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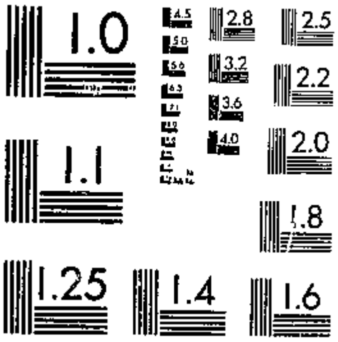

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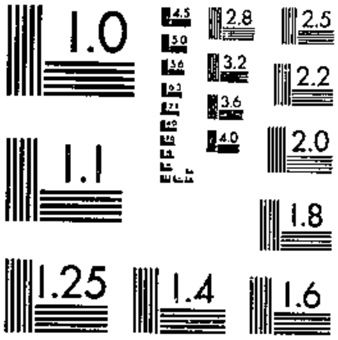

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Temperature, Moisture, and Penetration Studies of Wood-Staining Ceratostomellae in Relation to Their Control[1]

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CONTENTS

INTRODUCTION

Discoloring fungi that attack the sapwood of recently cut and stored forest products are of world-wide distribution and economic importance. Of the numerous species concerned, those causing bluish to gray blemishes commonly known as "blue stain" or "sap stain" are most prevalent. In the United States resulting damage is greatest in the Gulf States and Pacific coast regions, where moisture and temperature conditions favorable for the growth of the fungi occur through much or all of the year. Recently, several factors have been operating to increase the economic importance of these organisms. One of the foremost is the use of second-growth timber having a larger proportion of susceptible sapwood than is found in

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[2] The author gratefully acknowledges the encouragement given throughout this work by E. C. Stakman, University of Minnesota, and C. A. Richards and Carl Hartley, of the Division of Forest Pathology. His thanks are extended to Mae Spradling Chidester, T. C. Scheffer, and the late E. Seeliger, all of the Division of Forest Pathology, and to A. D. Chapman, formerly of this Division, for their helpful assistance in some of the laboratory and field work; also to those who kindly supplied cultures for use in the studies.

virgin timber. In the Gulf States, particularly, there is the necessary trend in the lumber industry of supplanting large logging and milling operations with smaller ones, which, because of limited facilities and different handling practices, are often confronted with serious discoloration problems. Finally, prejudice against stained wood is increasing greatly and has extended to light discolorations, which formerly were considered insignificant.

Research contributions from widely scattered sources have been stimulated by the ubiquitous wood-staining fungi. Much of this literature has covered control and taxonomic phases of the problem. During the past decade, extensive studies on control have resulted in the development of improved antiseptic treatments, which are now in wide and successful use on a variety of wood species and products (*16*).[3] Along taxonomic lines, the preponderance of evidence has been that the genus *Ceratostomella* contains some of the most common wood-staining species (*4*, *21*). However, the investigations of Lagerberg et al. (*11*) indicate that a group of miscellaneous Hyphomycetes is of equal or greater importance than *Ceratostomella* species in northern Europe. Similar Hyphomycetes occur as discoloring fungi in the United States but are believed to be less important than in the Scandinavian countries.

The present studies of wood-staining fungi concern temperature and moisture relations, rates of growth on agar and in wood, and certain practical aspects of the results in control programs. Sapwood of southern yellow pine and common species of *Ceratostomella* were used throughout the work. The several specific phases of the studies are conveniently treated separately.

TEMPERATURE IN RELATION TO GROWTH ON AGAR AND STAINING OF WOOD

There is surprisingly little literature on the relation of temperature to the development of staining fungi on agar and in wood. Such data as are available have been obtained largely from work by European investigators on the cardinal points for growth on artificial media. So far as is known, no attempt has been made to conduct comparative studies with similar or closely related staining species occurring in the United States.

Employing an incomplete series of controlled temperatures, Münch (*15*) considered the optimum for growth of *Endoconidiophora coerulescens* Münch and species of *Ceratostomella* to be between 20° and 25° C. Slow growth was observed at 7° C.

Falck (*5*) reported the critical temperatures for a questionable species to be 34°, 25°, and approximately 5° C. Although he mentioned *Ceratostomella piceae* Münch, Lagerberg et al. (*11*) believed that he worked with *Leptographium lundbergii* Lagerberg and Melin.

High resistance of *C. pilifera* (Fr.) Wint. to heat treatments applied to wood was reported by Hubert (*7*). Although wood-decaying organisms varied greatly in reaction to temperatures of 95° to 180° F. (35° to 82° C.), *C. pilifera* was outstanding in its ability to remain viable for a time at some of the intermediate temperatures.

Six discoloring species, including *Ceratostomella coerulea* Münch, were tested on malt agar by Lagerberg et al. (*11*). A periodicity

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[3] Italic numbers in parentheses refer to Literature Cited, p. 34.

in rate of growth was noted in contrast to the uniform rate shown by most Hymenomycetes. Optimum temperatures for the several species were between 22° and 25°, the minimum slightly above 0°, and the maximum above 27° C. *C. coerulea* had a broad optimum range, between 22.5° and 25°, whereas *Endoconidiophora coerulescens* and *Leptographium lundbergii* had restricted optima of 22.5° and 25°, respectively.

Jussila (*10*) reported greatest discoloration of export shipments of lumber at 22° to 25° C. At 35° and 0°, stain development was retarded. Little discoloration occurred in shipments of lumber from Finland during periods when temperatures averaged less than 10°.

According to Vanin (*20*), Lebedev's investigations of several species, including *Ceratostomella piceae*, *C. coerulea*, and *C. pini* Münch, showed the optimum temperatures to lie within the limits of 22.5° and 29°, the minimum between 0° and 10°, and the maximum between 27° and 39° C. Details of the methods of experimentation are not available.

Some of the discoloring species mentioned above do not occur commonly, if at all, in the United States. This is not the case with *Ceratostomella pini* and *Endoconidiophora coerulescens*, and may not be true of *Ceratostomella coerulea*. The last-named species apparently does not differ greatly in morphology from the common species recognized as *C. pilifera* in the United States.

The present studies included isolates of *Ceratostomella pilifera* from several widely separated regions, *C. pluriannulata* Hedgc., *C. ips* Rumbold, and *C. coerulea*, the last from Sweden and Canada. The specific purposes were to determine (1) critical temperatures and rates of growth on artificial media, (2) rate of hyphal penetration and stain development in wood as affected by temperature, (3) effect of alternating temperatures on growth rate, (4) possible thermal strains of *C. pilifera*, (5) comparative reaction to temperature of *C. pilifera* and *C. coerulea*, and (6) the importance of high temperatures as limiting factors in stain development in unseasoned lumber.

GROWTH ON AGAR AT DIFFERENT TEMPERATURES

METHODS

In a preliminary series, nine different temperatures, ranging in approximately equal steps from 4° to 36° C., were employed. Results of this work are not presented in detail because the chambers at 20°, 24°, and 28° were not controlled accurately. Since the temperatures at 4°, 32°, and 36° were fairly constant, some use of these data is made in estimating maximum and minimum points for development.

The growth studies were made in 90-mm. Petri dishes containing approximately 20 cc. of malt-extract agar, made of 2.5 percent malt extract and 1.5 percent agar. Blocks of fungus-covered substrate, 5 mm. on an edge, were transplanted from actively growing plate cultures to the center of the dishes. After 6 hours at room temperature, the inoculated dishes were distributed in eight controlled temperature chambers which ranged from 5° to 40° C. Diameter measurements of each culture were made daily for a period of 12 days, the size of the mycelial mat recorded representing an average of at least two different measurements. Eleven isolates were studied, each isolate being represented by two or three dishes at each temperature. The growth recorded daily for each isolate was based on the average growth of the three replicate cultures. Since the colonies were usually circular and the replicates varied little, measurement complications were slight on the whole.

For the study of growth at alternating temperatures, Petri-dish cultures similar to those described above were prepared for *C. pilifera* and *C. ips*. After incubation for 2 days at 25° C., the dishes, two for a given series with each organism, were shifted in various ways at 24- or 48- hour intervals among the eight different temperature chambers.

Collection and isolation data for the 11 isolates are given in table 1.

TABLE 1.—*Designation and collection data on cultures of Ceratostomella used in the studies* [1]

Fungus	No.	Collection and isolation data			
		Place	Wood	Date	Isolated by—
C. pilifera	322-73	Mississippi	*Pinus palustris* Mill	1932	R. W. Davidson.
	622	do	do	1932	Do.
	3-3/3	North Carolina	*Pinus taeda* L.	1924	C. T. Rumbold.
	523	Mississippi	*Pinus palustris*	1932	R. W. Davidson.
	608 E	do	do	1932	Do.
	313-92	Mexico	*Pinus ponderosa* Laws	1931	
	194 31 A/3	California	*Pinus lambertiana* Dougl	1929	C. T. Rumbold.
C. coerulea	392-B1	Canada	*Pinus strobus* L.	1930	E. A. Atwell.
	392-C14	Sweden			T. Lagerberg.
C. pluriannulata	198 7 O/10	Mississippi	*Liquidambar styraciflua* L	1929	C. T. Rumbold.
C. ips	745	Florida	*Pinus echinata* Mill	1932	R. W. Davidson.

[1] *C. coerulea* 392-C14 was obtained by the Forest Products Laboratories, Ottawa, Canada, from Prof. T. Lagerberg, of Sweden.

RESULTS

Data for the growth of 11 isolates of *Ceratostomella* on malt-extract agar maintained at constant temperatures are presented in table 2.

TABLE 2.—*Growth of Ceratostomella pilifera, C. pluriannulata, C. ips, and C. coerulea on malt-extract agar at temperatures of 5° to 40° C.*

Fungus [1]	Place of collection	Average daily diameter increment at indicated temperatures [2]								Estimated cardinal temperatures [3]		
		5	10	15	20	25	30	35	40	Minimum	Optimum	Maximum
		Mm.	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	°C.	°C.	°C.
C. pilifera	Mississippi	1.5	3.1	4.4	5.4	7.8	7.8	0	0	4	28–29	35
	do	1.0	2.6	4.3	5.2	7.7	7.7	0	0	4	28–29	34–35
	North Carolina	1.0	2.6	3.8	5.0	7.5	6.9	0	0	4	27–29	34–35
	Mississippi	1.0	2.6	4.0	5.0	7.0	6.9	0	0	4	28–29	34–35
	do	1.0	2.5	3.8	5.0	7.2	7.4	0	0	4	28–29	34–35
	Mexico	1.5	3.3	5.4	6.4	9.3	1.5	0	0	3	25–26	31–33
	California	1.8	3.3	5.0	6.1	7.8	2.6	0	0	3	25–26	32–34
C. coerulea	Canada	1.5	3.2	4.7	5.4	7.4	5.0	0	0	3	25–27	32–34
	Sweden	1.5	2.4	3.4	3.8	3.4	0	0	0	4	22–24	29
C. pluriannulata	Mississippi	1.0	2.2	3.4	3.8	6.2	6.2	0	0	4	28–29	34–35
C. ips	Florida	0	4.5	6.5	8.5	14.5	17.0	12	0	6–8	30–32	37–39

[1] Order as in table 1.

[2] Average daily increment of mat after normal growth rate attained, based on 2 cultures for each organism and temperature at 5°, 10°, and 15° C. and on 3 cultures at remaining temperatures.

[3] In estimating cardinal temperatures use was made of supplemental data from a preliminary series with controlled temperatures of 4°, 8°, 32°, and 30° C.

Growth for different 24-hour observation periods at a given temperature was not constant for any of the fungi. Variations of as much as 2 mm. appeared in successive daily readings, some of which were due probably to slight errors in measurement and possibly to small fluctuations in temperature. The differences occurred with no apparent regularity, so that a definite periodicity in rate of growth was not indicated. Likewise, there was no determinable increase or decrease in rate of growth with time in the relatively short periods of these tests.

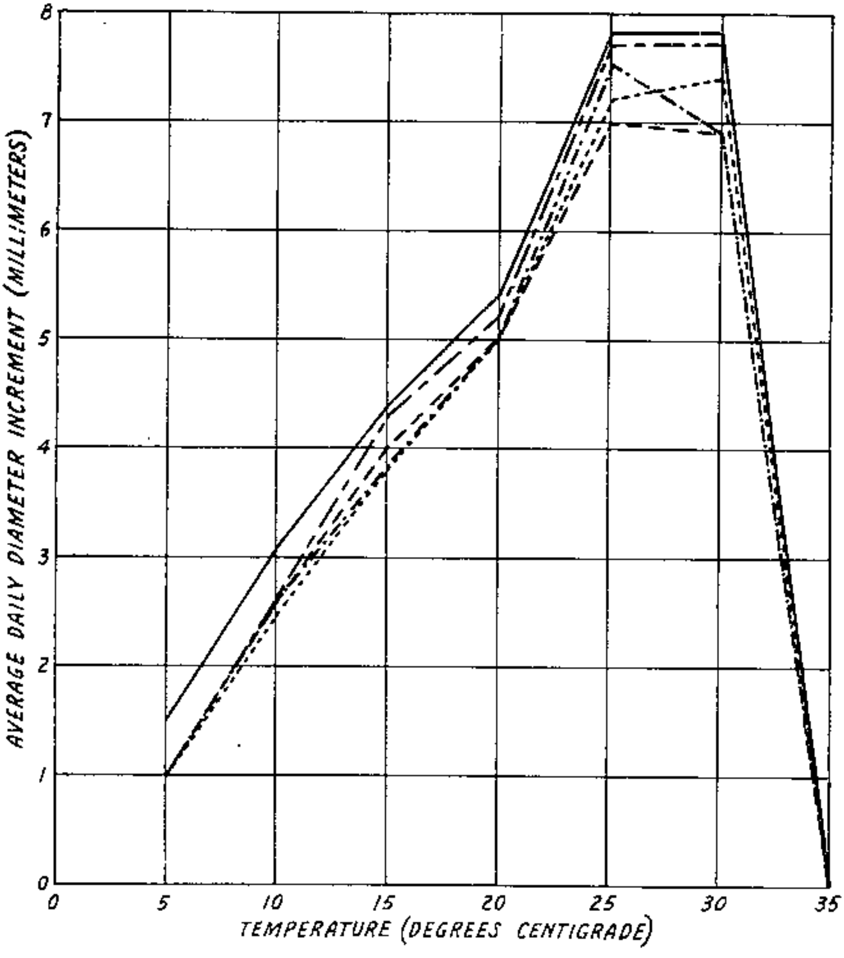

FIGURE 1.—A comparison of the average daily diameter increment on malt-extract agar of 5 isolates of *Ceratostomella pilifera* from the southeastern United States.

Significant differences in the reaction of the isolates to the various temperatures are evident in plate 1 and figures 1, 2, and 3. The *C. pilifera* isolates fall into two distinct groups which differ 2° to 4° in optimum and maximum temperatures for growth. The high-temperature group includes all *C. pilifera* cultures originating in

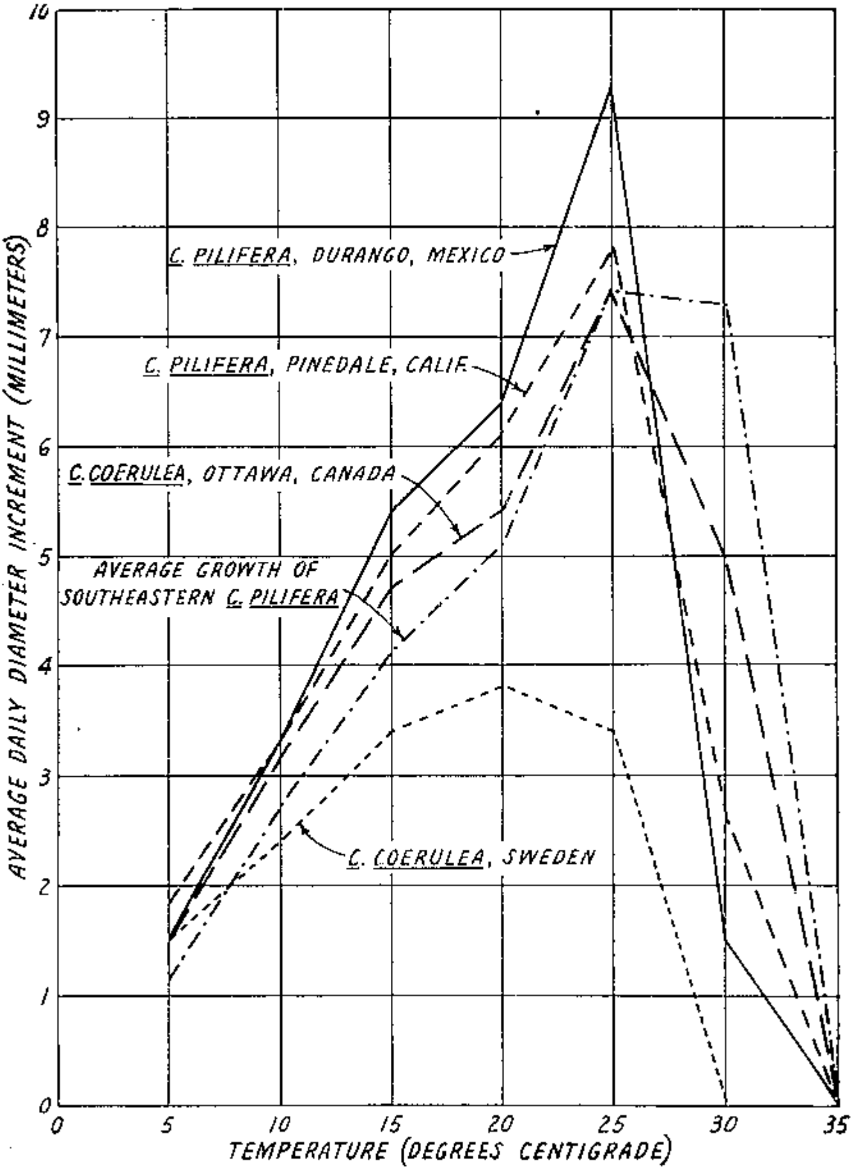

FIGURE 2.—A comparison of the average daily diameter increment on malt-extract agar of *Ceratostomella pilifera* and *C. coerulea* from different geographic regions.

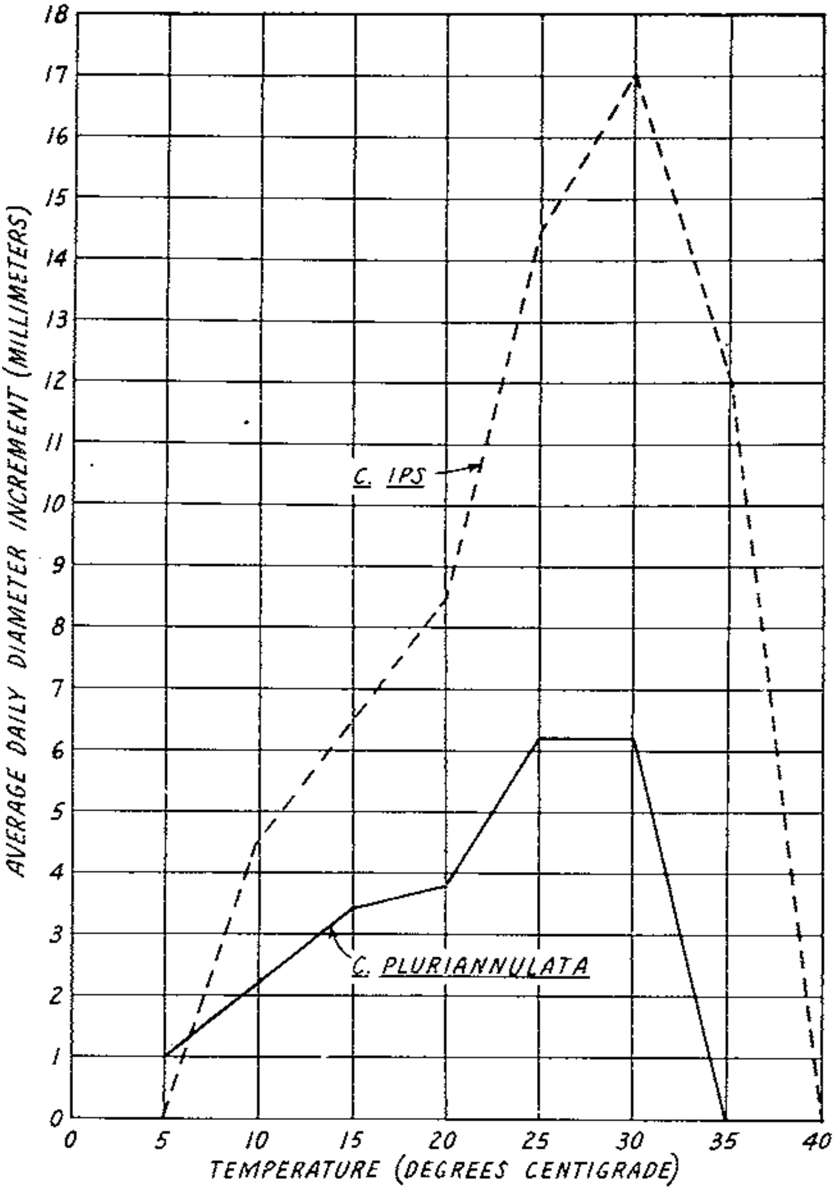

FIGURE 3.—A comparison of the average daily diameter increment on malt-extract agar of *Ceratostomella ips* and *C. pluriannulata*.

