FREQUENCY DISTRIBUTIONS FOR DURATIONS AND VOLUMES OF RAINFALLS IN THE EASTERN UNITED STATES IN RELATION TO ACIDIC PRECIPITATION

LANCE S. EVANS

Laboratory of Plant Morphogenesis, Manhattan College, The Bronx, NY 10471, U.S.A.
Terrestrial and Aquatic Ecology Division, Department of Applied Science, Brookhaven National Laboratory, Upton, NY 11973, U.S.A.

GILBERT S. RAYNOR

Atmospheric Sciences Division, Department of Applied Science, Brookhaven National Laboratory, Upton, NY 11973, U.S.A.

and

DOUGLAS M. A. JONES

State Water Survey Division, Illinois Institute of Natural Resources, Champaign, IL 61820, U.S.A.

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Abstract. A significant percentage (between 17 and 40%) of all showers recorded on Long Island, NY, Urbana, IL, Franklin, NC, and Seaside Park, NJ, had durations less than 20 min. Similarly, a large percentage had durations less than 40 min (50, 46, and 32% for 3 yr at Urbana, IL, 65% at Coral Gables, FL, 50% at Franklin, NC, and 54% at Seaside Park, NJ). When all data from the six growing seasons were pooled, over 88% of all rainfalls were less than 160 min. Similar results were observed when volume measurements were made. Between 38 and 57% of all recorded showers had less than 1 mm at all five stations in the eastern United States. When all data were pooled, over 65% of all rainfalls were less than 3 mm. These data demonstrate that plant foliage is wetted during the growing season by numerous showers which are of short duration and low volume.

1. Introduction

Acidic precipitation, wet or frozen deposition with a H^+ concentration greater than 2.5 μeq L^{-1}, is an effect of air pollution in the United States and Canada. The dominant anions accounting for the H^+ in rainfall are sulfate and nitrate. Data from the National Atmospheric Deposition Program taken in 1978–79 show that the median pH of precipitation in some areas of Pennsylvania, Ohio, and New York was below 4.2. In

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addition, in most of the northeastern United States the median pH was below 4.4 (NADP, 1979; 1980a, b).

During the two plant growing seasons of 1979 and 1980 precipitation data recorded at Brookhaven National Laboratory, New York, show that most showers were of short duration and small amounts. During the 1980 growing season, 50% of all showers lasted less than 1 hr, and over 25% were shorter than 30 min. Over 50% had amounts below 0.3 mm and most events occurred at rates below 1.5 mm hr^{-1}. Only 12.5% of all showers had rates greater than 3.5 mm hr^{-1} (Evans *et al.*, 1982).

Effects of acidic precipitation on soils and watersheds may be related to total acid deposition and not to H^+ concentrations during single or over many events. In contrast, effects of acidic precipitation on plant foliage may be related more to H^+ concentrations than to total H^+ deposition. Evidence for a concentration dependence is supported by a linear relationship between percent leaf area injured and H^+ ion concentration of simulated rainfalls (Evans, 1982).

Because foliar injury may result from ambient rainfalls and the amount of foliar injury may depend upon the duration of simulated rainfalls (Jacobson and Van Leuken, 1977), experimental data were evaluated to determine the durations and volume of ambient rainfalls at several sites in the eastern United States. Better knowledge of the chemical and physical characteristics of ambient rainfall will help researchers construct protocols to apply simulated rainfall for vegetation that more closely mimick ambient wet deposition.

2. Materials and Methods

During the crop growing season precipitation was evaluated for the following five sites:

Station 1: Urbana, Illinois, from 1 May through 30 September for the years 1969, 1970, and 1971.

Station 2: Coral Gables, Florida, from 7 August through 30 September, 1957 and 1 May through 19 August, 1958.

Station 3: Coweeta Hydrologic Laboratory near Franklin, North Carolina, from 1 May through 30 September, 1961.

Station 4: Island Beach State Park near Seaside Park, New Jersey, from 24 May through 30 September, 1961 and 1 May through 24 May, 1962.

Station 5: Brookhaven National Laboratory, Upton, New York, from 1 May through 29 September 1981.

Data from stations 1 through 4 were obtained from computer data tapes originally used to characterize radionuclide fallout in wet deposition during nuclear tests. All data tapes covered a 1-yr period but data from 1 May through 30 September were selected to characterize the crop growing season.

