.—Precipitation-throughfall relation for oak trees and manzanita bushes.

with a standard error of estimate of +10.0 percent and −9.0 percent (0.0401 log units). The broad-leaved oak trees permit less throughfall (0.74 in.) for a 1-inch storm than the needle-leaf juniper and pinyon trees (0.87 in.). Coffay (1962) found the equation for broad-leaved species to be

$$T=0.834P^{1.046}$$

with a standard error of about +19 percent and −16 percent. The equation for the precipitation (P) versus manzanita-bush throughfall (T_m) is

$$T_m=0.917P^{0.969}$$

with a standard error of +9.7 percent and −8.9 percent (0.0386 log units). The curve for precipitation versus manzanita-bush throughfall probably is influenced by precipitation ground splash. All the gages used to measure manzanita-bush throughfall were 18 inches from the ground to enable placement of the gages below the leafy part of the bush.

RELATION OF THROUGHFALL, STEMFLOW, INTERCEPTION, AND PRECIPITATION

The relation between throughfall (T), stemflow (S), interception (I), and precipitation (P) may be shown by the equation

$$T=P-S-I.$$

The amount of throughfall is equal to the amount of precipitation minus the quantity of water which reaches the ground by running down the stem of the tree minus the amount of the precipitation stopped by the leaves of the tree.

Stemflow was measured on nine trees, six Utah junipers and three pinyons, ranging in diameter from 0.30 feet to 1.3 feet. Stemflow increases slightly with decreasing tree diameter. The stemflow of a tree having a 4-inch bole diameter is used to show the relation between throughfall, stemflow, and interception, as follows:

The relation of precipitation to stemflow was found to be

$$S=0.09P^{1.25}.$$

The equation for the precipitation-throughfall relation was found to be

$$T=0.87P^{1.16}.$$

By substitution, the relation between precipitation and interception is

$$0.87P^{1.16}=P-0.09P^{1.25}-I.$$

By rearranging terms, the equation becomes

$$I=P-0.09P^{1.25}-0.87P^{1.16}.$$

Figure 6 graphs the preceding equation and shows that interception increases rapidly in the first part of a storm and reaches a maximum (0.072-in.) after 0.50-inch of precipitation. The mathematical curve can continue until negative interception is indicated. However, each constant is subject to error, and is defined only over the range of precipitation used. Therefore, the derived equation has a mean-square deviation of sample points from the estimated regression line at least equal to the sum of the mean-square deviations of each of the component equations. None of the curves of these equations may be extrapolated, for each would result in conclusions such as throughfall and stemflow being greater than precipitation or negative interception. Theoretically, after the leaves have become filled and precipitation increases, it is not unreasonable for the curve to approach a constant limiting value of I (Penman, 1963, p. 14); interception would be zero for the remainder of the storm. The dashed line on figure 6 is an estimate of uniform conditions. The relation would be expected to vary in the late stages of a storm because of climatic forces such as wind.

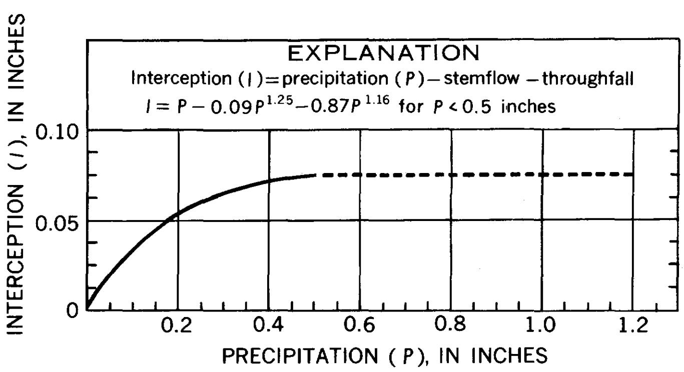

FIGURE 6.—Relation between precipitation and interception.

CONCLUSIONS

1. The summer-storm throughfall for juniper does not vary from that of pinyon on the Cibecue Ridge study area. The equation for throughfall in a juniper-pinyon woodland is

$$T=0.873P^{1.156}$$

where (T) is throughfall and (P) is precipitation, in inches.