Mississippi and North Carolina and has as estimated cardinal points slightly below 4°, 27° to 29°, and 34° to 35° C. The low-temperature group, which consists of isolates from California and a mountainous region of Mexico, has as estimated critical points slightly below 3°, 25° to 26°, and 31° to 34° C. Figures 1 and 2 clearly show these differences and also the degree of similarity within each group.

The two isolates of *Ceratostomella coerulea* varied widely in rates of growth and response to temperature (fig. 2).[4] The isolate from Canada showed close agreement in critical points and increment with *C. pilifera* from California and Mexico, the former particularly. Similar to these, its rate of growth was reduced appreciably at 30° C. and was more rapid than that of the southeastern cultures of *C. pilifera* at temperatures below the optimum. The Swedish isolate of *C. coerulea* showed the narrowest temperature range of any of the fungi tested, and its growth rate at favorable temperatures was about one-half that of the Canadian *C. coerulea* and the reported rate for this species in Sweden. Considering these differences, some doubt must exist as to the normality of the culture. Although it failed to produce perithecia in contrast to all other isolates, Lagerberg et al. (*11*) state that this often is true of old cultures of *C. coerulea*. Its ability to discolor wood was not determined, but its cultural characteristics resembled those of staining fungi.

Of the several species, *Ceratostomella pluriannulata* showed the slowest growth rates and *C. ips* the highest (fig. 3). The cardinal temperatures for *C. pluriannulata* were similar to those of the southeastern isolates of *C. pilifera*. *C. ips* was the highest temperature organism of the group; it failed to grow at 5° C., made fairly rapid growth at 35°, and had cardinal points varying from 2° to 8° above those of the other isolates.

Temperatures above the optimum caused a pronounced retardation of growth in all cases. An increase of 5° to 8° C. above the optimum resulted in inhibition of growth, whereas a decrease of 5° to 8° below the optimum never reduced growth more than 40 percent and usually not more than 25 to 30 percent. A drop of 20° or more was required to stop growth at low temperatures.

The time of appearance of brown-colored hyphae, and the rate of change from hyaline to brown, varied with the different isolates and temperatures. Brown hyphae appeared earlier at favorable temperatures for growth than at 5° or 10° C., and there was evidence that with hyphae of a given age, the change from hyaline to brown progressed more rapidly as temperatures approached the optimum point. The fact that rate of hyphal darkening might have been affected by differences in the amount of light in the temperature chambers cannot be disregarded.

There was a direct relationship between the critical temperatures for growth and viability of the isolates at unfavorably high temperatures. This was evident from the recovery made at 25° by cultures that had been incubated at 35° C. for 7 or 14 days. After 7 days,

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[4] A letter from E. A. Atwell, Forest Products Laboratories of Canada, Ottawa, states in part: "There can be no doubt of the identity of the Swedish culture of *C. coerulea* since it was received directly from Professor Lagerberg and has been kept with our stock cultures ever since. It is possible, however, that continuous growth on artificial media caused certain changes in the culture. I am not so sure of the identity of our own culture B_1. The original culture identified for us by Professor Lagerberg as *C. coerulea* became contaminated and was discarded. The one sent to you was one of several others from the same piece of wood as the identified culture, all of which appeared to be the same fungus, although no measurements of the perithecia of the unidentified cultures were made."

Ceratostomella pilifera from California and *C. coerulea* from Sweden were no longer viable; after 14 days *C. coerulea* from Canada and *C. pilifera* from Mexico failed to resume growth. All other isolates eventually attained normal growth, but at rates that indicated a definite carry-over effect for 3 to 4 days from the incubation at 35°. The *C. pilifera* isolates from Mississippi attained a normal rate of growth most rapidly, followed by *C. pluriannulata* and *C. pilifera* from North Carolina.

Loss of viability occurred at temperatures only slightly higher than the maximum points for growth. As mentioned above, *C. coerulea* and two cultures of *C. pilifera* no longer were viable after either 7 or 14 days at 35° C. After 2 days at 35°, the possibly abnormal *C. coerulea* from Sweden failed to grow; after 7 days at 30°, growth was resumed. None of the isolates except *C. ips* resumed growth after 2 days at 40°. One day at 40° was fatal only to *C. coerulea* from Sweden and occasional cultures of *C. coerulea* from Canada and of *C. pilifera* from California and Mexico. *C. ips* failed to grow after 7 days at 40°.

The effect of daily change of temperature on the growth of *C. pilifera* and *C. ips* is shown in figure 4. The average daily increment under conditions of constant temperatures is given for the purpose of comparison.

It is evident from figure 4 that both organisms became adjusted immediately to the new thermal environments and continued growth at a normal rate, when the daily shifts were made between near optimum and suboptimum temperatures from 5° to 30° C. In all such cases the daily increment was neither significantly higher nor lower than that of cultures maintained constantly at a given temperature. However, when the cultures were subjected, in the course of shifting, to temperatures slightly above the maximum points for growth, a condition of retarded increment was evident for about 2 days. Thus, *C. pilifera* showed subnormal growth for 2 days at 15° and 25°, following incubation at 35° for 1 day. Likewise, *C. ips* grew at a reduced rate at temperatures of 15° and 30°, after being subjected to 40° for 1 day.

HYPHAL PENETRATION AND DEVELOPMENT IN WOOD AT DIFFERENT TEMPERATURES

METHODS

Blocks, approximately 1.5 by 2 by 0.7 inches, were quarter-sawed from a fresh bolt of *Pinus echinata* sapwood. Immediately after a surface treatment of 5 seconds in boiling water, the blocks were placed in sterile Kolle flasks and inoculated by means of a platinum loop with a suspension of ascospores and conidia of *Ceratostomella pilifera* (No. 3–3/3). The flasks were then distributed in chambers having at the start 4° temperature intervals from 4° to 36° C. Fluctuations of 2° to 3° developed in the 20°, 24°, and 28° chambers while the tests were in progress.

One test series, consisting of a flask with 2 heavily inoculated blocks at each temperature, was for the purpose of observing hyphal development and the time of visible staining of the wood. A second

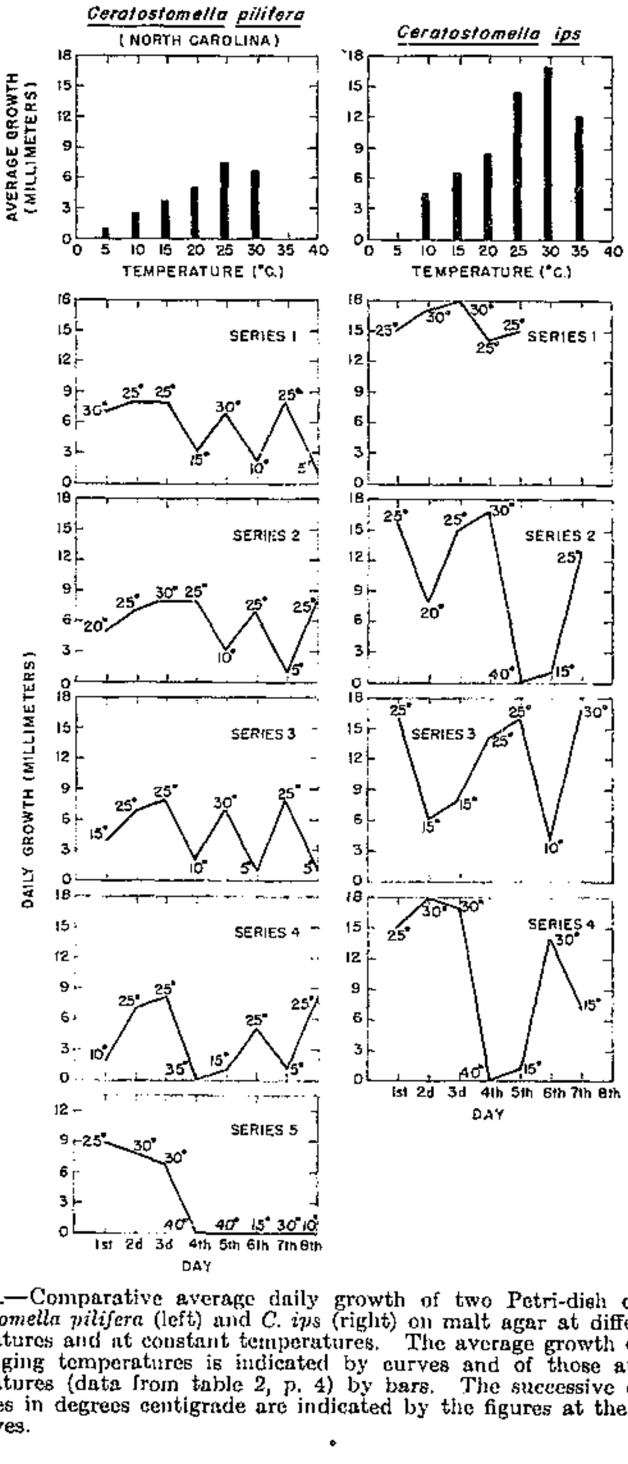

FIGURE 4.—Comparative average daily growth of two Petri-dish cultures of *Ceratostomella pilifera* (left) and *C. ips* (right) on malt agar at different daily temperatures and at constant temperatures. The average growth of cultures at changing temperatures is indicated by curves and of those at constant temperatures (data from table 2, p. 4) by bars. The successive daily temperatures in degrees centigrade are indicated by the figures at the points on the curves.

and larger series was intended for the study of radial and longitudinal penetration of the hyphae in wood. In the latter series, each flask contained 2 blocks, 1 of which was inoculated on a tangential and the other on a transverse surface. The blocks were inoculated by placing a spore suspension in a marked area on one surface of the block. Either 3 or 6 flasks were incubated at each of the different temperatures, the smaller number being used for the temperatures considered less critical. After 24, 48, and 96 hours, 1 or 2 flasks were removed from each temperature chamber, and the moisture content of the blocks, based on oven-dry weight, was determined. Sections for microscopic examination were then prepared from each block by cutting out small cubes of wood at the point of inoculation. The cubes were boiled immediately in water and stored in a 50–50 mixture of glycerin and alcohol. Usually 10 sections, 10 to 20 microns thick, were cut from each cube; these sections were stained in Pianeze III b and, after dehydrating and clearing, were mounted in canada balsam.

RESULTS

The stages of development of *Ceratostomella pilifera* on blocks of *Pinus echinata* that were incubated at various temperatures are compared in table 3. The data are based largely on observations made through Kolle flasks with the unaided eye; consequently, the earliest occurrence of some stages probably was not recorded.

TABLE 3.—*Type of development of Ceratostomella pilifera on the surfaces of Pinus echinata blocks incubated for 3 to 20 days at 4° to 32° C.*

Days after inoculation (number)	Stages of fungus growth	Development at indicated temperature (° C.)[1]							
		4	8	12	16	20	24	28	32
3	White growth	0	0	0	0	Sparse	Sparse	Sparse	0
	Colored hyphae	0	0	0	0	0	0	0	0
	Perithecia	0	0	0	0	0	0	0	0
	Stained wood	0	0	0	0	0	0	0	0
5	White growth	0	0	0	Light	Medium	Heavy	Heavy	0
	Colored hyphae	0	0	0	0	Light	Light	Light	0
	Perithecia	0	0	0	0	0	0	0	0
	Stained wood	0	0	0	0	Sparse	Light	Light	0
7	White growth	0	0	Sparse	Medium	Heavy	Heavy	Heavy	0
	Colored hyphae	0	0	0	Light	Heavy	Heavy	Heavy	0
	Perithecia	0	0	0	0	Light	Light	Light	0
	Stained wood	0	0	0	Light	Medium	Heavy	Heavy	0
10	White growth	0	0	Medium	Heavy	Heavy	Heavy	Heavy	0
	Colored hyphae	0	0	Light	Heavy	Heavy	Heavy	Heavy	0
	Perithecia	0	0	0	Medium	Heavy	Heavy	Heavy	0
	Stained wood	0	0	Light	Heavy	Heavy	Heavy	Heavy	0
15	White growth	Sparse	Medium	Heavy	Heavy	Heavy	Heavy	Heavy	0
	Colored hyphae	Sparse	Light	Heavy	Heavy	Heavy	Heavy	Heavy	0
	Perithecia	0	0	Light	Heavy	Heavy	Heavy	Heavy	0
	Stained wood	0	Sparse	Medium	Heavy	Heavy	Heavy	Heavy	0
20	White growth	Light	Heavy	Heavy	Heavy	Heavy	Heavy	Heavy	0
	Colored hyphae	Sparse	Medium	Heavy	Heavy	Heavy	Heavy	Heavy	0
	Perithecia	0	Light	Heavy	Heavy	Heavy	Heavy	Heavy	0
	Stained wood	Sparse	Medium	Heavy	Heavy	Heavy	Heavy	Heavy	0

[1] Microscopic sections made at the end of 10 days revealed hyaline and occasional colored hyphae at 4° C.; also a few hyaline hyphae in surface layers at 32°.

The reaction of *C. pilifera* to different temperatures was in general the same on surfaces of wood as on agar. Differences were limited to the absence of growth on wood at 32° C., the very slow appearance of visible growth on wood at the lower temperatures, and the relatively slight variation in hyphal development between 20° and 28°. The studies on agar indicated that 32° was below, but probably close to, the maximum temperature for growth and that development was distinctly slower at 20° than at either 25° or 30°. Microscopic sections showed some penetration of hyphae at 32°, but neither mycelial growth nor staining was visible on the blocks after 20 days. At favorable temperatures, between 20° and 28°, colored hyphae and light staining of the wood surfaces were visible after 4 or 5 days. Heavy staining of the surfaces and development of perithecia were evident within 7 days at these temperatures. A decrease in temperature from 20° to 16° and from 20° to 12° resulted in delaying the appearance of stain for 2 and 4 days, respectively. Only light development of colored hyphae and incipient staining were observed after 15 days at 8°.

The effect of different temperatures on the rate of penetration of *C. pilifera* into sapwood of *Pinus echinata* is shown in table 4. After 1 day, scattered hyphae, confined largely to the surface layers of the wood, had developed only at temperatures between 16° and 28° C. After 2 days, slight hyphal penetration was evident at 8° and 12° but not at 32°. Penetration was greatest at temperatures of 20° to 28°; it reached 1.9 mm. in a radial direction and 6.8 mm. in a longitudinal direction. In general, penetration was three to four times as rapid longitudinally as radially. After 4 days, scattered hyphae were found in the surface cells of only a few sections of blocks incubated at 32° and no growth was evident at 4° or 36°. Again, the rate of penetration at the several temperatures between 20° and 28° was variable, particularly in a radial direction. Considering all temperatures except 32°, penetration was three to six times as great longitudinally as radially.

Although direct comparisons between tables 2 and 4 are not possible at most temperatures, a general correlation is apparent between growth on agar and development in wood. At 4° C., evidences of hyphal development were lacking both in wood and on agar after 4 days.[5] However, at 8° slight surface penetration in wood was apparent after 2 days, whereas no growth was recorded on agar after a similar period. There was a further difference at 32°; growth was evident on agar within 2 days, but slight penetration in wood was recorded only after 4 days. It appears from the moisture-content determinations that there was little loss of moisture at the higher temperatures during the first 48 hours, but that the trend was toward lower water contents after 96 hours. Slight drying of the surfaces of the wood at 32° could have been a limiting factor in penetration, even though total water content of the blocks indicated favorable conditions for growth.

In comparing actual rates of growth on agar and penetration in wood, use is made of the radial increment on agar rather than the diameter of the mat. On this basis, it appears that growth during the first day was somewhat more rapid on agar than in wood at the

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[5] Records of growth on agar at 4°, 8°, and 32° C. were obtained from a preliminary series that is not reported in detail because some of the intermediate temperatures varied excessively.

favorable temperatures between 20° and 30° C. However, after 2 and 4 days, the maximum longitudinal penetration in wood was almost equal to, and in several cases more than, the average daily growth on agar at all temperatures except 32°. Penetration in a radial direction in wood was about one-half to one-fifth that of growth on agar.

TABLE 4.—*Penetration of Ceratostomella pilifera into blocks of Pinus echinata sapwood incubated for different periods at different temperatures*

Period (days)	Temperature [1]	Depth of penetration [2]				Hyphal development	Average moisture of blocks (oven-dry basis)
		Radial		Longitudinal			
		Average	Maximum	Average	Maximum		
	° C.	*Mm.*	*Mm.*	*Mm.*	*Mm.*		*Percent*
1	4	0	0	0	0		110
	8	0	0	0	0		107
	12	0	0	0	0		103
	16	.2	.3	.1	.2	Very sparse; in surface layers only	109
	20	.4	.5	.6	.8	Sparse; in tracheids largely	100
	24	.3	.4	.6	.7	Sparse; most sections with nothing	94
	28	.1	.1	.2	.3	do	107
	32	0	0	0	0		96
	36	0	0	0	0		101
2	4	0	0	0	0		109
	8	0	0	.1	.2	Very sparse; in surface layers only	106
	12	.5	.8	.9	1.4	Hyphal development sparse and hyaline	100
	16	.8	1.0	3.0	3.5	do	90
	20	1.3	1.7	5.9	6.8	do	105
	24	1.4	1.8	5.0	6.0	do	107
	28	1.0	1.9	5.2	6.1	do	111
	32	0	0	0	0		103
	36	0	0	0	0		101
4	4	0	0	0	0		101
	8	.4	.6	2.0	3.5	Sparse; many sections with nothing	103
	12	1.5	1.8	4.5	7.0	Rather sparse; hyphae hyaline	106
	16	2.4	2.8	8.0	10.5	Fairly abundant; hyaline	110
	20	2.9	3.4	10.0	11.5	Abundant; interior hyphae hyaline	96
	24	2.8	3.2	10.0	14.5	do	85
	28	2.6	3.4	14.0	17.5	do	95
	32	.3	.4	.6	.8	Very sparse; most sections with nothing	81
	36	0	0	0	0		93

[1] The 20°, 24°, and 28° C. chambers fluctuated within a range of ±2°.

[2] Each figure based on measurements of 10 to 40 sections from 1 or 2 blocks, the latter usually. Average penetration equals an average of the maximum penetration in each of the blocks of a series. Maximum penetration equals the greatest penetration recorded in any of the blocks of a series.

TEMPERATURES IN PILES OF UNSEASONED LUMBER

METHODS

During the summer of 1932, air temperatures were recorded in and around piles of lumber seasoning at three southern sawmills located at Couchwood, La., Natalbany, La., and Hattiesburg, Miss. This general region is one of important blue-stain occurrence and high summer temperatures. The readings were taken between 10 a. m. and 3 p. m. on days that were clear except for occasional clouds. Commercial piles of pine lumber that had been drying for less than 1 day to 40 days were selected. Partially or fully seasoned piles were usually adjacent to those in which temperatures were recorded.

All records inside of the piles were taken on the top surface of the board adjacent to the outside board, and at a point 4 to 6 feet from the front of the piles. The heights tested were 2 feet above the bottom, midway, and 2 feet below the top of each pile. The temperature of the surrounding air was recorded in the shade at a distance of 1 to 2 feet from the pile, and at the same levels as the pile readings.

Seventeen piles of lumber, each having one series of temperatures taken for any 1 day, are represented in the comparative results. Some piles were used for only one series of readings and others for several series on different days. For purposes of presenting the results, the temperatures recorded for piles of approximately the same ages are averaged. In the group representing piles 1 day or less in age, all readings concern different piles; for groups covering a range of several days in age, several readings on the same pile are represented to some extent in the averages.

RESULTS

The temperatures that were recorded in and around piles of lumber seasoning at three southern sawmills are summarized in table 5. In presenting these results, it is realized that a number of factors, including size, type, location, and age of pile, as well as time and place of observation, would have to be considered in any detailed study of temperature variations in piles of lumber during seasoning. Nevertheless, the data reported herein are believed to indicate whether high temperatures are an important limiting factor in the discoloration of unseasoned lumber.