For stations 1 through 4 a weighing bucket rain gauge (32.13 cm in diameter) was used. Precipitation rates of 0.0042 mm min^{-1}, equivalent to 0.25 mm hr^{-1}, were recorded on a minute-by-minute basis. Precipitation of less than 0.0042 mm (the threshold) during a 1-min interval was scored as 'no rain'.

For station 5, the methods used to characterize precipitation chemistry have been described (Raynor and McNeil, 1979; Raynor and Hayes, 1978, 1979). Frequency distributions of ambient shower durations and volumes were derived from a rotary rain indicator (Raynor, 1955) and a tipping bucket gauge, respectively. A rotary rain indicator records all precipitation events except light drizzle, fog, and dew. Data from the tipping bucket gauge coupled with that of the rotary rain indicator provide precipitation amounts with a time resolution of less than 1 min. For all stations, a shower is defined as a wet precipitation event separated from all other wet precipitation by 60 min (Evans *et al.*, 1982). To determine if the data used in this study were unusual for the individual regions, amounts of precipitation on a monthly basis for the five stations were compared with data from the closest NOAA stations for which 20-yr means are available (NOAA, 1982).

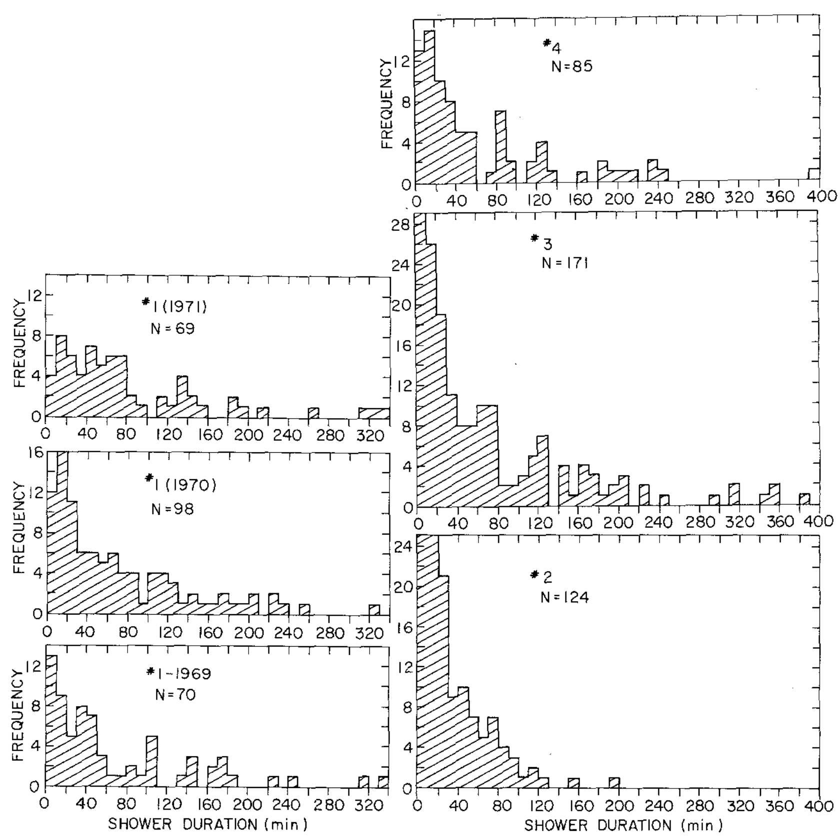

Fig. 1. Frequency distribution of ambient rainfall shower durations (min) for stations 1 through 4. N values denote the total number of showers per station. For station 1 (1969) one shower of 1080 min is not shown. For station 1 (1971) showers of 532 and 567 min are not shown. For station 2 showers of 510 and 610 min are not shown. For station 3 of 415, 435, and 1238 min are not shown. For station 4 showers of 437 and 679 min are not shown.