2. The amount of throughfall the gage catches is a function of the direction in which the gage is located. It was found that throughfall in the Cibecue Ridge study area is greater on the north and east sides of the tree because (1) the summer storms have a greater frequency of moving in from the north and east and (2) the foliage may be thicker on one side of the tree than on the other.

3. The tree sizes tested (1–3 and 3–10 in. in diameter) do not vary in throughfall more than would be expected by chance. Of the five storm groups tested, none show a significantly different throughfall for different tree sizes.
4. For gages located at four different distances from the tree bole, it was found that the throughfall differed in three of the five storm groups tested. For the storms that showed a variation in throughfall with distance from the tree bole, it was found that: (1) the two gages nearest the tree trunk have similar throughfall, (2) the gage at the edge of crown cover received different throughfall for the two largest storms tested but not for the smallest storm, and (3) the gage farthest from the tree bole has significantly more throughfall for the two smallest storms tested but not for the largest storm.
5. The combined effect of direction and distance from the tree bole causes a significant difference in throughfall catch for all storm groups tested. The gages nearest the tree bole on the east side and farthest from the tree bole on the north side receive throughfall amounts that are significantly different from those received at gages located at other combinations of distance and direction.
6. Broad-leaved oaks were sampled for throughfall on Cibecue Ridge and were found to have less throughfall than juniper and pinyon during large storms.
7. Interception increases in the initial stages of a storm. It was assumed that as precipitation increases, interception approaches a constant value that will vary depending on climatic forces such as wind.
8. The results of this investigation substantiate the findings of Stout and McMahon (1961) and Beall (1934): that throughfall under a tree varies with direction and distance from the tree bole.

SELECTED BIBLIOGRAPHY

Beall, H. W., 1934, The penetration of rainfall through hardwood and soft wood canopy: Ecology, v. 15, p. 412–415.

Brownlee, K. A., 1960, Statistical theory and methodology in science and engineering: New York, John Wiley & Sons, Inc., 570 p.

Cochran, W. G., 1953, Sampling techniques: New York, John Wiley & Sons, Inc., p. 87–109.

Coffay, E. W., 1962, Throughfall in a forest: Bull. International Association of Scientific Hydrology, v. 7, no. 2, p. 10–16.

Cramer, Harald, 1946, Mathematical methods of statistics: Princeton, N.J., Princeton Univ. Press, 575 p.

Dixon, W. J., and Massey, F. J., Jr., 1957, Introduction to statistical analysis: New York, McGraw-Hill Book Co., 488 p.

Hoover, M. D., 1953, Interception of rainfall in a young loblolly pine plantation: Southeast Forest Exp. Sta. Paper 21.

Horton, R. E., 1919, Rainfall interception: Monthly Weather Rev., v. 47, p. 603–623.

Huff, F. A., 1955, Comparison between standard and small orifice rain gages: Trans. Am. Geophys. Union, v. 36, p. 689–694.

Kittredge, J., 1948, Forest influences: New York, McGraw-Hill Book Co., 394 p.

Mitchell, J. A., 1930, Interception of rainfall by the forest: Jr. Forestry, v. 28, p. 101–102.

Ovington, J. D., 1954, A comparison of rainfall in different woodlands: Forestry, v. 24, p. 41–53.

Penman, H. L., 1963, Vegetation and hydrology: Technical Communication No. 53, Commonwealth Bureau of Soils, Harpenden, 111 p.

Rowe, P. B., and Hendrix, T. M., 1951, Interception of rain and snow by second-growth ponderosa pine: Trans. Am. Geophys. Union, v. 32, p. 903–908.

Scheffe, Henry, 1961, The analysis of variance: New York, John Wiley & Sons, Inc., 455 p.

Snedecor, G. W., 1946, Statistical methods: Iowa City, Iowa State College Press, 476 p.

Stout, B. B., and McMahon, R. J., 1961, Throughfall variation under tree crowns: Jour. Geophysical Research, v. 66, no. 6, p. 1839–1843.

Trimble, G. R., Jr., and Weitzman, S., 1954, Effect of a hardwood forest canopy on rainfall intensities: Trans. Am. Geophys. Union, v. 35, p. 226–234.

Voigt, G. K., 1960, Distribution of rainfall under forest stands: Forest Science, v. 6, p. 2–10.

Wood, O. M., 1937, The interception of precipitation in an oak-pine forest: Ecology, v. 18, p. 251–254.