TABLE 5.—*A comparison of temperatures outside and within piles of southern pine lumber of different degrees of dryness*

Age of piles (days)	Piles tested	Average temperature in different locations									Highest temperatures recorded					
		Top of pile			Midway			Bottom			Top		Midway		Bottom	
		Outside	Inside	Difference	Outside	Inside	Difference	Outside	Inside	Difference	Outside	Inside	Outside	Inside	Outside	Inside
	No.	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*	*°C.*
0–1	3	33.1	27.0	6.1	31.5	26.7	4.8	30.4	26.3	4.1	34.8	28.0	33.8	26.5	32.1	26.8
1 to 2	6	33.0	28.7	4.3	31.5	27.1	4.4	30.2	26.5	3.7	35.2	30.6	34.6	28.2	34.0	27.2
5 to 8	6	28.6	26.1	2.5	27.8	25.8	2.0	27.2	25.1	2.1	29.8	26.0	28.8	26.2	27.9	25.9
18	3	31.5	27.3	4.2	29.9	27.1	2.8	27.0	26.3	1.3	31.5	28.5	30.1	28.0	27.6	26.7
30 to 40	13	30.0	27.6	2.4	29.1	27.1	2.0	28.4	26.6	1.8	33.3	31.5	33.1	30.5	33.3	30.7

The average of temperatures for the respective tested locations within the piles ranged from 1.3° to 6.1° C. lower than those of the surrounding air. The differences were least toward the bottom of the piles in most cases. Noticeable also is the general trend of smaller differences between outside and inside temperatures as the age of the piles increased; there was a 6.1° C. difference in the upper portion of piles that had been stacked less than 1 day, as compared with a 2.4° difference in piles of 30 to 40 days in age.

The highest temperature that was recorded within any one pile was 31.5° C. This pile had been drying for over 30 days and in all probability was no longer susceptible to stain. In piles that were less than 18 days old, inside temperatures seldom exceeded 28°, but in one case they reached 30.6°. In contrast, the outside temperatures usually were above 30°, and in one case reached 35.2°.

Both outside and inside temperatures decreased toward the bottom of the piles. This would be expected because of the downward and outward movement of the cool air resulting from evaporation of moisture from lumber.

In this study, the inside temperatures were recorded on boards that were adjacent to the outside boards in the pile. It is probable that such temperatures were somewhat higher than those that would have been recorded farther within the pile. On the other hand, the outside boards undoubtedly were subjected to higher temperatures than those recorded; however, any effect of temperature on stain development in such exposed boards would be greatly overshadowed by the influence of rapid drying.

Discussion

Among the factors that might affect growth response of fungi at different temperatures are the substratum, time of making observations, thermal history, and the favorableness of other environmental factors.

Considering wood-inhabiting fungi only, Wolpert (*22*) reported that optimum temperatures for growth varied to some extent with the substratum. However, the differences in reaction were not of sufficient magnitude to preclude grouping the organisms tested into certain thermal classes. Correlations between the rates of wood decay and mycelial growth on culture media at different temperatures were attempted by the author (*14*). Temperatures that were favorable for mycelial growth were likewise conducive to rapid decay, but whether the cardinal temperatures or relative rates of growth were the same on agar and in wood was not determined. Gäumann (*6*) recently reported that the optimum temperature for vegetative growth of two wood-rotting fungi was 2° to 3° C. higher than that for decay of wood. In comparing growth and respiration rates at different temperatures, Lehmann and Scheible (*12*) found that with a given amount of substratum, respiration might continue to increase at temperatures above the optimum for growth. Decay of wood was believed to proceed at the greatest rate under thermal conditions that were most favorable for the growth and ramification of the hyphae. Scheffer and Livingston (*17*) suggest that the optimum temperature for decay may be expected to lie somewhat above the optimum but considerably below the maximum temperature for mycelial growth. Although this difference in optima for growth and decay apparently is considered slight, they point out that it might prove greater under conditions in which growth of the fungus into unoccupied wood represents only a small part of the total activity of the organism.

No significant differences were detected in the present study between the growth-temperature relations of *Ceratostomella pilifera* on malt agar and on wood. Penetration of hyphae and discoloration of wood were greatest at temperatures that also favored mycelial growth on agar. The average longitudinal spread in wood over a period of 4 days was in general close to the average radial increment on agar at given temperatures. There was some evidence that the thermal range for rapid penetration and staining of the wood was broader than that for rapid mycelial growth on agar, and that establishment might occur somewhat more readily in wood than on agar at the lower temperatures. The scarcity of penetration at 32° C. might indicate that maximum limits are lower on wood, but the possible influencing factor of surface drying of the wood cannot be disregarded at this temperature. While recognizing that slight variations may occur, it is believed that the temperature relations of *C. pilifera* are practically the same on wood and agar, and that growth of this organism in wood under different thermal environments can be determined with sufficient accuracy for most purposes from comparative tests on agar.

Changes in the growth-temperature relations with time have been reported for several groups of fungi. If the factor of time is important, the effect of it would seem to be particularly evident in comparisons of growth of wood-rotting organisms for short periods on agar as against decay of wood during periods of several months. In such cases, however, the possible effect of differences in substrata, as well as in time, would have to be recognized. Humphrey and Siggers (*9*) reported that for 7 of 21 fungi studied, the optimum temperatures for growth on agar shifted to lower points with increase of incubation periods. This change suggested that the optimum temperatures for decay of wood over long periods might be lower than those indicated by the agar tests of short duration. The author (*14*) noted that for 1 of 3 fungi studied there was a slight reduction in growth on agar and decay of wood with time at the higher temperatures. In the present study with *Ceratostomella pilifera*, there was no definite periodicity in growth rate, as suggested by Lagerberg et al. (*11*) for certain staining fungi. Furthermore, there was no apparent shifting downward of optimum and maximum temperatures for growth on agar or in wood with increase in time of incubation. The rapid development of most staining fungi on wood, as well as on agar, would make the factor of time less significant than might be true of many other wood-attacking organisms.

Data have been lacking on the effect of prior temperatures and of fluctuating versus maintained thermal conditions on the growth relations of wood-staining fungi. In the present study, the subjection of cultures of *C. pilifera* and *C. ips* to daily changes of temperature within the range bounded by the optimum and minimum points for development resulted in neither stimulation nor retardation of growth. Departures from characteristic growth under conditions of constant temperatures were evident only when the cultures were subjected, in the course of the daily changes, to temperatures slightly above the maximum points for development. Incubation for 1 day at unfavorably high temperatures resulted in retarded growth of the culture for about 2 days in more favorable thermal environments. Such evidences of retarded growth, which might have been due to killing of the actively growing hyphae at the margins of the culture, were most pronounced for the organisms with the lowest optima. Except for the retarding or killing effect of temporary exposures to supramaximum temperatures, it is doubted that important variations in growth reaction of these organisms result from changing as compared to maintained temperatures. It is realized that differences of short duration might have been obscured in the daily measurements employed in this study, and that the daily and sudden changes of temperature are not typical of the fluctuating conditions occurring naturally.

There was a direct relationship between critical temperatures for growth of the isolates and viability at unfavorably high temperatures. In all cases, the isolates with the lowest optima were the first to be killed and the last to recover from incubation at 35° and 40° C. Likewise, the highest maxima were possessed by those isolates with the highest optimum points. A comparison of the work on wood-destroying fungi by Liese (*13*) and Cartwright and Findlay (*1*) shows, according to the latter, that the group with low optima are in general the most sensitive to killing by heat. Humphrey and Siggers (*9*) apparently found no consistent relation between the maximum and optimum temperatures for growth of a large number of Hymenomycetes, although their data show a direct correlation for most of the species.

The limiting effect of extremes of temperature on the distribution of wood-inhabiting fungi has been mentioned by Cartwright and Findlay (*1*). They observed that fungi that are of wide occurrence have a broad temperature range. Furthermore, dominance of species in an environment in which other factors are equally favorable was believed to depend on the relative rates of growth at different temperatures. The use of only three distinct species, the lack of data on the relative frequency of their occurrence, and their predilection for different wood substrata make comparisons along the above lines of little value in the present study. Interesting to note, however, was the occurrence of thermal strains of *Ceratostomella pilifera* which differed 2° to 4° in optimum and maximum temperatures for growth. All cultures obtained from the warm southeastern section of the United States were in the high-temperature group. *C. coerulea* from Canada conformed closely in growth to the low-temperature group, which also seems to be true of *C. coerulea* in Europe (*11*). Differences in seasonal and regional distribution and prevalence of these and other staining fungi probably are to be expected from the variations shown in cardinal points for development. Recent studies by Verrall (*21*) show a general correlation between the seasonal frequency of staining fungi and their growth in relation to temperature.

On the basis of the present work, high temperatures, as they occur naturally, are not considered an important limiting factor in the discoloration of lumber during seasoning. Although the cardinal temperatures of other strains and staining species probably are not within the limits of the determined ones, it does not seem probable that many of the common discoloring organisms have optimum and maximum points much below 23° and 30° C., respectively. The studies in southern lumber yards indicated that air temperatures around piles of lumber are often above the maximum for growth of staining fungi, but that temperatures within the piles of drying lumber usually are favorable for rapid stain development. These records were taken during warm summer months in a region where temperatures are probably as high as in any other locality of important stain development in the United States. Temperatures unfavorably high for growth undoubtedly occur at times on the top courses and outside boards of unseasoned piles, and also throughout piles of dried lumber; however, stain development usually is precluded under such conditions as a result of rapid loss of moisture from the wood. Within the limits of moisture content favorable for growth of these fungi in wood, loss of water from wood continues and is accompanied by the cooling effect of evaporation; if evaporation ceases, a moisture equilibrium between the wood and atmosphere has been reached and staining is unlikely, regardless of temperature conditions. The principal effects of high temperatures probably are those of retarding growth and reducing inoculum on exposed surfaces of lumber and logs, and of influencing the relative development of different staining species that vary in their temperature relations.

The importance of low temperatures in retarding and inhibiting stain development varies with the locality and season of year. Minimum points for development of the several species of *Ceratostomella* employed in these studies were in the region of 4° and in one case between 6° and 8° C. Other species probably have somewhat higher minimum points, although few, if any, would be likely to exceed 10° as a lower limit. In the Gulf States region, low temperatures during the cooler months would be expected to retard, but seldom inhibit, stain development for extended periods. In such northern regions as the Lake States, cessation of staining would seem to be the case during most of the winter season. Such conclusions are clearly corroborated by practical experience in the two regions. In the Gulf States, losses due to discoloration are encountered throughout the year, but, with favorable moisture conditions, are likely to be more severe in the warm summer months. Control treatments are applied throughout the year in much of this territory. In the Lake States, seasonal variations in stain occurrence are particularly pronounced, and definite efforts at control are expended only during the warm, moist periods.

It is apparent from field observations that the effectiveness, as well as use, of preventive methods is influenced by temperature in relation to growth of staining fungi. Where temperatures of 20° to 30° C. prevail, inconsistent control of stain is obtained if the application of antiseptic dips or sprays to the surfaces of lumber is delayed for more than 2 days after sawing. At 5° or 10°, the effectiveness of such treatments is little impaired by a similar or somewhat longer period of delay in application. Differences in the rate of penetration of the organisms at various temperatures might likewise influence the effectiveness of other methods of control.

Ceratostomella ips, which occurs in common association with tree and log-attacking beetles, had the highest cardinal temperatures and most rapid rate of growth of any of the isolates studied. The optimum temperature for growth of this species was close to the maximum for development of the other isolates. Available literature does not disclose whether the staining species associated with insects usually are of a high-temperature and rapid-growing type. Temperatures under bark, particularly of logs lying in the sun, often exceed those of the air, and at times would preclude the development of many staining fungi.

MINIMUM MOISTURE REQUIREMENTS FOR DEVELOPMENT OF CERATOSTOMELLA PILIFERA

Moisture is the most common limiting factor in the development of staining fungi in wood. Unless storage of wood under water is practicable, information on the minimum moisture requirements of staining organisms is of greatest usefulness in the development and application of control measures. Previous investigations have emphasized the minimum points, and the following review of literature is confined to this phase of the moisture problem.

Münch (*15*) reported only slight development of *Ceratostomella coerulea* in wood of *Pinus sylvestris* L. with moisture contents in the region of 28 percent, oven-dry basis. He apparently considered 28 percent as being close to the lower moisture limit for the growth of this organism. Moisture gradients in the experimental material throw some doubt on the opinion that slight discoloration is possible without the presence of free water in the cells.

Lagerberg et al. (*11*) used sections of pine and spruce that had been partially sterilized at 50° C. The minimum moisture content for *C. coerulea* proved to be slightly below 27 percent, oven-dry basis. The limit for *Endoconidiophora coerulescens* was some what higher than that for most of the species studied. No effect on lower moisture requirements resulted from the partial paraffining of the surfaces of the experimental material. They concluded that stain development at, or immediately below, the fiber-saturation point was of no practical significance, and that free water in the parenchyma cells was necessary for important discoloration of wood.

After analyzing data from his own and other investigations, Hubert (*8*) concluded that little development of any of the sap-stain fungi occurs at or below 20-percent moisture, oven-dry basis. The results of a number of studies employing several discoloring species and kinds of wood were presented in tabular form. Minimum moisture limits were shown to vary from 25 to 60 percent in the several tests; differences were great even for the same fungus on a given wood.

Colley and Rumbold (*3*) tested *Ceratostomella pilifera* on sterilized *Pinus taeda* sticks in which a moisture gradient was established during the incubation period. The lower limit for staining was believed to be approximately 24 percent, but a moisture content of 20 percent was suggested as a practicable and safe working limit.

Jussila (*10*) reported that export lumber with less than 24 percent moisture at the time of shipment did not discolor in transit. Considerable stain was encountered in lumber that had more than 24 percent of moisture at the time of loading, or that was exposed to wet conditions during transport.

According to Vanin (*20*), Lebedev reported that there was possible stain development at different moisture contents, oven-dry basis, as follows: 22 to 33 percent for *Ceratostomella coerulea*, 28 to 33 percent for *C. pini*, and 30 to 33 percent for *C. piceae*. No stain development was reported for *C. coerulea* at 22 percent, for *C. pini* at 28 percent, and for *C. piceae* at 30 percent. The details of Lebedev's experimental procedure and interpretation of results are not available.

Most of the previous work did not permit accurate control or determination of the moisture content of the wood during the initial stages of penetration of the staining fungi. In the present study, methods differing from those used previously were employed in determining the critical lower limit of moisture for penetration of *C. pilifera* into *Pinus echinata* sapwood. The manner in which moisture content was controlled is considered less subject to error than the earlier methods of drying wood to various degrees and attempting to maintain constant moisture conditions subsequently, or of setting up moisture gradients in moist sticks with, or without, one end in water.

METHODS

Blocks, approximately 1.5 by 1.5 by 0.3 inches were cut from uninfected *Pinus echinata* sapwood shipped in log form from Louisiana. Transverse specimens were made because moisture changes and fungus penetration in wood are more rapid longitudinally than either radially or tangentially. The blocks were brought to moisture equilibrium in a room with automatically maintained relative humidity of 65 percent. They were then placed in stoppered flasks and steamed in an autoclave for 20 minutes at atmospheric pressure. The blocks were distributed among eight large airtight desiccators, each of which contained a saturated solution, with excess chemical, designed to give a series of maintained relative humidities in the space above the solutions. These solutions are listed in table 6. Wire screens suspended about 2 inches above the surface of the liquid kept the blocks from becoming moistened. The desiccators, solutions, and screens were sterilized before inserting the blocks, as a precaution against later contamination of the wood.

Three blocks intended for controls and three for later inoculation were transferred under as aseptic conditions as possible from the sterilized flasks to each desiccator. The desiccators were stored in a room maintained at a temperature of approximately 25°C. After 5 days, 2 of the blocks in each desiccator were removed and their moisture contents were determined. Three of the remaining four blocks were inoculated by transferring with a small needle ascospores and conidia of *C. pilifera* (No. 3-3-3) to one of the blocks, and droplets of a spore suspension in sterile distilled water to the other two. After 10 days the oven-dry moisture contents of the three inoculated and one control block were determined, and small cubes were then cut from the place of inoculation for sectioning purposes. Hyphal penetration and development were determined by microscopic examination of 12 sections from each block.

A second series was established in which fewer chemical solutions were used, and the blocks were not subjected to a preliminary sterilization treatment; otherwise, the methods were similar to those described above.

RESULTS

The data on the development of *Ceratostomella pilifera* in small blocks of *Pinus echinata* sapwood maintained for 10 days at different moisture contents are summarized in table 6.

The moisture contents reached in the blocks were not in all cases the expected ones for the chemical solutions used; nevertheless a fairly satisfactory range was obtained in the region of the critical points. Close similarity on the whole is evident between moisture contents at the time of inoculation and at the completion of the test. The agreement indicates that an equilibrium of the wood with the air had been reached at the time of inoculation and that approximately the same water content was maintained throughout the incubation period. Although differences are seen in the moisture percentages of the six blocks in each series, the greatest deviation from

TABLE 6.—*Development of Ceratostomella pilifera in small inoculated blocks of Pinus echinata sapwood maintained for 10 days at different moisture contents*

Solutions determining relative humidity of atmosphere surrounding blocks,[1] time of examination, and treatment	Moisture content of blocks (oven-dry weight basis)	Microscopic sections showing hyphal presence[2]	Remarks
	Percent	*Percent*	
Dipotassium phosphate (K_2HPO_4):			
At inoculation	14.5 14.2		
At end of test:			
Inoculated	12.2 13.1 13.5	0 0 0	No surface or interior growth.
Check	14.1	0	
Potassium chloride (KCl):			
At inoculation	16.8 17.1		
At end of test:			
Inoculated	15.7 16.3 16.3	0 0 0	Do.
Check	18.3		
Potassium chromate (K_2CrO_4):			
At inoculation	19.8 19.6		
At end of test:			
Inoculated	17.7 18.0 18.2	0 0 0	Do.
Check	18.8	0	
Barium chloride ($BaCl_2.2H_2O$):			
At inoculation	19.6 20.5		
At end of test:			
Inoculated	18.7 18.8 19.4	0 0 0	Do.
Check	18.4	0	
Sodium sulfate (Na_2SO_4):			
At inoculation	22.8 22.1		
At end of test:			
Inoculated	20.0 20.9 23.1	0 0 0	Do.
Check	23.0	0	
Sodium dibasic phosphate ($Na_2HPO_4.12H_2O$):			
At inoculation	23.4 23.7		
At end of test:			
Inoculated	23.1 23.7 24.0	60 100 50	Surface growth visible only in block with 24-percent moisture. No stain. Hyphae in wood sparse, short, thick with stubby protuberances.
Check	24.7	0	
Potassium sulfate (K_2SO_4):			
At inoculation	24.1 23.7		
At end of test:			
Inoculated	24.4 24.7 28.5	100 100 100	Cottony surface growth but no visible stain. Hyphae mostly hyaline, fairly abundant in rays and tracheids.
Check	24.5	0	
Water (H_2O):			
At inoculation	27.7 38.0		
At end of test:			
Inoculated	27.2 29.9 34.5	100 100 100	Wood visibly stained. Brown hyphae abundant in wood rays and tracheids, particularly in blocks of 34.5 and 29.9 percent moisture.
Check	47.2	0	

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[1] 2 blocks in each series were used only to determine approximate moisture contents of the blocks at the time of inoculation.

[2] 12 microscopic sections were examined from each of the 4 blocks. The fourth block in each series is an uninoculated check, none of which showed surface or interior growth.

the average within six of the seven series employing chemical solutions was less than 2 percent, and in four of them, approximately 1 percent. Unsatisfactory control of moisture content was obtained over water, three of the blocks being close to the fiber-saturation point and the remaining three from 5 to 20 percent higher. Absorption of some water of condensation and wetting in the case of one block undoubtedly were factors in these differences.

Visible staining of the surface was noted only in the blocks exposed to a saturated atmosphere over water. There was a cottony growth of white mycelium on the blocks ranging from 24.4 to 28.5 percent in moisture in the potassium sulfate series. Sparse mycelium developed on the block with 24-percent moisture in the dibasic sodium phosphate series, but no hyphae were evident on the blocks having 23.7 and 23.1 percent of moisture.

Hyphae were observed in the rays and tracheids of sections taken from blocks having 23.1 percent and higher moisture. In the block having 23.1 percent of moisture, only a few short filaments were found close to the point of inoculation in two-thirds of the sections. At moisture contents above 24.4 percent, hyphae were fairly abundant in both the wood rays and tracheids. The uninoculated check blocks for all series showed no interior or exterior evidences of fungus growth.

Hyphal appearance and distribution in the wood cells varied considerably in blocks of different moisture contents. Mature brown hyphae, which result in discoloration of wood, were relatively abundant at moisture contents above 29, infrequent at 27 to 29, and absent below 27 percent. Hyaline filaments were well distributed through rays and tracheids at moisture percentages above 24.4. At the critical moisture contents of 23 to 24 percent, hyphal growth was limited to a sparse xerophytic type, which had penetrated only a short distance from the inoculated edge of the sections. The filaments were short, thick, heavy-walled in appearance and had stubby protuberances rather than definite branch development.

Because of contamination, definite results were not obtainable from the series of tests in which unsterilized wood blocks were used. The blocks apparently had been exposed to *Rhizopus* sp. before being placed in the desiccators. It appeared from the limited data that the minimum moisture limits were not significantly different from those in wood given the fairly mild heat treatment. Likewise, no determinable difference in results was obtained in the use of dry spores and minute spore suspensions as inoculum.