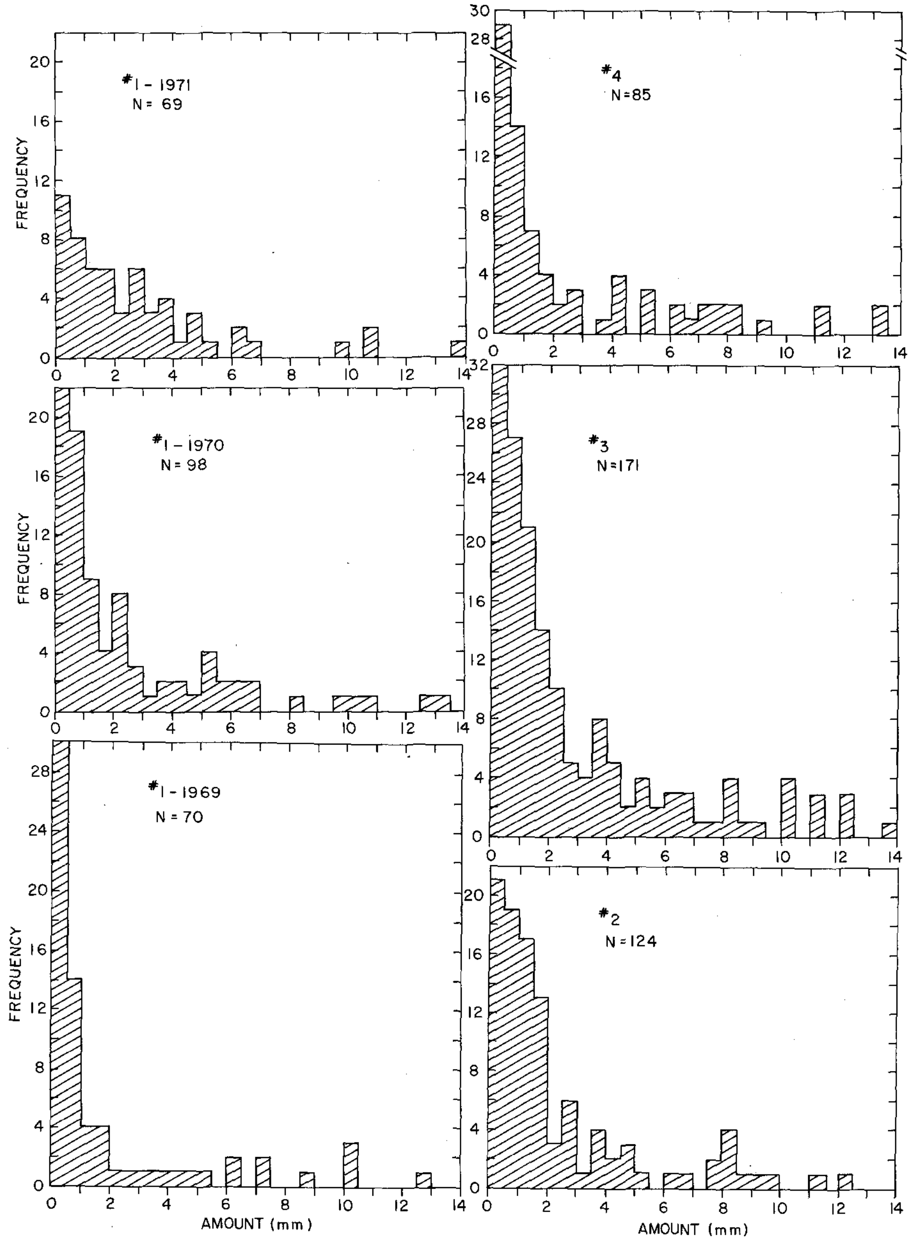

Fig. 2. Frequency distribution of ambient rainfall shower amounts (mm) for stations 1 through 4. N values denote the total number of showers per station. For station 1 (1969) showers of 15.6, 16.1, 20.4, 22.0, 45.0, and 72.3 mm are not shown. For station 2 (1970) showers of 19.7, 20.3, 20.9, 21.2, 24.5, 24.9, 27.9, 34.6, 46.1, 47.5, and 57.6 mm are not shown. For station 1 (1970) showers of 15.1, 15.2, 15.2, 16.0, 17.1, 20.2, 20.2, 20.2, and 25.0 mm are not shown. For station 2 showers of 14.1, 14.3, 14.4, 14.7, 15.0, 15.0, 15.8, 16.1, 18.8, 20.3, 20.6, 21.8, 23.5, 23.7, 25.6, 27.3, 31.6, 50.3, 58.6, and 69.5 mm are not shown. For station 3 showers of 15.2, 15.4, 15.4, 16.6, 17.5, 18.6, 20.2, 21.2, 25.6, 25.9, and 104.2 mm are not shown. For station 4 showers of 16.2, 17.7, 20.5, and 24.2 mm are not shown.