Discussion

After 10 days, slight development of *Ceratostomella pilifera* in shortleaf pine sapwood was noted at moisture contents between 23 and 24 percent, oven-dry basis. However, it is not believed that hyphal development under such conditions would have progressed to the discoloring stage. At moisture contents between 24 and 25 percent, hyaline filaments were well distributed through the wood rays and tracheids and appeared likely to continue development to maturity with longer incubation periods. Above 27 percent in moisture content, the blocks contained mature brown hyphae and usually were visibly stained at the end of 10 days of incubation. The conclusion reached is in close agreement with that reported by Colley and Rumbold (*3*)—that a moisture content in the region of 24 percent is the lower limit for staining of wood caused by *C. pilifera*.

Doubt has existed as to whether free water in the cell cavities of wood is required for stain development. Most investigations, including the present, have found the minimum moisture limit to be in the region of the reported fiber-saturation point of the wood (27+ percent). The fiber-saturation point is not a definite and constant value, but varies to some extent with different woods and treatment of the wood. It is generally accepted that it cannot be reached in an unsaturated atmosphere. Wood incubated in atmospheres of high humidity, but not saturated, showed fairly abundant penetration of hyphae; however, there was visible staining during the incubation period of 10 days only in blocks exposed to saturated atmospheres over water. Although free water apparently is not essential for limited hyphal penetration and development, and possibly slight staining over an extended period of time, it seems evident that significant staining from a practical standpoint occurs only when the wood is at or above the fiber-saturation point.

Insufficient moisture has never been considered a factor in the usual absence of stain development in the sapwood of living trees. Most investigators are inclined to ascribe this condition to excessive water contents instead (*8*, *15*). With certain tree species in which 150 percent or more moisture in the sapwood is not uncommon, this explanation undoubtedly holds true in part at least, although other possible contributing factors cannot be disregarded entirely. In the case of heartwood in the living tree, insufficient moisture has been mentioned as one of the possible reasons for the absence of staining fungi (*8*, *11*). This explanation is believed untenable for most species in that heartwood in the tree is usually, if not always, at or above the fiber-saturation point. In addition, relatively high water contents are not uncommon in unstained heartwood exposed to moist conditions of storage and use. The absence of sugars, starches, and other materials in the parenchyma cells or the presence of inhibitory extractives is considered a more probable influencing factor.

It has been suggested (*3*, *8*) that a moisture content of 20 percent in wood be considered a safe and practicable working limit for control purposes. Such a limit is considered reasonable even though minimum moisture contents for stain development undoubtedly vary to some extent for different organisms and for woods with different fiber-saturation points. Concerning the effect of different wood substrata on moisture relations, Snell (*18*) reported that the optimum and maximum moisture contents for decay were inversely proportional to the specific gravity of the wood. Whatever relations exist for wood-decaying fungi in this connection might reasonably be expected to hold for staining fungi also. It is improbable, however, that minimum moisture requirements are influenced by specific gravity to such an extent as are the optimum and maximum points.

Wide use is made of the minimum point for stain development in control efforts that are directed at regulating the moisture content of wood. The maximum point is of practical usefulness principally for logs and large timbers that can be stored under water. While moisture contents below the minimum are reached eventually in air-seasoned wood, the determining factor in stain occurrence is the rate at which the wood dries. The rapid penetration and subsequent development of discoloring fungi require that the drying rate be fairly rapid if staining is to be avoided. Under certain conditions of drying, wood may come to, or below, fiber saturation at the surface but retain a high moisture content in the interior. If this occurs after the staining organisms have penetrated into the interior but while the hyphae in the surface layers are still in the hyaline stage, a type of discoloration known as "interior stain" may develop.

Wood that has been dried below the fiber-saturation point is still subject to discoloration upon remoistening. The relative susceptibility of remoistened and fresh wood varies for different organisms, woods, and methods of handling the wood (*11*). Discoloration of seasoned wood that is placed under moist conditions of use or storage is not uncommon. In the case of export shipments, Jussila (*10*) reported that stain was common in dry lumber that was exposed to moist conditions at the time of loading and unloading, in the holds, or on deck during transport. Similar observations have been made on shipments of lumber from the Gulf States.

PENETRATION OF CERATOSTOMELLA PILIFERA INTO WOOD AND ITS RELATION TO CONTROL PROBLEMS

It is generally recognized that staining fungi concentrate in the parenchymatous elements of sapwood and require the contents of such cells as a ready source of food. While hyphae are not uncommon in the tracheids of coniferous woods, they are primarily massed in wood rays and resin ducts. In wood that is stained thoroughly by some of the common *Ceratostomella* species, parenchymatous cells sometimes are decomposed to the extent that structure is obliterated. Tracheids usually are left intact except for occasional bore holes in the walls. Passage of the fungi from cell to cell is often through pits in the radial walls, but direct penetration of the tangential walls of tracheids is not uncommon. The mechanism of penetration is a disputed point; Lagerberg et al. (*11*) believe penetration is accomplished ordinarily by mechanical means, whereas Hubert (*8*) considers secretion of enzymes by the hyphal tips as a more probable explanation. The constriction of hyphae in forcing passage through pits and walls and the occurrence of swellings at the points of entrance and emergence are common for some species, but apparently not for all.

Information on the rate of penetration of staining fungi into wood has been limited largely to general indications yielded by studies of factors affecting stain development. Münch (*15*) reported an average longitudinal growth for *C. pini* of 5 to 10 mm. per day. There was little or no penetration in freshly cut wood, but complete penetration within 10 to 12 days was obtained in cross sections, 8 cc. in height, after a loss of water equivalent to 10 to 15 percent of the weight of the wood. Lagerberg et al. (*11*) present some general figures which indicate daily radial rates of penetration of the magnitude of 1 to 1.8 mm. for *C. coerulea*, and 2 to 2.5 mm. for *C. pini*, under favorable or semifavorable conditions for growth. Greatly reduced rates of penetration were indicated for both organisms as moisture, oxygen, and other conditions affecting growth became less suitable. The relation of temperature to the rate of penetration of *C. pilifera* into pine sapwood has been considered in the present bulletin.

The purposes of these studies were to determine rates of penetration of *C. pilifera* in the different structural planes of pine sapwood, and to use such data in ascertaining how soon chemical treatments must be applied to freshly cut wood in order to obtain efficient control. The occasional failure of chemical-control measures that are in wide commercial use has sometimes been the result of delaying treatment until the staining organisms had penetrated beyond the depth reached by the antiseptic solution

RATE OF HYPHAL PENETRATION INTO WOOD

METHODS

Sapwood blocks, 2 by 2 by 2 inches, were quarter-sawed from an uninfected log of *Pinus echinata* that averaged about five growth rings per inch. Care was taken to obtain as true radial, tangential, and transverse cuts as possible. All surfaces of the blocks except the one to be inoculated were dipped immediately for a few seconds in a hot bath of paraffin (about 100° C.), followed by transfer to a cooler paraffin bath (about 60° C.). Single blocks were then placed in sterile 2-quart jars that had been plugged with cotton and sterilized. The blocks were inoculated by placing a spore suspension of a monosporus culture of *Ceratostomella pilifera* in a small area in the center of the surface to be tested. The jars were distributed between two rooms maintained at 60 and 90 percent relative humidity and a temperature of 25° to 28° C. After incubation periods of 24, 48, 72, 96, and 288 hours, six jars, containing blocks inoculated on the three types of surfaces, were removed from each room. Microscopic sections were made from small cubes that were cut from the blocks at the place of inoculation. The maximum penetration recorded in all blocks of a given series and an average of the maximum penetration in each of the blocks of a series, based on the examination of 10 sections from each block, are used in presenting the results. Moisture contents of the large blocks were determined from samples taken adjacent to the area from which the cubes were removed.

To compare penetration from springwood and summerwood surfaces, 16 blocks, 2 by 1.3 by 0.7 inches, were cut in such a manner that wide bands of either springwood or summerwood were exposed on the tangential surface. The blocks were taken from a single bolt and from the same annual rings insofar as possible. Half of the blocks were either surface-sterilized in boiling water for 5 seconds or autoclaved for 15 minutes at 15 pounds' pressure. Four blocks of each series of eight were then inoculated on either a summerwood or a springwood surface. Incubation was for 84 hours in a room maintained at 90 percent relative humidity and a temperature of 25° to 28° C.

RESULTS

The data for the blocks incubated at 60 and 90 percent relative humidity are grouped because no significant difference in hyphal penetration or moisture content of the blocks could be detected. The average moisture contents of the blocks after the several incubation periods, based on six specimens in each case, were 104, 98, 106, 105, and 100 percent in the room at 90 percent relative humidity;

and 106, 107, 96, 102, and 96 percent in the room at 60 percent relative humidity. It is obivous that the method of handling the blocks permitted little loss of water, even after 12 days.

The depth of radial, tangential, and longitudinal penetration of *Ceratostomella pilifera* in blocks incubated for 24 to 288 hours is shown in table 7. Although penetration varied considerably in different sections from a single block, and occasionally in different blocks of a given series, the rates shown are typical of the great mass of the data.

TABLE 7.—*A comparison of radial, tangential, and longitudinal penetration of Ceratostomella pilifera into Pinus echinata blocks incubated for 24 to 288 hours at 25° to 28° C.*

Incubation period (hours)	Penetration [1]						Remarks
	Tangential		Radial		Longitudinal		
	Average	Maximum	Average	Maximum	Average	Maximum	
	Mm.	*Mm.*	*Mm.*	*Mm.*	*Mm.*	*Mm.*	
24	0.0	0.0	0.3	0.5	0.5	0.7	No measurable tangential penetration.
48	.3	.4	1.2	1.4	5.5	6.0	Tangential penetration sparse.
72	.8	.9	1.7	2.0	10.5	11.5	All hyphae hyaline.
96	1.1	1.3	3.0	5.5	16.0	17.5	Interior hyphae hyaline.
288	6.0	8.0	10.0	12.0	45.0	51.0	Brown hyphae present in all cases.

[1] Based on the microscopic examination of 20 to 40 sections from 2 to 4 blocks in each case. Average penetration equals an average of the maximum penetration in each of the blocks of a series. Maximum penetration equals the greatest penetration recorded in any of the blocks of a series.

Definite daily rates of penetration, which were maintained throughout the several incubation periods, are not apparent in table 7. Except for the first 24 hours, however, the data indicate an approximate daily rate of 0.5, 1, and 4.5 mm. in the tangential, radial, and longitudinal direction, respectively. Rates of a somewhat similar magnitude apparently were being maintained at the end of 288 hours. Using these data as a basis, a ratio of 1:2:9 for the relative rates of penetration in the three structural directions is indicated. Earlier studies in the field, in which a number of measurements were made of visible discoloration in pine lumber, had shown radial penetration to be two to four times as rapid as tangential penetration and one-third to one-seventh as rapid as longitudinal penetration.

A comparison of tables 4 and 7 shows close agreement on the whole in the depth of radial and longitudinal penetration for similar incubation periods and temperature. Again, the rate of longitudinal penetration into wood is indicated to be as great or greater than the average radial growth on agar (table 2).

The radial penetration from summerwood surfaces was slightly less than from springwood surfaces, both in steamed and unsteamed wood (table 8). Although the differences were small, they were fairly consistent for all blocks. A pronounced effect on rate of penetration resulted from steaming at 15 pounds' pressure for 15 minutes. It is noted, however, that the depth of penetration into the unsteamed wood was somewhat less than would be expected from table 4 and 7. Unfortunately, determinations of moisture content were not made in this series; therefore, it is possible that moisture conditions were somewhat more favorable for rapid penetration in the steamed than in the unsteamed wood. Nevertheless, radial penetration into the steamed wood was two to three times as great as that recorded in any of the other tests.

TABLE 8.—*Radial penetration of Ceratostomella pilifera from inoculated springwood and summerwood surfaces of steamed and unsteamed Pinus echinata blocks incubated for 84 hours at 25° to 28° C.*

Surface inoculated	Treatment of blocks	Radial penetration [1]	
		Average	Maximum
		Mm.	*Mm.*
Springwood	5-second dip in boiling water.	1.4	1.5
Summerwood	do	1.2	1.3
Springwood	15 pounds' steam for 15 minutes	8.5	9.0
Summerwood	do	7.0	8.0

[1] Based on the examination of 40 sections from 4 blocks in each case. Average penetration equals average of the maximum penetration in each of the blocks of a series. Maximum penetration equals the greatest penetration recorded in any of the blocks of a series.

RATE OF HYPHAL PENETRATION AS AFFECTING USE OF CHEMICAL-CONTROL TREATMENTS

METHODS

Radial and tangential boards, approximately 1 by 6 by 14 inches, were cut from uninfected *Pinus echinata* sapwood. The boards were sprayed immediately with a spore suspension of *Ceratostomella pilifera* and then placed in solid piles in a room maintained at 90 percent relative humidity and a temperature of 25° to 28° C. After periods of 1, 12, 24, 48, 72, or 96 hours, a given number of boards were dipped for 10 seconds in a 0.24 percent aqueous solution of a proprietary compound containing 5 percent of ethyl mercuric chloride. The treated boards were stored in small piles in the humidified room for a period of either 21 or 28 days, at which time they were examined for surface and interior stain development. Two series, consisting of 24 and 36 boards, were handled in the manner described. Depending upon the series, two or three radial boards and an equal number of tangential boards were tested for each of the six periods of delay of treatment.

In determining the approximate depth of penetration of antiseptic solutions applied as 10-second dips, use was made of solutions that give a color reaction in wood. Freshly cut boards were dipped for 10 seconds in each of the following: 5 percent sodium bichromate, 5 percent sodium dinitrophenolate, 10 percent hydrochloric acid (tested for red color with phloroglucin), and 4 percent zinc chloride (tested for blue color with a mixture of 1 percent potassium ferrocyanide, 1 percent potassium iodide, and a 5 percent starch solution). Supplementary evidence was obtained from measurements of the bright outer zone in 20 boards that had been given a 10-second treatment with the ethyl mercuric chloride solution either 72 or 96 hours after inoculation with *C. pilifera*.

RESULTS

In table 9 is presented a summarized statement of stain development in *Pinus echinata* boards that were dipped in an antiseptic solution within 1 to 96 hours after inoculation with *Ceratostomella pilifera*. The data for radial and tangential boards are not segregated, because they showed no important differences in interior stain development. Surface stain and mold were somewhat less abundant on radial than on tangential boards, but there was no basis for concluding that a longer delay of treatment would have been safe. From a practical standpoint, true radial boards of any size cannot be cut; furthermore, tangential side surfaces and transverse end surfaces always provide for the more rapid radial and longitudinal penetration of hyphae. Therefore, any differences that might have appeared in the present studies would have had little practical significance.

Conditions were somewhat less favorable for severe staining and molding in series 1 than in series 2, and this is indicated by the differences in surface development. In the former series, progressive drying of the boards during incubation was facilitated by leaving a 1-inch space between the individual pieces in the pile. In series 2 the boards were separated only one-quarter to one-half inch in the pile. Differences in the original moisture content of the pieces were not a factor, as the range in both series was between 100 and 110 percent, oven-dry-weight basis.

TABLE 9.—*Development of surface and interior stain in Pinus echinata boards inoculated immediately after sawing with Ceratostomella pilifera and dipped within 1 to 96 hours in an antiseptic solution*

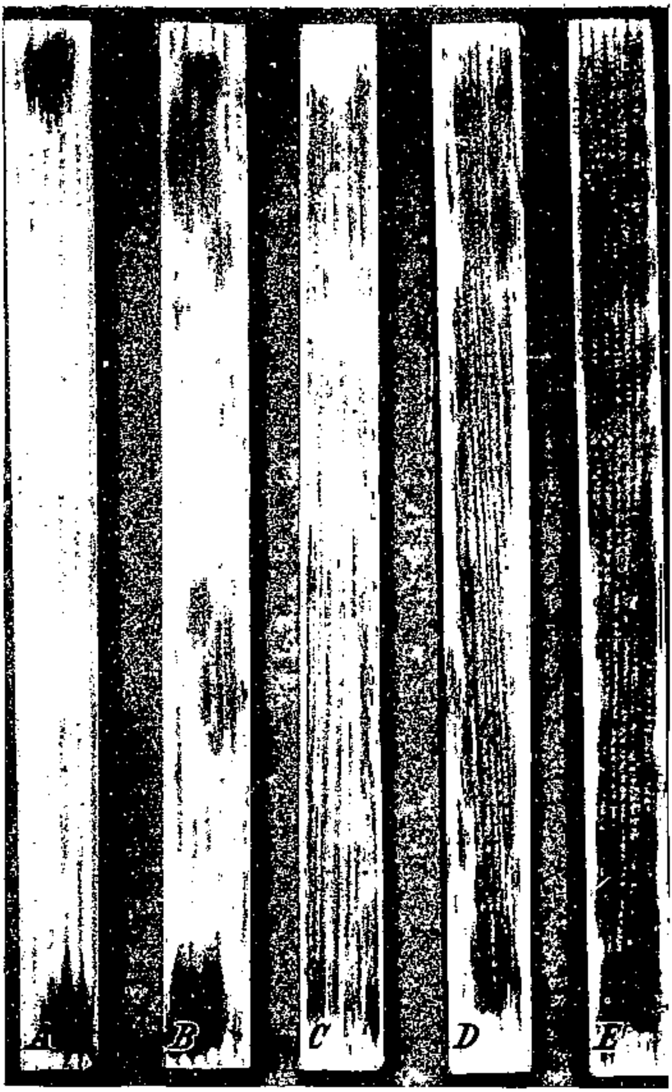
Series and treatment delay (hours)	Surface stained	Mold intensity [1]	Interior stain
Series 1: [2]	*Percent*		
1	0	Light to medium	Patch of end stain in 1 board.
12	0		Patch of end stain in 2 boards.
24	0		End stain in all 4 boards; 2 small patches of stain away from ends.
48	0–5		20 to 50 percent of stain in 3 boards. End stain only in fourth.
72	0–10		Thoroughly stained except for bright shell.
96	10–30		Thoroughly stained except for partially bright shell.
Series 2: [3]			
1	0–2	Heavy	Patch of end stain in 2 boards.
12	0–4		Patch of end stain in 3 boards.
24	4–8		End stain in all 6 boards; 2 patches of stain away from ends.
48	15–25		65 to 75 percent of stain in all boards. Bright outer shell.
72	20–45		Thoroughly stained except for partially bright shell.
96	20–50		Do.

[1] Surface molding was caused by organisms present in the humidified incubation room.

[2] Based on 2 radial and 2 tangential boards for each delay in treatment. The boards were separated 1 inch in pile during incubation of 28 days at 90 percent relative humidity and at temperatures ranging from 25° to 28° C.

[3] Based on 3 radial and 3 tangential boards for each delay in treatment. The boards were separated ¼ to ½ inch in pile during incubation of 21 days.

There was heavy development of stain in the interior of the boards when treatment was delayed 48 hours or longer after inoculation (table 9). Although a 48-hour delay apparently was close to the critical time for efficient control of interior discoloration, it obviously was too long under the very favorable conditions provided for staining.



Interior stain development in *Pinus echinata* sapwood inoculated immediately with *Ceratostomella pilifera* and treated after different periods of time with an antiseptic solution. *A* and *B*, treated 24 hours after inoculation. End stain was general in this series and there were patches of interior stain in occasional boards. *C*, *D*, and *E*, treated 48, 72, and 96 hours after inoculation, respectively. The unstained areas indicate to some extent the depth to which the antiseptic solution penetrated and prevented the development of stain.

Delays longer than 48 hours resulted in complete discoloration of the interiors, except for a partially bright outer shell of 1 to 4 mm. (pl. 2). The bright outer zone was less distinct with increase of stain on the surfaces of the boards, which increase became important when the treatment had been delayed 72 hours or longer in series 1 and 48 hours or longer in series 2. Daily examinations of the boards after inoculation showed that light patches of stain had developed before treatment, particularly in the 96-hour series. In addition to such slight stain as was present at the time of treatment, failure of the solution to give continuous protection during the prolonged severe conditions undoubtedly contributed to stain development on the surfaces.

Patches of end stain were found occasionally in boards treated immediately or within 12 hours, and were general when the treatment was delayed 24 hours (pl. 2). Such stain cannot be attributed to rapid longitudinal penetration alone. Either the treatment failed to give complete protection to the ends, or inoculum was carried into the wood beyond the depth reached by the solution. Failure of the treatment could have been immediate, or after exposure for a time to the severe conditions of the test.

Although the antiseptic solution employed in these studies is used widely and effectively for the control of stain in lumber and other wood products, no ready method for determining the depth of penetration is available. Longitudinal penetration of other aqueous solutions ranged from 5 to 10, with an average of 7 mm.; and the radial and tangential penetration was from 1.5 to 3.5, with an average of approximately 2 mm. Supplementary evidence, obtained from the measurement of the bright outer zone in 20 radial and tangential boards having interior discoloration, indicated an average longitudinal penetration of the solution of 8 mm. and a radial and tangential penetration of 1.5 to 2 mm. Comparing these depths of penetration of the solution with the rates of hyphal penetration into wood, it appears that 48 hours is close to, but possibly longer than, the maximum delay of treatment for efficient control of stain.

HYPHAL DISTRIBUTION AND DEVELOPMENT IN TEST BLOCKS SUBJECTED TO DIFFERENT CONDITIONS

The type and abundance of hyphae, both on and in wood, varied considerably with the incubation period, the surface inoculated, and the method of handling the blocks. Earlier and more abundant development of white and colored hyphae was evident on tangential and transverse surfaces than on radial surfaces. This was true also of steamed in comparison with unsteamed wood; after 96 hours, brown hyphae were not pronounced on most of the unheated blocks, whereas conspicuous development of colored hyphae and light staining were evident on all steamed blocks. No recognizable difference in growth on summerwood and springwood surfaces could be detected after the rather short incubation period of 84 hours.

Hyphal development within the wood was most abundant in the blocks inoculated on the transverse and tangential surfaces. Colored hyphae usually were confined to the surface layers in wood incubated for periods of 96 hours or less. In steamed wood incubated for 110 hours, colored hyphae extended 4 to 5 mm. from a transverse surface, whereas in unsteamed wood, such hyphae were present only 1 mm. or less from the inoculated surface. Hyphal development was more abundant in all cases in steamed than in unsteamed wood.

As to distribution in the wood elements, the hyphae were concentrated in wood rays and resin ducts, but were not uncommon in tracheids (pl. 3). In the 288-hour series, the rays were compacted with thick brown hyphae, and frequently only a semblance of the original parenchyma-cell structure remained. Penetration of the tracheid walls occurred usually through bordered pits in the radial walls (pl. 3, *C* and *D*). Direct penetration of walls of tracheids was observed occasionally but pronounced dissolution was never evident.

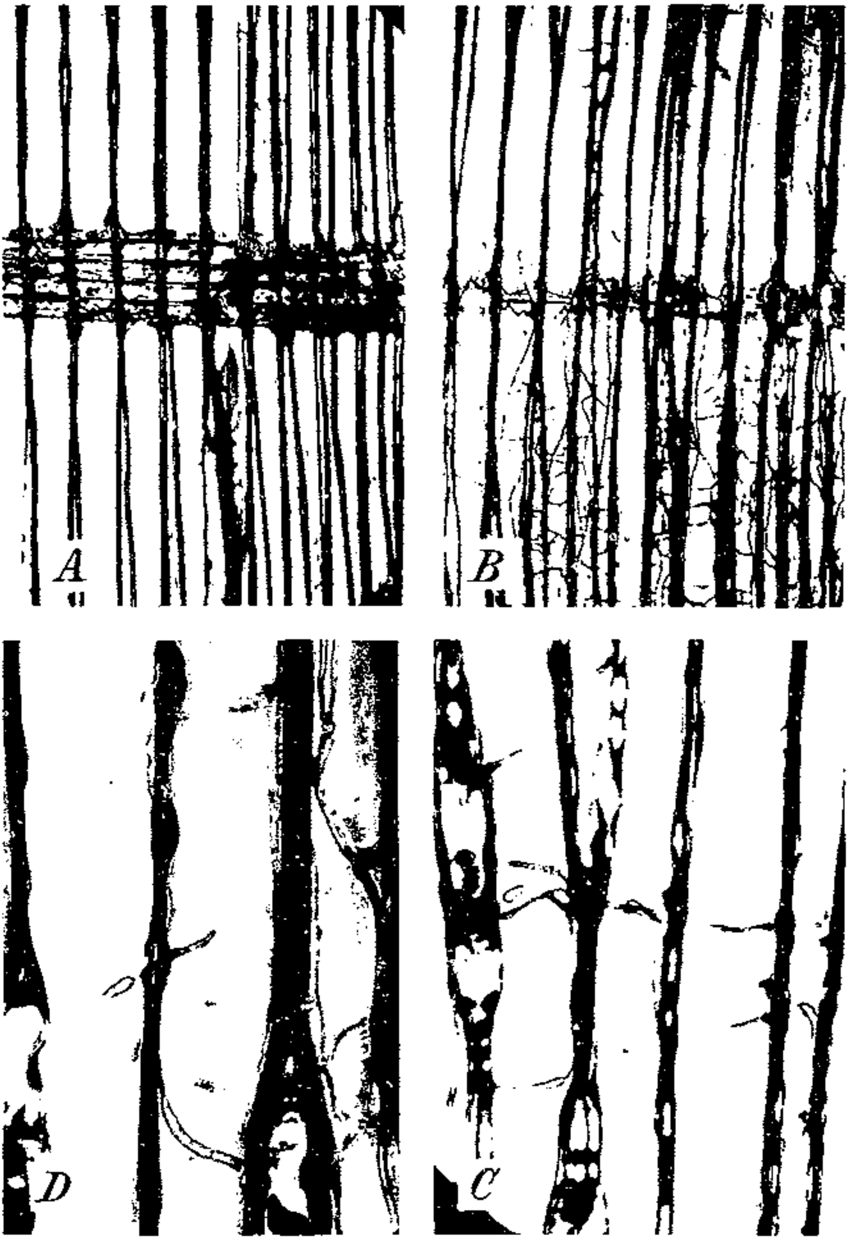
In boards with interior stain, hyphae were observed in microscopic sections that included a portion of the bright outer zone and the discolored wood below (pl. 3, *B*). A definite line of demarcation, in both abundance and type of hyphae, was evident in passing from the clear outer area to the discolored interior. Hyaline hyphae were found in the clear outer wood, but the mature brown stage was lacking. Development in this zone was sparse, and the scattered hyphae gave evidence of protoplasmic disturbance or disintegration. In the stained wood, hyphae were abundant in rays and tracheids and were largely of the mature brown type. There was little doubt that the interior-stain condition had resulted from killing of the hyphae in the surface layers of the wood before the colored stage had been reached, as indicated by the bright wood at the edges and uncut end of board *B* in plate 4, but not until some of the hyphae had penetrated beyond the depth reached by the chemical treatment.

DISCUSSION

Penetration of a given blue-stain fungus into wood is influenced by a number of factors, including moisture and oxygen conditions, temperature, and physical and chemical differences which either occur naturally or are induced in wood.

In the present study no attempt was made to compare wood at different moisture contents, but there is reason to believe that water and oxygen conditions of the test material favored rapid growth of *Ceratostomella pilifera*. This belief is supported by the facts that rates of penetration differed little in paraffined and unparaffined wood, longitudinal penetration into wood equaled the rate of radial growth on malt-extract agar, and stain development was rapid in boards from which little or no loss of water was possible. The moisture content of the wood ranged from 95 to 110 percent in practically all cases. The possibility that the rate of penetration might have been somewhat greater at other moisture contents, however, is not discounted. Lagerberg et al. (*11*) reported slow penetration of *C. coerulea* into pine sapwood of 150 to 160 percent moisture content, oven-dry weight basis. Penetration was rapid at 110 to 120 percent unless diffusion of oxygen into the wood was retarded artificially.

The effect of different temperatures on rate of penetration has been described earlier in these studies. Penetration of *C. pilifera* into sapwood was most rapid at temperatures that likewise favored greatest growth of mycelium on agar. The incubation temperature (25° to 28° C.) employed in the present series of tests undoubtedly provided favorable thermal conditions for rapid growth.



Distribution and type of penetration of hyphae of *Ceratostomella pilifera* in *Pinus echinata* sapwood. *A*, Concentration of hyphae in the wood rays. Radial section. *B*, Radial section from the transition zone between bright and discolored wood [illegible] stain. Note fragmentary development of hyaline hyphae in bright zone in contrast to numerous mature brown hyphae in discolored zone. *C*, Tangential penetration of hyphae through bordered pits in radial walls of tracheids. Note decomposed cell walls of wood rays. Tangential section. *D*, Penetration of a hypha through a bordered pit in the radial wall of a tracheid. Tangential section.

Comparison of stain development in boards inoculated with *Ceratostomella pilifera*. *A*, No antiseptic solution applied subsequently. *B*, Dipped in an antiseptic solution 72 hours after inoculation. The top end represents a cut through the board and not the surface to which the solution was applied.

Physical and chemical differences which occur naturally or are induced in wood of a given species may have an appreciable effect on the penetration of staining fungi. Lagerberg et al. (*11*) found that changes in the nutritive value of wood cut at different seasons of the year had little effect on penetration. Likewise, variations in the density of wood were not important for most of the fungi studied. On the other hand, staining was greatly retarded in wood that had been either stored in water or seasoned and later remoistened. The loss of water-soluble and other nutritive substances from immersion, action of other micro-organisms, etc., was considered to be primarily responsible for the reduced susceptibility of the wood. In the present studies, steaming of the wood seemed to increase the rate of radial penetration of *Ceratostomella pilifera*. Changes in the chemical or physical conditions of the wood, rather than in moisture content, are believed to have been concerned. Greater penetration, or other evidences of attack, in steamed wood has been reported by Chapman (*2*) for blue-stain fungi and by Spradling (*19*) for *Trichoderma lignorum* (Tode) Harz. In the present work, radial penetration was somewhat less rapid in summerwood than in springwood. Apparently, the difference, if any, is slight, and its effect would be of little significance either in initial penetration or in continued development of hyphae in woods with different amounts of springwood and summerwood.

Under favorable moisture and temperature conditions for growth, *Ceratostomella pilifera* penetrated into unheated sapwood at approximate daily rates of 0.5, 1, and 4.5 mm. in the tangential, radial, and longitudinal directions, respectively. Other staining species undoubtedly differ from *C. pilifera* in rate of penetration. From the studies of growth on agar, *C. ips* would be expected to penetrate more rapidly, and *C. pluriannulata* somewhat more slowly than *C. pilifera*. It is not known whether relative growth of different species on agar is a fairly reliable index of relative penetration into wood, although it seems likely such would be found to be the case if suitable agar and wood substrata were used in the comparative studies.

A general ratio of 1:2:7 to 1:4:19 would be expected to cover relative penetration of *C. pilifera* in the three structural planes of wood. Differences between staining species in ratios of penetration in different planes probably would be less than in relative penetration in one plane. As a general rule, longitudinal penetration occurs in the tracheids and resin ducts primarily, both of which present only few obstructions in the form of cell walls. Tracheids in pine are often 5 to 6 mm. in length. Radial spread takes place largely in the wood rays, the cells of which apparently offer no great resistance, and may extend continuously throughout the sapwood. Penetration in a tangential direction can be accomplished only through numerous walls, mostly of tracheids. Nevertheless, it is obvious from the present studies that tangential penetration is not insignificant.

Rate of penetration of discoloring fungi has a direct bearing on the use of surface treatments for the control of stain in lumber. The failure of antiseptic dips in current use is sometimes the result of delay in applying the solutions to wood until the hyphae have penetrated beyond the depth reached by such treatments. Comparisons of depth of penetration of solutions with rate of hyphal penetration of

C. pilifera into wood indicated 48 hours to be close to, but longer than, the maximum delay for efficient control. Although the depth of hyphal penetration after 48 hours usually was less than that reached by the solution, maximum hyphal spread in the radial and tangential directions often was greater than the recorded minimum depth of the solution. A delay of 48 hours in treatment proved definitely inadequate in tests in which inoculated boards were dipped at various intervals in a recognized control solution. There was heavy development of interior stain in practically all boards treated 48 hours or longer after inoculation. Moisture and temperature conditions favored rapid hyphal development in the wood throughout these tests.

The evidence available indicates that a delay of more than 1 day in treating lumber is not advisable, if control of *C. pilifera* is to be expected under all conditions. Treatments that are delayed 2 days might prove effective under many environmental conditions, but cannot be considered as generally safe. Treatment after delays of 3 or 4 days, particularly during periods of rapid stain development, would seem to have little value except in reducing inoculum and retarding further staining on the surfaces. Use of chemical dips for this purpose alone could not ordinarily be justified. In actual practice the use of other chemical solutions and the possible presence of other organisms that penetrate more rapidly than *C. pilifera* would have to be considered; also, the possibility that some longitudinal penetration of hyphae might occur from side surfaces that have not been sawed exactly parallel to the orientation of the tracheids. Nevertheless, it is believed that a delay of no longer than 1 day will lead to satisfactory control in practically all cases.

SUMMARY

Eleven isolates of *Ceratostomella*, including seven cultures of *C. pilifera* from different geographic regions, *C. coerulea* from Canada and Sweden, *C. pluriannulata*, and *C. ips*, showed significant differences in reaction to temperature on malt-agar. The *C. pilifera* isolates comprised two distinct groups which differed by 2° to 4° C. in optimum and maximum temperatures for growth. The low-temperature group and *C. coerulea* from Canada had as approximate critical points 3°, 25° to 26°, and 31° to 34°; the high temperature group and *C. pluriannulata*, 4°, 27° to 29°, and 34° to 35°. *C. ips* had cardinal points varying from 2° to 8° above any of the other fungi tested. An increase of 5° to 8° above the optimum inhibited growth, whereas a decrease of 20° or more was required to inhibit growth at low temperatures.

While daily increments at a given temperature were not constant for any of the fungi, neither a definite periodicity in growth rate nor a determinable change in rate with time was indicated.

There was a direct correlation between cardinal temperatures for growth on agar and viability of the isolates at unfavorably high temperatures.

Loss of viability occurred relatively early at temperatures only slightly higher than the maximum points for growth. *C. coerulea* and two cultures of *C. pilifera* were no longer viable after 7 or 14 days at 35° C. All isolates except *C. ips* failed to resume growth after 2 days at 40°.

The time of appearance of brown hyphae and the rate of change from hyaline to brown varied with the different isolates and temperatures. Brown hyphae appeared earliest at the most favorable temperatures for growth, and there were indications that hyphae of a given age changed from hyaline to brown more rapidly at such temperatures.

Daily changes of temperature between the optimum and minimum points for development had no effect on the growth-temperature relations of *C. pilifera* and *C. ips*. Both organisms became adjusted immediately to the new thermal environment and continued growth at a normal rate for that temperature. The only departure from typical growth rates in constant thermal environments was retarded increments for about 2 days at favorable temperatures, following exposure of the cultures for 1 day to temperatures slightly above the maximum points for growth.

A direct correlation was apparent between growth of *C. pilifera* on agar and development in southern pinewood at different temperatures. Penetration of hyphae into wood was most rapid at temperatures that likewise favored rapid mycelial growth on agar. The rates of longitudinal penetration into wood and of radial growth on agar were closely similar.

The average of temperatures for the respective locations within piles of unseasoned lumber at three southern sawmills ranged from 1.3° to 6.1° C. lower than those of the surrounding air. The highest temperature recorded within any one pile was 31.5°. It appears that high temperatures are not an important limiting factor in the practical problem of discoloration of lumber during air seasoning.

The minimum moisture content for development of *C. pilifera* in *Pinus echinata* sapwood was determined as approximately 24 percent, oven-dry-weight basis. There was slight penetration of hyphae at moisture contents between 23 and 24 percent, such hyphal development being limited to short, thick, heavy-walled filaments. There was fairly abundant hyphal penetration in wood subjected for 10 days to atmospheres of high humidity, but not saturated.

After 10 days, mature brown hyphae were relatively abundant in wood above 29 percent in moisture, infrequent at 27 to 29 percent, and absent below 27 percent. There was visible staining only in wood that was at or above the fiber-saturation point (27+ percent). Although free water in the wood did not appear essential for limited development, important staining is not considered likely in wood below the fiber-saturation point.

Ceratostomella pilifera penetrated into *Pinus echinata* sapwood at approximate daily rates of 0.5, 1, and 4.5 mm. in the tangential, radial, and longitudinal directions, respectively. Penetration was slightly less rapid in summerwood than in springwood, but the difference was too small to be significant. Radial penetration was greater in steamed than in unsteamed wood.

Under favorable conditions for growth, hyphae of *C. pilifera* penetrated into wood beyond the determined depth reached by control treatments within 48 hours, or shortly thereafter. Delays of 48 hours or longer in applying an antiseptic treatment proved excessive for the control of stain in boards which had been inoculated immediately after sawing. A delay of more than 1 day in the application of treatments in practice is not considered advisable, if control of *C. pilifera* is to be expected under all conditions.

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TB 808 (1942) USDA TECHNICAL BULLETINS UPDATA
CLIMATE AND ACCELERATED EROSION IN THE ARID AND SEMI-ARID SOUTHWEST
THORNTHWAITE, C W SHARPE, C F S DOSCH, E F 2 OF 2

Bedrock is not exposed in the gully in the upper end of the Tusayan Washes section, but near the mouth of the Wepo the Mancos shale has been cut through and the first of several exposures of the underlying more resistant formations is encountered. Similar outcrops are found at intervals downstream from the vicinity of Coyote Springs to about 6 miles above Red Lake trading post. Low cliffs become more prominent down valley, especially on the southeastern side, and culminate in the Navajo-Wingate cliffs, which close in 1.5 miles below Coyote Springs (figs. 25 and 35).

About 17 miles northeast of the Red Lake trading post the Navajo-Wingate cliffs recede from the wash. The Polacca then traverses a broad lowland developed on the weak Chinle formation and elongated in a northwest-southeast direction parallel to the strike of the rocks. Here, about 2 miles east of Red Lake trading post, Oraibi Wash formerly joined the Polacca by several flood channels.

FIGURE 49.—View up the Polacca Gully from about 5 miles southwest of Polacca village. The gully here is about 40 feet deep.

As the surface is covered by a mantle of sand, the areal distribution of fill material in much of the Tusayan Washes section is not well known. Some evidence can be obtained from exposures along the gullies (fig. 49) and from aerial photographs. In the Tolani Lakes region (fig. 25), the fill is remarkably uniform. It appears to have been derived both from upstream and from the valley sides. Fans and leveed channels have spread the depositional material over the valley floor.

Although the lateral slopes of the valley appear to be relatively smooth when viewed from a distance, closer examination shows that they are ridged with many longitudinal sand dunes (*76, p. 121*) paralleling the prevailing southwest winds (fig. 40). The sand largely covers the pediment slopes of the area, and in places long fingers of sand extend from the valley to the top of the bordering cliffs.

There has been little recent erosion of the lateral slopes in the area up valley from Coyote Springs, in part because of the plant cover and in part because the practice of the Hopi Indians of utilizing for irrigation all flood waters off the slopes above their fields has acted as a check on run-off and has prevented the formation of large lateral gullies. Drainage of the lateral slope zone is obstructed and incomplete, and most of the gullies are small and discontinuous. Small streams survive for short distances, only to be absorbed by the surface sand (figs. 50 and 51). Little of the run-off of the area ever reaches the main Polacca Gully.

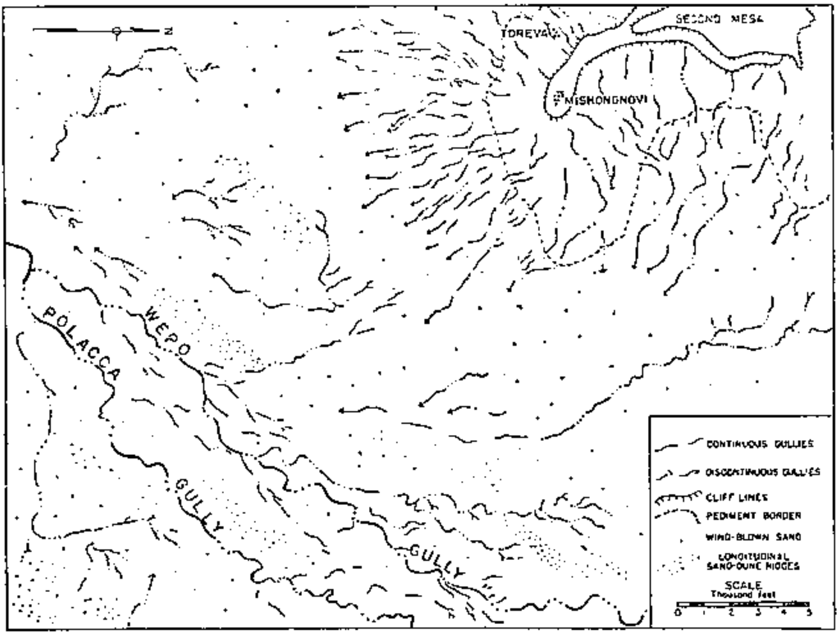

FIGURE 50.—Physiographic map of an area north of the junction of the Polacca and Wepo Gullies, showing the absorption of streams by the broad sand-mantled alluvial surface.

The Tolani Lakes area is somewhat warmer and drier than the area above Coyote Springs and is now a broad expanse of sand flats overgrown with brush, willows, and weeds, such as Russian-thistle. Navajo families inhabiting the area have stripped it of much of its natural vegetation. Movement of sand and encroachment of undesirable plant species have resulted.