3. Results

Data in Figures 1 and 2 illustrate duration and amount of precipitation, respectively, for the Illinois, Florida, North Carolina, and New Jersey sites. A significant percentage (between 17 and 40%) of all showers recorded at stations 1 through 4 had durations less than 20 min (Figure 1). Similarly, a large percentage had durations less than 40 min (50, 46, and 32% for the 3 yr studied at station 1; 65% at station 2; 50% at station 3; and 54% at station 4). When all data from the six growing seasons were pooled, over 88% of all rainfalls were less than 160 min.

A significant percentage (between 38 and 57%) of all recorded showers had amounts less than 1 mm at stations 1 through 4 (Figure 2). Similarly, a large percentage had amounts less than 2 mm (69,55, and 45% at station 1; 56% at station 2; 55 at station 3; and 64% at station 4). When all data from the six growing seasons were pooled over 65% of all rainfalls were less than 3 mm in amount.

Precipitation events at Upton, New York, have been classified by many physical and chemical characteristics (Raynor and Hayes, 1981, 1982a, b). Experimental results of the tipping bucket gauge and rotary rain indicator show that most showers lasted less than 60 min (Figure 3) and produced less than 0.3 mm of rainfall (Figure 4). Most showers had rates below 1.5 mm hr^{-1} and only 12.5% of all showers, greater than 1 min in duration, had rates greater than 3.5 mm hr^{-1}. During the sampling period there were 48 other showers of less than 1 min and less than 0.25 mm of rainfall. These 48 momentary showers are not included in Figures 3 or 4, but field observations have demonstrated that plant foliage was wetted by these showers.

Precipitation amounts on a monthly basis for the five stations for the time period with data were compared to long-term means derived from National Oceanic and Atmospheric Administration data (NOAA, 1982). For station 1, years with data show close similarity to the mean monthly amounts (Table I). Data from station 2 for the 2 yr

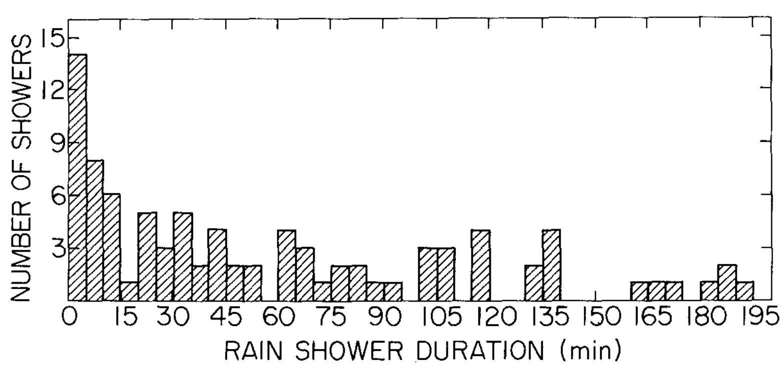

Fig. 3. Frequency distribution of ambient rainfall shower durations from the period of 30 May through 29 September, 1981 at Brookhaven National Laboratory, Upton, Long Island, New York. A shower is defined as a precipitation event in which no additional precipitation occurs within 60 min after the end of the event. Other rainfall showers of 215, 240, 263, 307, 320, 366, 367, 434, 482, 932, and 975 min were not plotted. These higher-duration rainfalls accounted for 11.0% of all showers. During the growing season there were 48 other showers with a duration of less than one minute with less than 0.25 mm of rainfall per shower. These showers are not included in this figure.