The condition of the present Polacca Gully in the Tusayan Washes section is somewhat different in the reaches above and below the mouth of the Wepo. Downstream to the mouth of the Wepo the Polacca Gully contains remnants of small terracelike benches, which

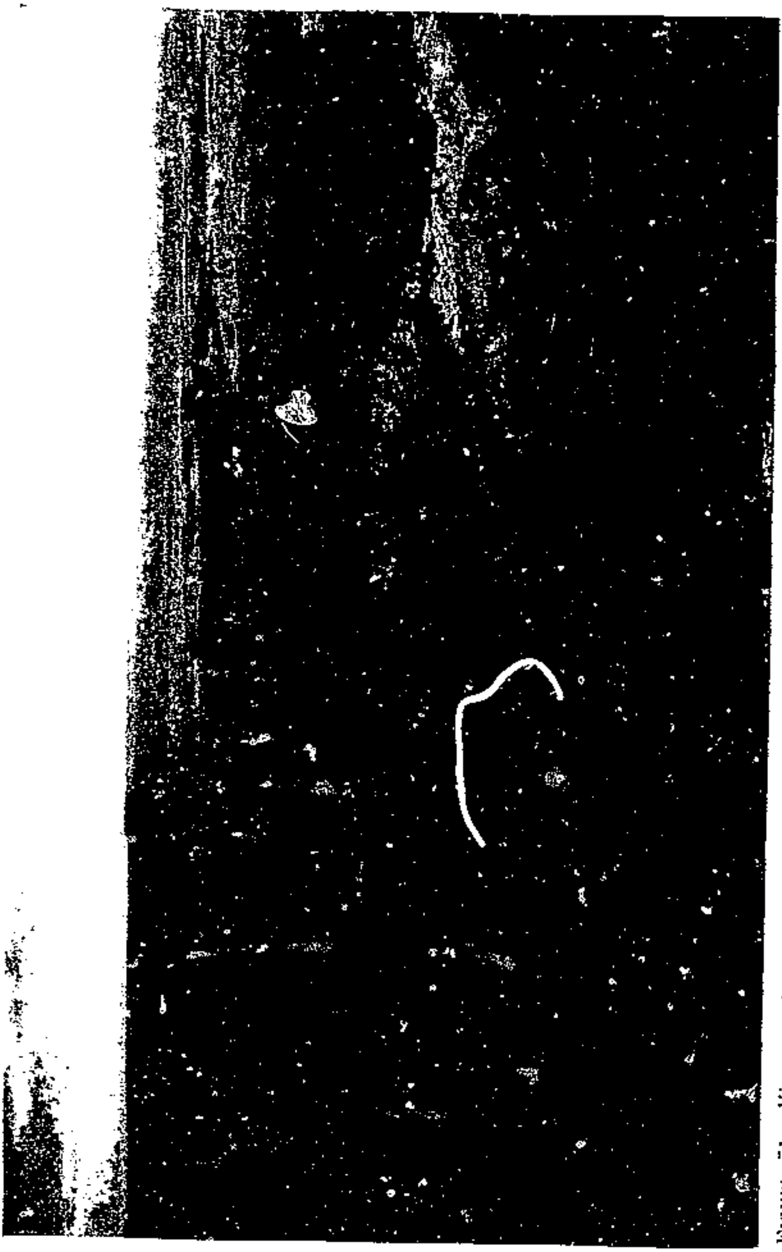

FIGURE 51.—View southwest over the Polacca Wash from First Mesa. Few of the channels on the lateral slope in the foreground reach the Polacca Gully, which is seen winding across the middle of the view.

suggest that this portion of the channel may have undergone four distinct, though probably very brief, phases of recutting. Below the mouth of the Wepo the suggestion of multiple recutting disappears. A possible cause for successive stages of cutting is found in the increase in volume of flow effected when gullies in the Wepo, Burnt Corn and Keams Canyon Washes became joined to the Polacca and in the junction of the lower and upper Polacca gullies.

Evidence of the history of past cutting of the Polacca Gully near the mouth of Wepo Wash is indistinct. Wind-blown material has so mantled the surface that the presence of an old, gently sloping, longitudinal fan, such as would have been formed at the lower end of a discontinuous gully, might well be obscured. It seems probable, though, that the cutting that started the extensive gullying of the upper wash began in the vicinity of the bedrock outcrops close below the junction of the Wepo and the Polacca (fig. 26, between *E* and *F*). This is suggested by the greater breadth of the upper part of the gully upstream from this point (fig. 26, *E*) and also by recollections of the Hopis that gullying of the Polacca Wash was first observed in approximately this location.

The cutting of the Polacca Gully through the remainder of the Tusayan Washes section is thought to have set in somewhat later than that above the mouth of the Wepo. The location of the initial cutting points is obscure, but channel cross sections suggest one about 8 miles below Coyote Springs (fig. 26, between *G* and *H*).

PAINTED DESERT SECTION

At the south end of the Tolani Lakes area the Polacca passes through a break in its last barrier, the cliffs of the Chinle formation, and reaches the valley of the Little Colorado River (fig. 25). Corn Wash enters from the east near the upper end of the section. On the present flood plain of the Little Colorado River the Polacca Wash turns and parallels the main stream for nearly 3 miles before joining it about three-quarters of a mile west of the town of Leupp.

This section of the Polacca Wash is transitional between the Tolani Lakes area and the flood plain of the Little Colorado. The surface changes from the light-colored sand, characteristic of the higher parts of the wash, to a dark chocolate-red material, mostly silt, which appears to have been brought here from the flood plain of the Little Colorado by wind. This process is now very active, and places were noted where the vegetation of the previous year had been buried 8 to 14 inches.

From the upstream end of this section to the flood plain of the Little Colorado River, the Polacca Gully is deeply entrenched in the valley fill. Numerous channels and distributaries mark former courses of the Polacca and Corn Washes, but none were observed that indicated that the channels had ever before been so deeply cut. Meandering and recutting of the gully are evident in this reach and increase downstream, particularly below the point of entrance of the Corn. Here, as above the mouth of the Wepo, recurrent down cutting may have been brought about by increase in flow caused by the integration of drainage described at the top of this page.

PROCESSES AND EFFECTS OF NORMAL AND ACCELERATED EROSION

In the Polacca Wash, as in most other valleys of the Southwest, two groups of land forms can be distinguished. The first of these includes all the major and many minor features of the area—forms that have been produced by the normal action of natural processes. Superposed on these, and altering their shape and character, are land forms of the second group, which result from a recent quickening of the erosion processes. This acceleration of erosion has been sufficient to alter greatly the physiographic and ecologic aspects of the region.

DEVELOPMENT OF THE POLACCA DRAINAGE PRIOR TO THE RECENT ACCELERATION OF EROSION

CANYON CARVING AND VALLEY FILLING

The carving of the Grand Canyon and other major valleys of the Southwest, according to Gregory, began some time after the Eocene (*52, p. 26*), when uplift and tilting of the land introduced the present or "canyon" cycle of erosion. What had been a low-lying plain with shallow valleys was rapidly dissected to an intricate pattern of deep, narrow, vertical-walled canyons with ungraded floors. The main features of the Polacca Wash were probably eroded at that time.

There is no reason to think that conditions have been continually favorable to degradation since the beginning of the period of canyon cutting. Local erosion levels, rock benches, and perched stream gravels have been taken to indicate a lack of uniformity of tectonic movements or of climate, or both (*52, pp. 26–27*). In the dry climates, where channels carry water only during and after infrequent rains, irregularity of regimen is one of the most marked characteristics of streams and may in itself explain many of the features sometimes attributed [illegible] larger changes. At any part of a channel aggradation in one rain may be succeeded by degradation in the next, and during local showers parts of the stream course may carry heavy run-off while other parts remain dry. Under these conditions there is no reason why cutting should be confined to the upstream area and deposition to the lower reaches. There may be many local alternations of erosion and aggradation in valleys as long as those draining Black Mesa to the southwest.

The canyon cycle is still in progress, but for much of the last several thousand years deposition rather than cutting has been the dominant process. During this phase, called by Gregory the "epicycle of alluviation," parts of many of the canyons of this region were filled to a depth of 50 to 100 feet or more. Pottery and corn cobs buried in fills in the Navajo country indicate the recency of at least some of the deposition. Gregory describes in the upper Moenkopi Valley old cottonwood trees lately exhumed, whose trunks were buried in 10 to 30 feet of fill (*51, p. 130*).

Most of the Polacca Valley fill is water-laid, but aeolian material is present in scattered localities throughout the area and is prominent in the lower valley and in some of the larger tributaries. Irregular lenses of sand, silt, and clay are common in the fill (fig. 52), and stringers of gravel are abundant locally. Lenses vary from less than an inch to a few feet in thickness and extend as much as several hundred feet laterally. Thickness appears to bear little relation to length; lenses only a few inches thick may persist for hundreds of feet whereas others several feet thick can be traced for only a few tens of feet along the gully wall. Trenching of the valley fill by gullying reveals buried talus and slide material and buried rock cliffs in addition to the many old channels (fig. 52). These are characteristically sand-filled, but in places they contain mud balls and other kinds of detrital material.

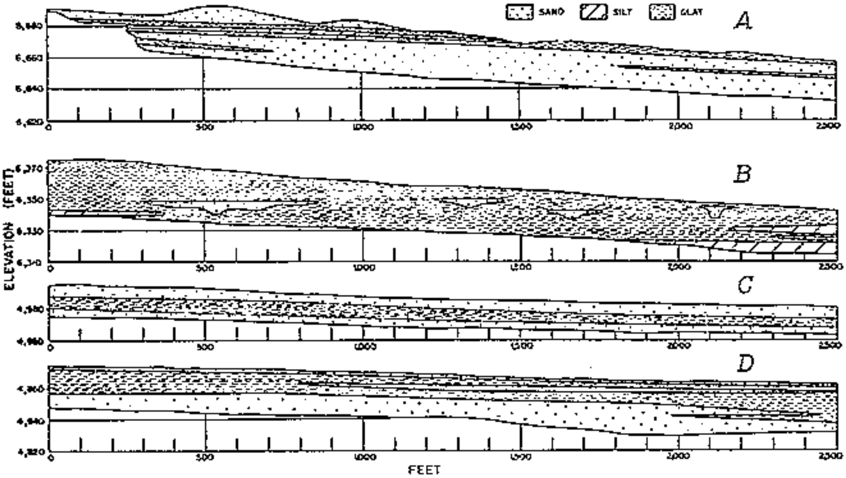

FIGURE 52.—Fill sections exposed along the Polacca Gully: *A*, Extends down valley from a point one-quarter mile above the mouth of Red Canyon Gully and includes the uppermost knickpoint of the main Polacca; *B*, extends down valley from a point 12 miles above the mouth of the Burnt Corn Gully and exhibits 4 sand-filled buried channels; *C*, represents the regularity of sequence of sand, clay, and sand layers in the Tolani Lakes area 7 miles northeast of the Red Lake trading post; *D*, in the upper end of the Painted Desert section, 12 miles northeast of Leupp, shows how the beds are more lenslike than in the Tolani Lakes area.

The fill material of the box canyons in the headwaters area of the Polacca drainage is largely sand. Minor gravel lenses are present locally, and there is some silt and clay. From about the mouth of Red Canyon Wash to the mouth of the Burnt Corn the fill is finer, consisting of clay and silt and minor amounts of sand. From there to the village of Polacca sand and clay are present in about equal amounts, and there are only minor lenses of silt. From Polacca village to a few miles below Coyote Springs (fig. 25) the fill is principally sand, with very little silt, but locally contains groups of clay lenses. Small gravel lenses are better developed in this section than elsewhere in the Polacca; bedrock is exposed in the gully at numerous places. The fill is largely water-laid and is gray except for local lenses of red material. Buried sands of possible dune origin are not uncommon.

The fill material in the Tolani Lakes area and for 10 to 12 miles up valley has unusually regular and continuous beds (fig. 52, *C*). These are: (1) A lower sand, 2 to 20 feet thick, prevailingly gray and water-laid; (2) a clay horizon 4 to 25 feet thick, containing an admixture of sand and silt, generally gray but having red lenses in the downstream portion; and (3) an upper horizon of sand 2 to 10 feet thick, containing both water- and wind-deposited material, prevailingly gray but also having red lenses in the downstream reaches. No buried channels and only one exposure of bedrock were noted in this reach of the present Polacca Gully.

From the Tolani Lakes area to the flood plain of the Little Colorado River the fill is composed of a lower gray horizon of sand, containing locally some clay, and an upper red horizon of clay containing minor amounts of sand (fig. 52, *D*). Lenses of red sand and clay are only rarely found within the lower horizon. Bedding is uniform for considerable distances in some parts of this section but in others it is markedly lenticular. No buried channels or outcrops of bedrock were noted.

Certain generalizations can be made on the distribution of alluvial materials in the Polacca with relation to the position of the gully in the wash. The evidence is obtained principally from exposures on the walls of the main Polacca Gully and its tributaries.

1. The coarser materials tend to occupy side positions and the finer types predominate in the central part of the canyons except (a) where a large tributary whose drainage is entirely from the Mesaverde enters at a relatively narrow part of the main canyon and carries the coarse material well out past the center of the main canyon so that fine materials can be present only along the farther wall, and (b) where the coarser materials are largely lacking because the tributary drains only the Mancos shale.

2. Sand lenses in a central position within the canyon frequently thicken rapidly toward one side of the canyon and thin toward the other.

3. Sand lenses, particularly those in a border position, often grade both up and down canyon, through silt to clay.

4. Along the central part of the canyons, especially the broader ones, the fill is commonly clay with only scattered lenses of sand and silt.

5. A fill composed almost exclusively of sand is found only in small, narrow, high-gradient canyons, which are so situated that the source of material is confined to the Mesaverde formation.

The distribution of material in the valley fill is characteristic of processes still operative. The major process of filling, even in valleys as large as the Polacca, was by fan building. Part of the material came down from the headwaters of the canyon and was deposited in longitudinal fans. By far the larger part of the fill in the upper half of the Polacca, however, was derived from mesas bordering the wash and was brought in along the sides of the canyon by tributary drainage. Material from both sources was carried down and deposited in the lower Polacca.

Sedimentation is believed to have taken place first along the lower reaches of the wash, probably in the Tolani Lakes area. There the infilling by the Oraibi and Polacca Washes began early in the epicycle of alluviation, and filling by local run-off from the surrounding slopes is still active.

Following or simultaneously with infilling in the Tolani Lakes area deposition began in the other basins along the course of the lower Polacca. The reaches of lowest gradient and flattest cross section tended to be filled first. Deposition was irregular and spotty, however, and changed according to location of intense rains and movement of wind-blown sand. The floor of the wash gradually approached a graded condition, first in the basin areas and later in the narrower canyon reaches between.

In the canyon sections the process of infilling was by no means simple. Except in a few short narrow canyons of high gradient the surface development was largely controlled by transverse transport. Alluvial fans and aprons were the dominating surface features, and the down-canyon drainage made its way between or over the extremities of the marginal fans. For this reason the main drainage was sinuous and subject to change in position and gradient as these transverse forms developed. Shifting of the drainage lines led to local alternation of deposition and removal, with gradual advance of the material down drainage. Fans and aprons were most abundant along the margins of the wash, but large fans were also built at places in the main longitudinal drainage line.

SECONDARY CHANNELING AND FILLING

The walls of deep gullies and arroyos reveal that the fills of many of the valleys of the Southwest contain large buried channels and are not uniform but appear to record several stages of deposition (*55*). Buried channels may be seen in the fill of parts of the Polacca Valley (fig. 52, *B*), but this valley shows little evidence of successive stages of filling. In the Jadito, Oraibi, and other valleys, Hack (*55*) has found many filled channels and sufficient sedimentary, physiographic, and archaeologic evidence to lead to the conclusion that there have been three stages of filling and cutting since the original carving of the valleys. These stages have been interpreted as due to climatic causes. Consideration of the processes at work in the valleys, however, will show that regional changes from erosion to deposition and back again as a result of climatic change are not necessary to explain the conditions found. More than that, regional changes from erosion to deposition would fail to explain fully the channeling and other features of the valley fill.

Under natural conditions few of the valleys of the semiarid and arid regions contained perennial streams or even continuous channels down the drainageways. Arroyos were cut locally, and the material removed was carried a short distance down valley and deposited as a fan. The growth of discontinuous arroyos was much like that of the discontinuous gullies formed in many of the valleys in recent years by accelerated erosion. Series of discontinuous gully channels can still be observed in the headwaters reaches of Keams Canyon, Red Canyon, Burnt Corn Canyon, and others in the Polacca drainage (pp. 92–95). Before the formation of the great Polacca Gully, a traverse down the length of the valley at any one time would show that areas of arroyo cutting alternated with areas of deposition.

Each discontinuous arroyo ended down valley in a fan. These arroyos lengthened upstream by headward erosion and at their lower ends became buried by their own debris. Where a complete series of discontinuous channels was developed down a drainageway the head of each arroyo cut into the alluvial fan being built by the next arroyo up valley.

Headward working of arroyos with deposition at the lower ends by backfilling of the channels (*57, p. 29*) produced waves of sedimentation that migrated up valley. Material removed from the head of the arroyo was transported downstream a few feet or a few miles and deposited. Although the sediment load moved down valley, the enlargement of individual deposits by addition to their up-valley ends resulted in the upward migration of each locus of sedimentation.

During floods resulting from occasional intense precipitation the flow carried farther than usual. Channels were cleared out, and fans were dissected. Deposition of the sediment load formed a down-valley extension of the fan, or, if the lengthened channel intersected another channel down drainage, the load might be carried much farther to form a new fan. Especially in these longer channels persistent down-valley migration of bends and meanders greatly increased channel width (fig. 53), and in time they could even cut out an entire valley fill. Run-off from heavy or protracted rains, then, by cutting out of older fills caused a down-valley migration of the locus of sedimentation.

Erosion alternates with deposition as the sedimentation waves migrate past any one place. Several waves of sedimentation may be depositing fills in a single long valley simultaneously. An apparently continuous fill, if formed by a wave of sedimentation, may vary greatly in age in different parts of a valley. Age correlations on valley fills, therefore, are hazardous and cannot safely be extended for any considerable distance.

The stages worked out by Hack for filling and cutting in the Jadito Valley and several other valleys of the Hopi and Navajo country and a similar history postulated by Bryan, and Albritton and Bryan, for valleys in New Mexico and Texas (*11, 30*) are explained as the result of changes of climate. Hack recognizes that one chronology will not apply to all parts of a valley. Regardless of climatic conditions deposition cannot go on simultaneously throughout an entire drainage because part of the area must be undergoing erosion to provide the sediment load. The normal processes of erosion and sedimentation, as outlined above, are adequate to produce successive filling and cutting of various parts of valleys without any change of climate, and complex interactions of the up-valley and down-valley waves of sedimentation offer an almost infinite variety of fill sequences. The sedimentary history of the Polacca Valley and similar valleys in the Southwest is far more complicated than is revealed by the few exposures on gully walls, but even so, it is believed that the explanation of successive deposition and removal of fill lies in sedimentary processes and irregular occurrence of heavy storms rather than in any change of climate.

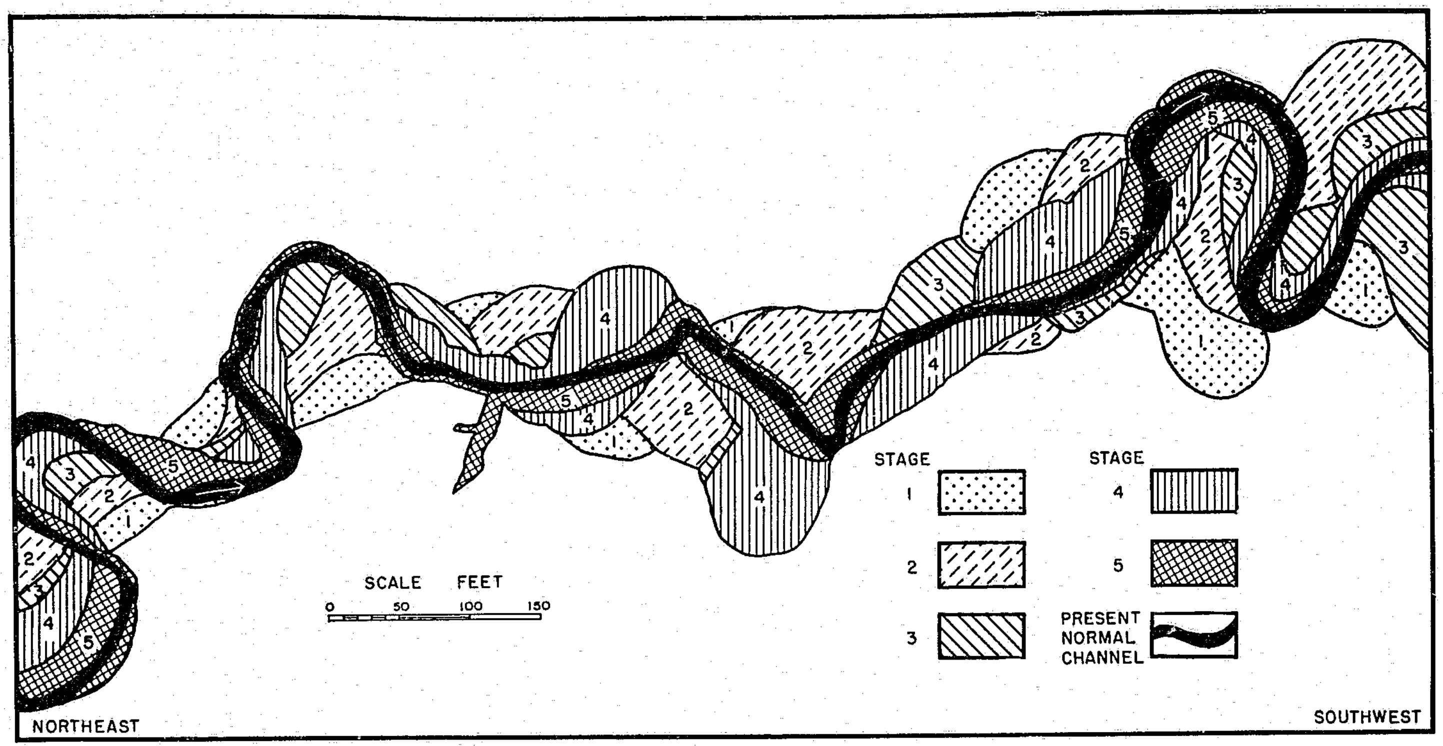

FIGURE 53.—Segment of the Polacca Gully about a mile south of Polacca village. The numbered patterns indicate minor erosion levels occupied temporarily by the channel as it cut downward and migrated down valley.

Wind activity has played a part in the normal development of the Polacca Wash and neighboring washes. It was much greater at some times than at others. Sand, believed to have been deposited by wind, is found buried in the valley fill, but whether there was ever such a widespread development of dunes in the Polacca drainage as was found by Hack (*55*) in the Jadito is not known. Some of the sand deposits of the Polacca fill, interpreted as old dunes, may be correlative with those between what Hack has designated as the No. 1 and No. 2 fills in the Jadito Valley.

RECENT ACCELERATED EROSION

The Polacca drainage shows evidence of all three major processes of accelerated erosion: Sheet wash and rilling, gullying, and wind erosion.

SHEET WASH AND RILLING

Sheet wash, although far less spectacular than gullying, is active throughout the Polacca drainage. Even before the acceleration of erosion, sheet wash, sometimes called slope wash, was effective in the down-valley and lateral movement of weathered materials. Distribution of sediments indicates that a large percentage of the total valley fill of the canyon section moved in from the flanking slopes by lateral wash. Today, with impoverishment of the vegetal cover, even more soil and coarser debris are carried down the alluvial slopes and fans by sheet wash or by shallow rills, whose courses change from one rain to the next. Smoothness of the lateral slopes can be attributed to the grading action of these processes. Sheet wash and rilling deliver soil material to the gullies and transport debris through reaches of the canyon section that have no channels. As has been noted on p. 73, all the material leaving Dripping Springs, Horse Pasture, and Little Hill on Top of the Mountain Canyons at the present time is moved by sheet wash or the related but more viscous and heavily loaded sheet flood. It is not known whether mass movement and wind action are carrying appreciable amounts from these tributary canyons.

The present destructive effects of accelerated sheet erosion are most clearly seen on the mesa margins, where bare rock and scattered clumps of vegetation now characterize what was formerly a soil- and vegetation-covered surface. Depletion of the vegetal cover through heavy grazing of sheep and goats appears to have started the acceleration of sheet erosion on the mesa surfaces. Once started, the more rapid rate tends to continue. A good stand of vegetation, either grass, shrub, or tree, helps to perpetuate itself by retarding run-off and conserving water. As vegetation is removed by grazing or erosion less water can be stored in the plants or given back to the atmosphere by transpiration; infiltration is diminished, and more water is allowed to run off. Hence the removal of the remaining vegetation tends to proceed at an increasingly rapid rate.

Except on the flattest surfaces the main danger is that sheet wash may give way to rills and gullies. This transition is in progress along the intermediate slopes and seems to be directly related to depletion of vegetal cover. The present grass and herbaceous vegetation can hold little water on the slopes and are too sparse to be effective in keeping run-off dispersed.

GULLYING

The striking feature of the present landscape of the Polacca Wash is the great medial gully whose deep channel cuts the wash floor for a distance of 90 miles. Twisting along the center of the valley, with its bed 10 to 50 feet below the valley floor, the Polacca Gully has widened its channel by meandering, and has engulfed millions of tons of soil material in the process. It has ruined some of the best agricultural land of the Indians, has subdrained the valley floor, and has discharged great quantities of silt into the streams below. Large tributary gullies are present in the Burnt Corn, Wepo, Keams Canyon, and Oraibi Washes, and countless others are now extending their channels from the parent washes back into the flanking slopes and even to the mesa surfaces. These gullies are typically of the flat-bottomed, vertical-walled, box type, which during periods of active growth are characterized by rapid headward erosion.

CONTINUOUS AND DISCONTINUOUS GULLIES.—Gullies, at first, are short and discontinuous. With continuation of accelerated run-off they grow in length to join other discontinuous gullies upstream and downstream along the same drainage line. In this way are formed long "continuous" gullies, from which cutting progresses up tributary drainageways, further extending the gully system. A continuous gully has an unbroken channel from its head to its junction with a larger trunk gully or a natural arroyo or stream. Integration of discontinuous gullies into a continuous gully system has gone on until today the central gullies in most of the larger washes tributary to the Polacca form a part of the continuous channel system.

Although there are many reasons why humid-land and arid-land gullies should be of somewhat different form, both continuous and discontinuous types are common in both of these climatic regions. In humid lands, just as in the arid Southwest, discontinuous gully channels are a marked source of danger, because what may today be a short and relatively inactive gully emptying onto a small alluvial fan may tomorrow become incorporated in a long continuous gully system and may begin to deepen and lengthen rapidly.

Discontinuous gullies commonly, though not necessarily, lie in linear series along drainageways. Series of such gullies are still present in the upper end of the Polacca Wash and in most of its major tributaries such as Burnt Corn and Keams Canyon Washes. Gullies on the pediment and alluvial-fan zones, also, are characteristically of the discontinuous type.

A typical series of discontinuous gullies in the Polacca drainage is depicted in figures 54 and 55. The profile (fig. 55) shows that there are no abrupt changes in the gradient of the canyon floor. Slight bulges indicate alluvial fans that have developed at the lower ends of the discontinuous gullies. Discontinuous gully *A* has a convex break in its profile (8,800 feet above the junction with Red Canyon Gully). This suggests that the channel is composed of two parts that have recently joined. The presence of the knickpoint 300 feet downstream from the bedrock waterfall supports this evidence. Above the waterfall the channel is essentially on bedrock throughout its course. Between the mouth of gully *A* and the main head of gully *B* (fig. 55) is a Navajo cornfield. The important relation of discontinuous chan-

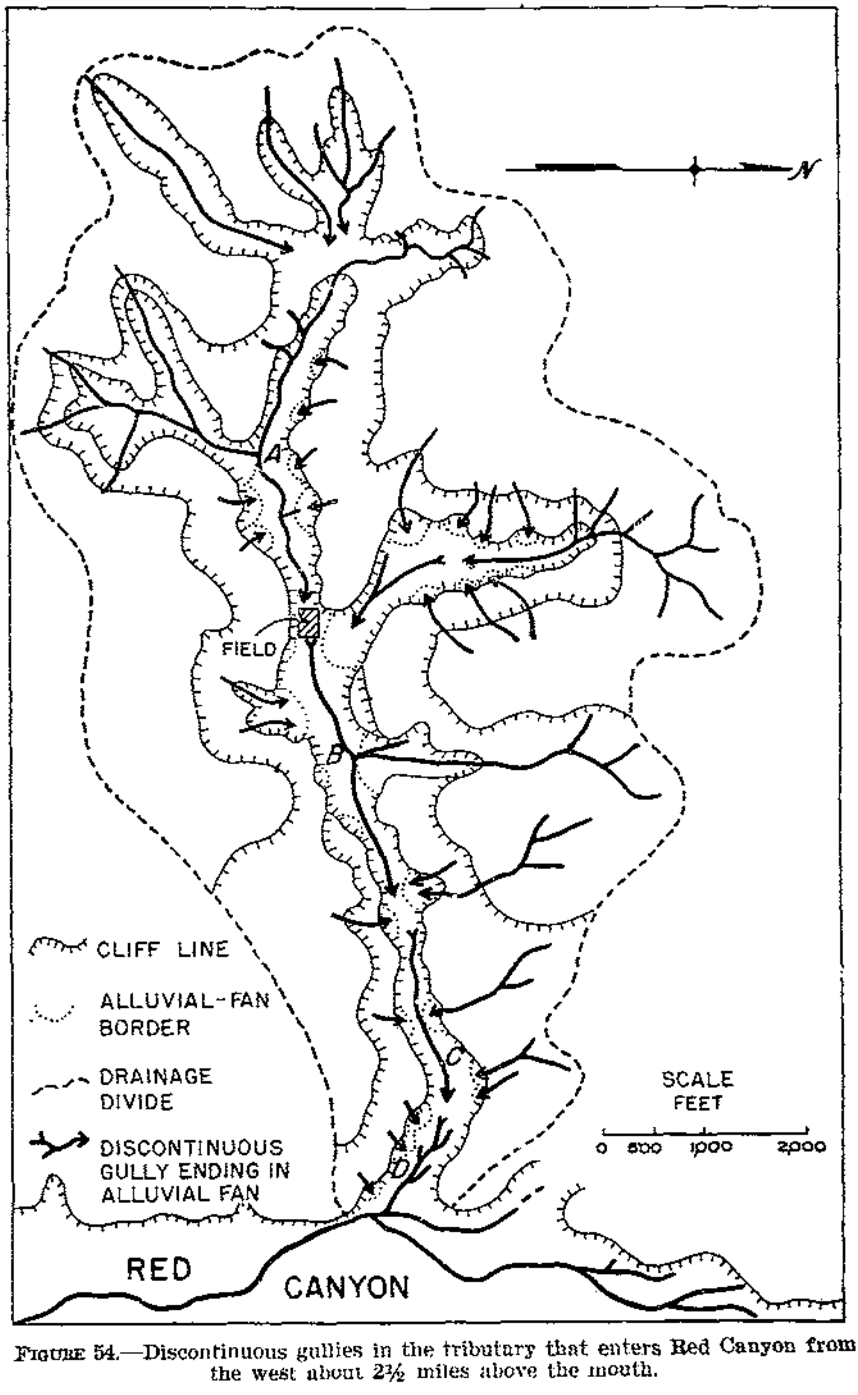

FIGURE 54.—Discontinuous gullies in the tributary that enters Red Canyon from the west about 2½ miles above the mouth.

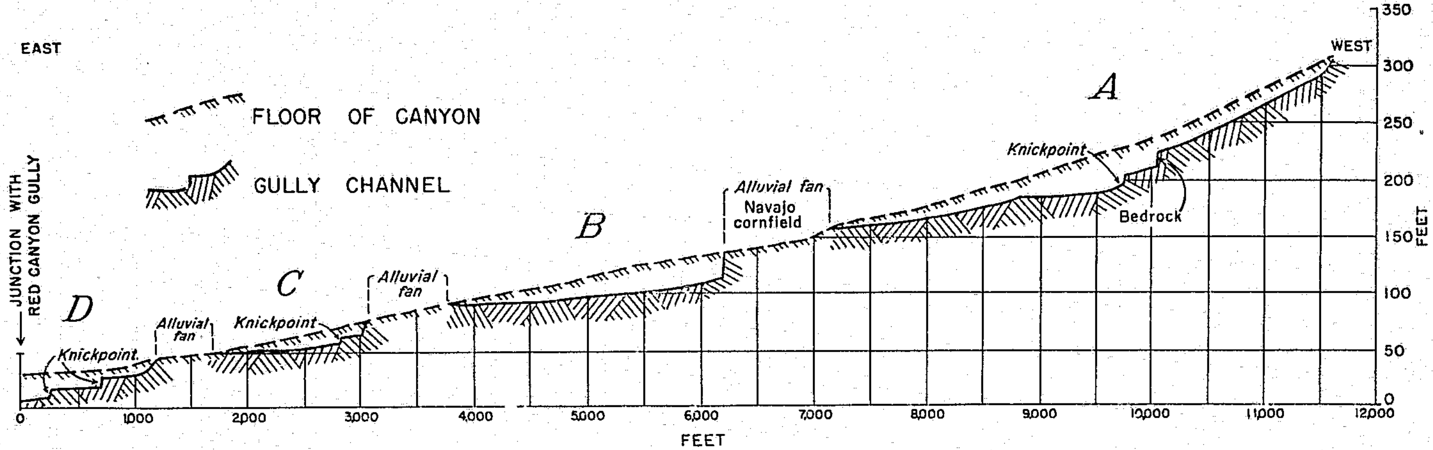

FIGURE 55.—Profile of discontinuous gullies in the tributary that enters Red Canyon from the west about 2½ miles above the mouth.

nels to floodwater farming of this type in the Southwest has been pointed out by Bryan (*29*). Gully *C* contains a knickpoint whose advance is deepening the channel and lowering the gradient. This is a common occurrence in gullies of the Polacca area and is frequently brought about by the increase in flow which results from headward elongation. Variations in the inherent erodibility of the different horizons of the fill may aid in the formation of knickpoints but are not essential. Gully *D*, which is continuous with the Red Canyon Gully, has worked headward into the lower part of the alluvial fan formed at the mouth of gully *C*.

STAGES IN GULLY GROWTH.—The exact processes of gully development and the stages through which the gullies in different parts of the country pass vary according to bedrock, soil, vegetation, and climate. Recent studies of the development of the large caving-walled gullies of the Piedmont of South Carolina (*69*) have indicated that gullies there pass through four well-defined stages: A stage of channel erosion by downward scour; a stage of headward cutting by the action of plunge pools; a healing stage; and, a stage of stabilization. Rejuvenation of cutting, owing to a lowering of base level or an increase in rapidity of run-off not uncommonly causes a reversion to one of the earlier stages. Gullies in the Polacca Wash area and elsewhere in the Southwest pass through four stages similar in general to those of the Piedmont gullies but differing in details. These are: (1) Initiation, which may take place in at least three different ways; (2) enlargement by headward elongation; (3) healing, by a reduction of slope of the walls and the establishment of vegetation; and, (4) stabilization, revegetation, and development of soil profile, and possible eventual filling and obliteration.

Stage 1.—Gullies may be initiated wherever there is sufficient acceleration of run-off. Denuded spots may form in vegetated drainageways and spread up and down valley with successive run-off periods until they coalesce and are deepened to produce a well-defined steep-walled channel. Leighly (*73, pp. 272–276*) has described this development along gently sloping natural drainageways in northwestern New Mexico. It is effective in the Polacca drainage and probably is operative throughout the Southwestern United States.

A method of gully initiation far more rapid than the first, and particularly common in the Polacca Wash drainage and in other regions of low annual rainfall, is effective where an intense storm centers on an area in which the vegetal cover is inadequate to protect the soil from erosion. It is most common in summer. One storm occurrence may give rise to one channel or to several, either along a single drainageway or scattered through the storm area in various positions where similar surface conditions exist. The length of the gully or gullies that are formed depends very largely on the size of the storm center and on the intensity and duration of precipitation. Although run-off is rapid in the Southwest, owing to the lack of close-growing vegetation, the flow does not ordinarily travel far. Much water is lost by sinking into the soil or passing into the atmosphere. Evaporation is effective because the climate is dry and most of the flows are shallow and broad, either in sheets or in small rills and distributaries. Short gullies may develop from intense storms on any slope, but they are formed most frequently where the surface is relatively steep.

Gullies may also be initiated by cutting in the side wall of an existing channel. Water entering the channel side tends to cause caving, and a reentrant is formed which readily develops into a well-defined tributary gully.

The boxlike cross section of gullies and arroyos in semiarid lands is almost as typical of channels a foot deep and less than 10 feet long as of large gullies and canyons. Box-shaped gullies develop rapidly, and a channel over 100 feet long and several feet deep may be formed by a single small rain. Shallow V-shaped channels, more characteristic of humid lands, are occasionally found in semiarid climates but are seldom over a few feet in length.

Stage 2.—Growth of gullies by headward elongation takes place at highly variable rates. In this stage the gradient of the gully is characteristically lower than that of the surface in which the gully is cut. The channel is commonly deepest near its head, although if knickpoints are present the greatest depth may lie immediately downstream from a major knick.

By headward erosion one gully may reach another upslope along the same drainage line and join with it to form a single longer gully. The cutting head of the lower gully then becomes a knickpoint and continues headward migration. Down cutting and a temporary steepening of the gradient of the old upper gully result. The increase in volume of flow may cause renewal of down cutting in the downstream part of the gully channel and the formation of a second headward-migrating knickpoint.

The presence of one gully increases the probability that others may be initiated down drainage. Unless the debris fan deposited by the gully is large enough to absorb most of the water poured into it, much of the flow will traverse the fan in a number of shallow distributary channels. If the water from these distributaries reunites below the fan this concentrated flow moving across the ungullied surface may be sufficient to induce channeling whereas the surface flow prior to the formation of the upper gully and fan was ineffective.

Headward extension of a gully is retarded as the drainage divide is approached because of the concurrent decrease in the area draining into the gully head. In most gullies in the Polacca area the drainage divide lies not in the alluvial fill but above it in the fan or pediment zones or on the mesa. Headward growth of the gully is greatly retarded when bedrock is reached and is practically stopped if the entire head wall is composed of rock. There is not necessarily any diminution of the volume of water entering the gully over the head wall, however, and downward erosion will continue until grade is reached.

Vertical incision of gullies is a far less continuous process in arid and semiarid lands than in more humid areas. Not only are rains less frequent in the dry climates, but the downward cutting of a gully during a storm is more likely to be partly obscured by aggradation of the channel when run-off diminishes.

In humid lands rains are frequent and permanent streams are relatively closely spaced. Much of the debris carved from a gully during a period of heavy run-off is carried directly to a perennial stream and thence by more or less continuous transport through successively larger watercourses to the sea. Although more material is carried at high water than at low, part of the load of permanent streams is constantly on the move. In arid and semiarid climates perennial streams are much more widely spaced. The infrequent heavy rains usually cover only relatively small areas and the run-off from only a few storms ever reaches permanent streams. Most of the load of the arroyos, washes, and gullies of semiarid lands is transported a short distance only to be dropped again where infiltration, evaporation, and transpiration have abstracted the water. In storms of wider extent, usually of lower intensity, more of the drainageways "run through" to perennial streams, but at any segment of the channel the load carried is far less than that moved by the run-off from the powerful local showers.

With the approach of a graded condition in a gully, vertical cutting diminishes. Lateral erosion becomes the dominant means of channel enlargement. This process can go on in the narrower canyons until all of the fill material above the level of the gully bed is removed. As the channel becomes wider, however, other conditions remaining unchanged, the effective volume of water is reduced, owing to the change in the proportions of the channel cross section, so that the rate of lateral erosion decreases.

As each gully that is tributary to a larger gully or stream is controlled in part by the larger drainage line, each change in gradient of the trunk gully is reflected in its tributaries. When overfalls or knickpoints advance up the trunk past tributaries, those tributaries become discordant and in turn begin to lower their channels by the headward erosion of corresponding falls. Furthermore, the average volume of water passing through the trunk gully does not become constant until all of the tributaries have ceased their headward elongation. The interdependence of the various parts of a continuous gully system is thus so close that the advance of any part to a later stage of development can take place only when the necessary conditions have been attained by the other portions of the network.

Stage 3.—When, for any reason, the downward erosion of the gully floors is retarded, healing gains dominance. Opposing processes are active at this time. Lateral cutting by the stream tends to retain the steep gully walls, and sheet wash, aided by mass movement, tends to reduce the walls to relatively low slopes. The duration of the lateral-cutting phase depends on the material of the gully walls and the volume and frequency of flow of water through the gully. With increase in mobility of the wall material or reduction in the frequency and volume of flows in the gully, lateral cutting diminishes; vegetation begins to establish itself on the reduced slopes, and locally deposition may take place. There is only scattered evidence to indicate that this stage has begun in the Polacca drainage area.

Reduction in slope of the gully walls by caving and sliding goes on so slowly that even a slight amount of lateral erosion will maintain the vertical walls. Evidence of the work of slope-reducing agents can best be seen on surfaces protected from stream erosion, such as walls above high benches along the channel.

Stage 4.—The final stage, stabilization, is represented in the Polacca drainage almost solely by channels formed at earlier periods. This stage may be divided into two phases. The first of these, stabilization proper, results from the establishment of vegetation within healed gullies. Slope, soil, and vegetation become adjusted to the climate so that normal conditions of erosion again exist. The stabilized gullies, however, act as drainage lines. They are the places where a rejuvenation of abnormal erosion is most likely to occur with any renewal of accelerated run-off.