TABLE I

Comparison between amounts of precipitation on a monthly basis in relation to long-term means

Station number	Year	Month	Amount of precipitation (cm)	Mean amount or precipitation (cm)	Deviation from mean (cm)
Station 1	1969	May	4.34	10.7	−6.36
Urbana, Illinois		June	4.62	11.5	−6.88
		July	7.57	8.86	−1.29
		Aug.	8.38	7.72	+0.66
		Sept.	14.6	7.72	6.88
		Total	39.5	46.5	−7.00
Urbana, Illinois	1970	May	4.37	10.7	−6.33
		June	8.26	11.5	−3.24
		July	11.6	8.86	+2.74
		Aug.	7.92	7.72	+0.20
		Sept.	17.8	7.72	+10.1
		Total	50.0	46.5	+3.50
Urbana, Illinois	1971	May	9.75	10.7	−0.95
		June	3.10	11.5	−8.40
		July	27.8	8.86	+18.9
		Aug.	3.63	7.72	−4.09
		Sept.	12.1	7.72	+4.38
		Total	56.4	46.5	+9.90
Station 2	1957	Aug.	25.6	12.9	+12.7
Coral Gables	1957	Sept.	14.7	17.1	−2.40
(Miami WB City Florida)	1958	May	41.0	10.8	+30.2
	1958	June	8.36	14.1	+5.74
	1958	July	18.2	15.3	+2.90
		Total	108.0	70.2	+37.8
Station 3	1961	May	10.5	13.2	−2.70
Franklin, North Carolina		June	27.2	16.3	+10.9
(Highlands, NC)		July	12.6	23.4	−10.8
		Aug.	29.8	19.4	+10.4
		Sept.	8.92	12.7	−3.78
		Total	89.0	85.0	+4.00
Station 4	1961	June	7.57	9.47	−1.90
New Jersey		July	24.5	10.2	+14.3
(Freehold)		Aug.	10.4	12.7	−2.30
		Sept.	6.32	9.83	−3.51
	1962	May	3.58	10.2	−6.62
		Total	52.4	52.4	0.00
Station 5	1981	May	5.59	9.73	−4.14
Brookhaven National Laboratory		June	8.22	6.91	+1.31
New York		July	6.69	8.86	−2.17
		Aug.	2.46	11.5	−9.04
		Sept.	12.8	8.7	+4.10
		Total	35.8	45.7	−9.90

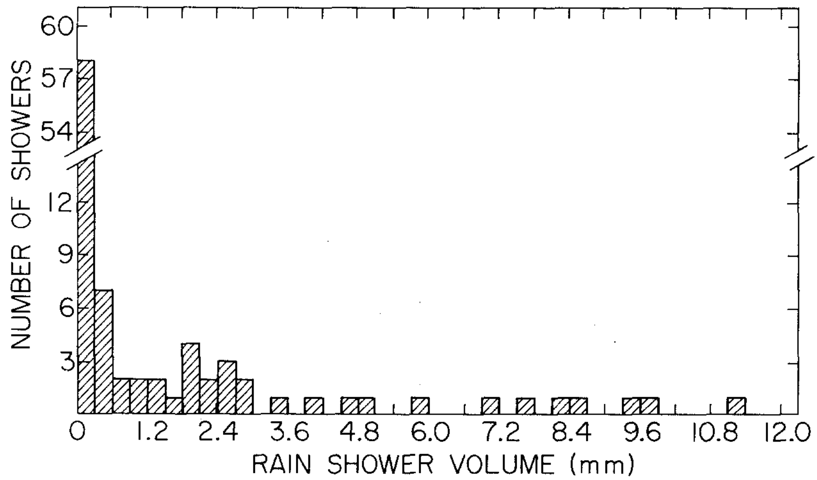

Fig. 4. Frequency distribution of ambient rainfall shower amounts from the period of 30 May through 29 September, 1981 at Brookhaven National Laboratory, Upton, Long Island, New York. A shower is defined as a precipitation event in which no additional precipitation occurs within 60 min after the end of the event. Other rainfall showers of 12.7, 16.0, 22.9, 32.4, and 43.0 mm were not plotted. These higher rainfalls accounted for 5.0% of all showers. During the growing season there were 48 other showers with a duration of less than one minute with less than 0.25 mm of rainfall per shower. These showers are not included in this figure.

considered were 50% higher than normal while results for stations 3 and 4 were close to their respective means. Data for station 5 for 1981 were lower than the mean. Precipitation amounts for Illinois (station 1) and New York (station 5) were very similar, while those for North Carolina (station 2) and Florida (station 3) were significantly higher than those recorded in Illinois (station 1), New Jersey (station 4), and New York (station 5). In general, the data used for this study are typical for the regions.

4. Discussion

In order to understand how acidic precipitation affects vegetation, variations in physical and chemical characteristics within and among ambient precipitation events must be known. Several studies of such variations have been performed (Raynor and Hayes, 1981, 1982a, b; Stensland, 1980; Evans *et al.*, 1981a). In addition, studies of short-duration, low-amount rainfalls as well as longer-duration, high-amount rainfalls may provide the data necessary to determine effects of ambient wet deposition on vegetation surfaces.

New York, Pennsylvania, New Jersey, and Ohio consistently show the highest rainfall acidity levels within the United States (NADP, 1979, 1980a, b; Evans *et al.*, 1981a). Most high-acidity rainfalls are recorded in the spring and summer (Raynor and Hayes, 1981). The hourly mean (weighted) H^+ concentration in rainfalls at Brookhaven National Laboratory was about 100 $\mu g\ L^{-1}$ during the growing seasons for 1976 through 1979. Values for spring were about 56 μg L^{-1} and mean concentrations for winter and fall were similar at 20 and 41 μg L^{-1}, respectively. These observations indicate that acidity of rainfall is highest when most plants are actively growing. Considerable variation in rainfall acidities was observed among rainfalls which had sufficient volume for analysis (Figure 5).

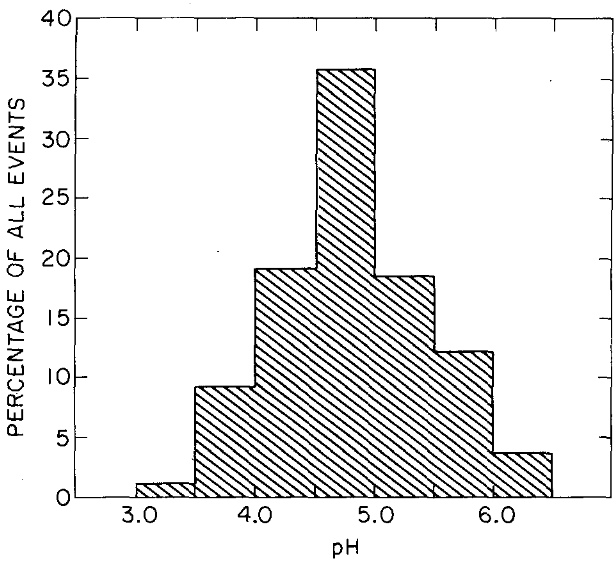

Fig. 5. Frequency distribution of the pH of ambient rain during the 1981 growing season on an event basis at Brookhaven National Laboratory. The figures represent the weighted average of hourly samples collected during each event for the period of 30 May through 29 September, 1981. No rainfall events had a mean pH below 3.0 or above 7.0. The volume weighted mean H^+ concentration of all rainfalls was 91.5 μeq L^{-1} (pH 4.04).

The frequency distributions of both shower amount and duration showed some variations over the three growing seasons at Urbana, IL. At Upton, NY, a greater frequency of short-duration and small-amount showers was recorded because the rotary rainfall indicator has a time resolution of less than 1 min. It is postulated that the relative frequency of such showers detected would have been higher in other sites if similar instrumentation at these stations was available.

The above data demonstrate that plant foliage is wetted during the growing season by numerous showers. Most of these showers are of short duration and small amount. In addition, plant foliage is also wetted many times by dew, which forms frequently during the growing season in the eastern United States. For example, during the crop growing season of 1979 dew formed at Upton, NY, 65 times for a total of 755 hr, in 1981, it occurred 36 times for a total of 226 hr (Evans *et al.*, 1981b). These data show that plant foliage in the eastern United States wetted on most occasions during the growing season by short-duration showers and dew. In addition, these frequent leaf wettings would solubilize many substances previously deposited dry.

Since injury to plant foliage may be more closely related to H^+ concentration than to total H^+ deposition (Evans, 1982) and since rainfall acidity varies markedly over both time and space (Evans *et al.*, 1981b), it is necessary to characterize rainfall chemistry with short time resolution. Many rainfall events may be subdivided into several showers in which foliage is alternately wetted and dried several times. In this manner, the chemistry of these individual showers may be related to plant injuries (Evans *et al.*, 1982).

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