With a continuation of deposition after stabilization an additional phase may be brought about in which the stabilized channels are completely filled and obliterated. The climatic transition along the Polacca from arid at the lower end to subhumid in the headwaters is favorable to eventual filling of the channels. The abundance of available material in the higher and more humid portions of the area would make possible rapid aggradation if conditions of normal erosion were reestablished.

MECHANICS OF GULLY ENLARGEMENT.—The processes of headward and lateral growth of the deep gullies of the Southwest vary with the amount of run-off being carried and the composition of the walls. The shape of the gully head, whether pointed, boxlike, bulbous, or dendritic, is determined largely by the relative rates of the headward and sideward growth and by the distribution and volume of flow of water over the rim.

Abrasion by flowing water at the top of the head wall is a relatively minor cause of the enlargement of deep gullies. Other conditions remaining the same, this abrasion increases with the velocity of the flow and is at a maximum during the height of the run-off.

A far more powerful cause of headward erosion in gullies is the caving of the upper walls as a result of undercutting. This process is especially active where the materials of the fill, instead of increasing in resistance downward, have the most resistant layers close to the surface. In the Southwest this weakness at depth is generally traceable to lenses of water- or wind-laid sand, which have very low binding qualities; to beds that are subject to drying and cracking, which makes them more vulnerable to the attack of running water; or to beds that become fluent when soaked.

When first subjected to a turbulent flow of water, clayey layers that have been broken down by cracking behave much as would a bed of gravel. Before the individual clods can be soaked through they are carried off in suspension or are rolled away along the stream floor. Even large chunks several inches in diameter are removed. These become rounded to form cobble-shaped mud balls, which are common in some parts of the area and have been found also in the fill in buried channels. Gravels may be embedded in the surface, but when the balls are broken open the interior structure is seen to be still that of a clod from the gully wall, and often shows bedding planes or a rectangular crumb fracture. Only the outside shell becomes plastic in the ordinary short period of transport during run-off. If left in water long the clay softens and the structure breaks down.

The presence of loosely cracked material and a cloddy structure in a gully wall depends on the presence of sufficient soil colloids to produce shrinkage when the soil is dried and on a lack of pressure from above to close the cracks as shrinkage takes place. In a typical section of a deep colloidal soil exposed in a gully bank, the uppermost layers have either a clodlike structure in which the interstitial spaces are about equal in size vertically and horizontally or a structure in which the horizontal spaces are slightly smaller than the vertical ones. Lower down, where the overburden is greater, the structure becomes essentially columnar. Horizontal cracks are small, and vertical cracks are larger but fewer in number.

Undercutting of gully banks for several inches, or even a few feet, without caving shows that the weight of the soil column is not transmitted uniformly to the lower layers but may be supported in part by a sort of cantilever suspension. Locally, deep in the fill, there are very commonly one or more massive clay-sand members sufficiently strong to support the overburden and permit horizontal as well as vertical cracking in the lower layers. Examples were noted where horizontal cracks open more than an inch were formed immediately below massive uncracked beds buried at a depth of 10 feet. Loose cracking of strata low in gully walls is far more a product of desiccation working laterally from the gully than of normal soil structure formed from the surface downward.

Even where the lower horizons are not columnar or blocky in structure, soaking during high water followed by flow and caving are the most effective processes of gully-head erosion. Soaking of the head wall takes place not only from flow on the gully floor but from the splashing of the water in the plunge pool and from the thin surface-tension film of water that trickles down the gully head. After the stage of maximum run-off, water that has soaked into the walls near the bottom of the gully tends to seep back out, carrying in suspension many fine soil particles. If the wall materials have been softened greatly by the soaking, portions of the bank give way. Such caving may continue for hours or even days after run-off has ceased.

Widening of the channel down gully from the head depends on the composition of the gully walls and on the rate and volume of flow.

The shallow depth to which the average fill material of this region is moistened by rain indicates that seepage of surface water downward through the soil is usually unimportant as an agent of gully enlargement. Cracks, animal burrows, or other surface openings, however, readily determine the direction of gully development. If water entering underground passages emerges from a gully wall through a continuation of the passage or by seepage along lower permeable horizons, soaking and slumping or flowage of material into the gully is intensified in that direction. Eventually the higher horizons will cave, and another gully channel will be started.

WIND EROSION AND DEPOSITION

In a climate as dry as that of most of the Polacca drainage basin the vegetal cover is rarely if ever sufficient to prevent completely the shifting of sand or soil by the wind. Under these conditions, common to a large portion of the Southwest, a decrease in vegetation or an increase in either erosion or deposition by running water permits wind erosion to set in.

In several parts of the Polacca drainage, especially from the vicinity of Polacca village downstream to the valley of the Little Colorado, sand blowing has recently been renewed, and active dunes now occupy the surface (fig. 56). Although the most noticeable effects are in the valley bottoms, wind deposits are also found on the uplands. In reentrants near the southwestern border of Black Mesa large dunes locally have buried the pediment zone and sweep from valley floor to mesa top. Sand dunes of well-defined barchan type occupy an area of more than a square mile on the surface of First Mesa, northeast of Walpi (fig. 57), and irregular hummocks extend over a greater area.

FIGURE 56.—Active sand dunes along the northwest side of the Polacca Wash at the south edge of Polacca village.

FIGURE 57.—Sand dunes of barchan type on the surface of First Mesa (outlined by white dashes), 4 miles northeast of Polacca village. The Polacca Gully cuts across the upper left corner of the view. Scale is approximately 2 inches to 1 mile. (North is at the bottom of the view.)

Longitudinal dunes (*76, p. 121*), oriented in a general southwesterly direction parallel to the prevailing winds (figs. 25 and 40), are the dominant type on the valley bottom. Dunes are especially abundant in the Tusayan Washes section, where sand storms are said to have increased in frequency during recent years.

Wherever wind-blown sand is found as a continuous surface mantle, it is effective in preventing erosion by running water. Parts of the Polacca drainage are almost immune to sheet wash and serious gullying because of absorption of the flowing waters by sand and because of the obstruction offered by drifting sand to the formation and maintenance of channels. By reason of their retention of water these sand areas are favorable for vegetative growth and are valuable to the inhabitants of the region as agricultural land.

ACCELERATED EROSION IN THE SOUTHWEST

Recent acceleration of erosion in the Polacca drainage and in the Southwest as a whole is now generally recognized. There is as yet, however, no general agreement as to the cause of that acceleration. Any valid explanation of this recent trenching must recognize that a large part of the region is affected by it and that in some localities it began as much as 80 to 100 years ago, though in most areas it had its start more recently.

Date of Acceleration of Erosion

THE SOUTHWEST

Rich, Gregory, Bryan, and others have gathered many records of the beginning of accelerated erosion in the Southwest. The dates vary from valley to valley as do also the nature of the terrain, time of settlement, type of land use, climate, and reliability of the information. Hough, in 1906, made a general statement for the entire region that acceleration of erosion began 30 years earlier or about 1875 (*64*). Bryan considers this too early and places the beginning of cutting about 1885 (*23*).[18]

Most accounts by early travelers in the Southwest indicate that acceleration of erosion did not begin until after the establishment of settlements and the expansion of the cattle industry. Local exceptions may be noted. Explorers and military parties that crossed the Rio Puerco of the Rio Grande drainage in New Mexico between 1846 and 1877 report banks 10 to 30 feet high and a channel as much as 100 feet wide (*10 pp. 466–467; 23, p. 339; 71, p. 432; 95, p. 71*). This would suggest that channeling had set in far earlier than the late eighties, the date given for it by local inhabitants (*23, p. 339*). The explanation of apparent disagreement of the two accounts may lie in the development of discontinuous channels, which eventually joined to form one great continuous gully (pp. 92–95). Albert, Simpson, and Jackson, whose journals tell of the early condition of this river, may have crossed some of the earlier channeled reaches. Later, as gullying spread up and down the valley, subdraining the bottom lands

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[18] BRYAN, KIRK. PRE-COLUMBIAN AGRICULTURE IN RELATION TO PERIODS OF ALLUVIATION IN THE SOUTHWEST. Paper presented before Anthrop. Sec., 8th Amer. Sci. Cong., May 16, 1940. Washington, D. C.

and impeding the diversion of water for irrigation, the population was more seriously affected. At least three river towns were abandoned (*22, p. 80*).

Judging from an early account by Simpson (*95, p. 78*), Chaco Canyon, a tributary of the San Juan River in northwestern New Mexico, had no gully in 1849. Jackson, in 1877, found an arroyo 16 feet deep and 40 to 60 feet wide (*71, pp. 431–450*), and by 1924 this channel had enlarged to 30 by 200 to 300 feet in section (*23, p. 340*).

Agricultural land along the Rio Salado, tributary to the Rio Grande at San Acacia, N. Mex., was settled in 1880. According to local inhabitants, an exceptional rain and flood in 1883 cut a new channel for the stream along the course of an old road. Most of the farming land of the valley has since been destroyed by further cutting that between 1882 and 1918 increased the width of the Rio Salado 10 to 40 times (*26*).

The channel that occupies what was once the main street of Silver City, in southwestern New Mexico, was cut largely in the years 1895 to 1905 (*32; 31, p. 11*). Intense rains fell in this area in July and September 1875, and July and August 1881 but it was not until the 6-inch rain of July 21, 1895, that the major excavation began. August 1903 had two more disastrous floods on successive afternoons. In 1917 the channel was over 100 feet wide and 37 feet deep (*79, pp. 24–25*), and by 1934 the depth was reported to have increased to at least 54 feet (*31, p. 41*).

Acceleration of erosion on the Gila River in southern Arizona and on various of its tributaries took place between 1870 and 1900 (*104; 113*). Rillito Creek, a tributary of the Santa Cruz River, began cutting a few miles northeast of Tucson after the opening of a United States Army post on the Rillito at Fort Lowell in 1872. Pantano Wash, entering the Rillito from the south, eroded rapidly during floods in 1881 and in the nineties (*96, p. 98*).

In 1870, the valley of the San Pedro, a long tributary of the Gila in southeastern Arizona, had a shallow grassy bed and banks covered with luxuriant vegetation. Willow, cottonwood, sycamore, and mesquite timber were abundant, and there were large beds of saccaton and grama grasses and sagebrush. By 1900, the river had cut 10 to 40 feet below its former banks. Trees and underbrush were gone, and cattle and horses trailing between feed and water had cut many small waterways from the hills to the river (*53, p. 12*).

Another account of the lower San Pedro says that until about 1888 the Valley consisted of a narrow strip of very fertile subirrigated fields. Beaver dams retarded the flow and prevented channel cutting. Trapping of the beavers and removal of grass from the hillsides allowed such an increase in erosion that by 1892 or 1893 a channel 3 to 20 feet deep had been cut almost the whole length of the river. Freshets each year carried away more of the bottom lands, and in addition to curtailing the area of good land, the deep channel drained the bottoms, killing the native grass and making irrigation more difficult (*53, pp. 13–14*). Bryan points to the change in plant associations in the San Pedro Valley as characteristic of the recently dissected valleys of the Southwest. Within the memory of men now living the *phreatophytes*, or shallow ground-water plants, have disappeared and have been replaced only by groves of mesquite (*27, pp. 475–476*).

The Gila itself has cut away much of the former flood plain in its upper course, but below the mouth of the Santa Cruz River it has deposited enough sediment to fill the old deep channel and form a sandy plain a quarter of a mile to half a mile wide (*23, pp. 342–343*).

Floods that have carved a large channel in the floor of Blue River Canyon in the Gila River drainage began in 1900. Between 1900 and 1921 the number of ranches in this basin decreased from 45 to 21 and the population from 300 to 95 (*23, p. 342; 74*).

The present channel of San Simon Creek, which enters the Gila River from the south about 4 miles east of Safford, is 10 to 30 feet deep, 600 to 800 feet wide, and 60 miles long. Olmstead reports that it developed after the cutting of a small floodway by settlers in 1883 (*23, p. 342; 79, p. 79*).

Arroyo cutting in streams tributary to the Mangas River, and so indirectly to the Gila, began between 1881 and 1891 (*86*).

In northern Arizona and southern Utah much of the channeling of flat-floored washes appears to have started between 1880 and 1890. According to Brady (*20*), the Rio de Flag, northwest of Flagstaff, Ariz., formerly flowed through a grassy flood plain but in 1936 was deeply entrenched. Cutting began in 1886–87, when a logging road down the center of the valley was in use. The arroyo enlarged rapidly between 1890 and 1892, and by 1900 it was 15 to 20 feet wide and 10 feet deep. When reported on by Brady in 1936 it was 60 feet wide and 20 feet deep.

Cottam and Stewart (*37, p. 614*) state that Mountain Meadow, in southwestern Utah, was dissected by huge gullies during a protracted period of torrential storms in the spring of 1884.

Davis reports that cutting on Kanab Creek is known to have begun in the flood of July 29, 1883, which was followed in 1884 and 1885 by high waters from unusually heavy snows. In these three years a gully 60 feet deep by about 70 feet wide and 15 miles long was cut in the fill of Kanab Creek (*39, p. 11*). Lakes known to have existed in Bonito Canyon in 1850 (*95, p. 110*), in Tyende Valley in 1880, and in Laguna Canyon in 1882 have been drained and the valleys deeply trenched.

According to Gregory (*51, pp. 130–131*), Navajo legend tells that the Segi region was bewitched in 1884. The lakes vanished and farm lands were cut out.

> In 1894 the flat-bottomed alluvial floor of Walker Creek was occupied by Indian farmers, and the bed of the Chinle was cultivated: in 1913 the terraces on Walker Creek were 80 feet above the stream and the Chinle flowed between alluvial banks 300 feet in height. Since the Mormon occupation of Tuba in 1878 the Moenkopi has intrenched itself in alluvium to depths of 15 to 40 feet.

Prospectors, pottery hunters, Government officials, Navajos, and Hopis agree, Gregory says, in placing the formation of terraces 25 to 35 years before he wrote, or between 1882 and 1892. Those on Pueblo Colorado Wash at Ganado were formed about 1890 (*51, p. 131*).

THE POLACCA DRAINAGE BASIN

The beginning of accelerated erosion in the Polacca drainage basin can be dated only approximately, but the several lines of evidence are all in general agreement. Early travelers through the Navajo country appear to have said nothing about the presence of gullied channels.

The first descriptions yet found are by Bourke, who visited the Hopi snake dance in 1881. He noted on August 16 that high wind-rippled sand dunes on the plain south or southwest of the tip of First Mesa provided heavy going for their mules (*17, p. 281*). To the west, in the center of the broad valley separating First and Second Mesas, he says, is a rainy-season stream, apparently Wepo Wash, flowing from the north and joining what is now called the Polacca Wash. Where his party crossed the Wepo it was a brook 20 feet wide and 3 to 6 inches deep, with a swift current. Corn, melons, pumpkins, and squashes were being grown along the valley (*17, pp. 281–282*). As he does not mention any difficulty in crossing it is presumed that the Wepo at the trail between First and Second Mesas was at that time a surface flow with only low banks. The "clay talus" forming the slopes from the base of the mesa cliffs to the plain, Bourke says, was "slashed and wrinkled in all possible directions by ravines and arroyos, ranging from 2 feet to 200 feet in depth, across and between which runs a maze of sheep and goat and donkey trails" (*17, pp. 282–283*). Dissection of these steep infertile slopes is probably almost as old as the congested settlements on the mesa tops above them and must have long preceded the widespread gullying of the wash floors.

On August 19 Bourke's party started southeast from the plain below Mishongnovi at the tip of Second Mesa. When scarcely a mile on their way they ran into an alkali flat full of mud holes, and their mules and wagon became deeply mired. After digging out they proceeded down drainage and succeeded in crossing at a place where the water flowed between vertical banks 10 feet high. The walls, of a crumbling sand and clay mixture, had to be graded down to allow the wagon to pass. Less than 250 yards farther another and more troublesome ravine was crossed in similar manner (*17, pp. 339–343*). The position of these mud flats and the two ravines suggests strongly that the miry area and the arroyo first crossed may have been along the Wepo. The second and larger arroyo or gully may have been the Polacca. From this it would appear that gullying along the Polacca had induced correlative cutting on the tributary Wepo or that both had trenched independently. In any event, cutting on the Wepo did not extend up drainage so far as the boggy area, which may have been on a broad alluvial fan. The place where the Wepo had been crossed 3 days before must have been still farther upstream. These few observations of valley trenching suggest that by 1881 acceleration of erosion had made a start in the central part of the Polacca drainage but that the gullies were not continuous up the washes and had not reached anything like their present width and depth.

The first topographic survey of the Polacca drainage, made in 1883, is shown on the Canyon De Chelly, Marsh Pass, and Tusayan reconnaissance maps of the United States Geological Survey. Because of the small scale (1:250,000) and reconnaissance nature of these old maps it is impossible to be sure that all drainageways were mapped. Permanent and intermittent streams are shown in several of the other valleys, however, and it is unlikely that a well-developed steep-walled gully down the Polacca Wash would have been ignored. Various springs in the Polacca drainage are shown, and the Canyon De Chelly quadrangle indicates a permanent stream about 4 miles long in one of the Polacca headwaters. As near as can be determined this channel was in Dripping Springs Canyon (fig. 42), and it may have been a natural feature. These early maps, therefore, suggest that gullying in the Polacca drainage was not well developed until some time after 1883.

According to information obtained from the Hopis, accelerated cutting of the Polacca Wash began in the 1890's at a point several miles below the village of Polacca. The exact location is not known, but field evidence suggests that cutting began about 7 miles down valley from the village (figs. 25 and 26 between *E* and *F*).

On the basis of the positions of longitudinal fans and on comparisons of cross sections of the present gully above and below the fans, the approximate positions of other old gully channels along the course of the present Polacca Gully can be located. One such discontinuous channel is thought to have extended from about a mile southwest of the mouth of Red Canyon (fig. 26 between *A* and *B*) upstream for at least 2 miles; one for a distance of about 3 miles up from the mouth of the Burnt Corn (fig. 26 between *C* and *D*); and one from about 6 miles to 9 miles above the mouth of the Burnt Corn. The longitudinal fans were formed by deposition from discontinuous channels and were later cut through when the channels became incorporated in the continuous gully system.

According to this interpretation, active discontinuous channels were present in four reaches of the main drainage of the Polacca Wash, possibly before the end of the last century. Integration of these channels under the influence of continued accelerated erosion produced the long, continuous Polacca Gully.

Evidence from the major tributaries of the Polacca also indicates that acceleration of erosion began some time after 1890. A land survey made in 1891-92 [19] shows a discontinuous gully in the Wepo Wash, terminating about 5 miles above the present junction of the Wepo with the Polacca—a reach that now contains a continuous gully channel. In Keams Canyon Wash, according to Hoover, writing in 1930 (*62, p. 437*):

> The greatest trenching has taken place within the last 10 or 15 years. Before 1880 there was no serious arroyo wash in Keams Canyon, but later the government experimental farm there was largely washed away and had to be abandoned. The school was moved two miles down the canyon to its present site. The wash is now about 25 feet deep and goes through the middle of the old fields and cemetery.

Gregory, who worked in this area intermittently from 1909 to 1913, said that the deep alluvial fill of Keams Canyon was then being removed so rapidly that location of roads and preservation of buildings was a serious problem (*51, p. 131*).

Cutting of neighboring washes has also taken place largely since 1900. Hoover says of the Oraibi (*62, p. 437*), the next wash west of the Polacca, in 1930:

> The old Oraibi Wash of 30 years ago was no more than five or six feet deep and can still be traced where it was abandoned for the great gash about 35 feet deep and several hundred feet across. Locally it has cut to bed rock, and here there is a constant flow of surface water. It is representative of what has taken place in all the valleys.

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[19] U. S. General Land Office. TOWNSHIP NO. 28 NORTH, RANGE NO. 18 EAST, GILA AND SALT RIVER MERIDIAN. Scale, 40 chains to an inch. [Ms. map, United States Department of the Interior.]

Jadito Wash, adjoining the Polacca drainage on the east, has a present channel in some places as much as 100 feet deep. Most of this, according to Hack, has been cut since 1914 (*55, p. 68*).

The weight of evidence indicates that accelerated erosion in the Navajo country began between 1880 and 1885, and gradually spread until by about 1914 all the major drainages and most of the larger tributaries were trenched by a system of continuous gullies. Since then gullies have cut deeper and have joined to form a more complex continuous gully system. Enlargement of channels and extension of the system continues. Parts of some of the larger gullies appear to be less active than they were a few years ago.

CAUSES OF ACCELERATION OF EROSION

DIASTROPHISM

Available information indicates that accelerated erosion in the Southwest was initiated at slightly different times in different areas but that by far the greatest incidence was in the period 1880–1900. In the search for the cause of acceleration of erosion these geologically short time limitations must be kept in mind.

Rejuvenation of stream action would be a possible explanation of the trenching of the valley floors. In individual streams this could be brought about by increase of flow, through capture, or by the cutting through of a resistant barrier such as a massive bed, lava flow, or landslide. More or less synchronous acceleration on streams throughout the Southwest could scarcely result from any such local causes.

A far more widespread cutting of gullies in valley floors could be brought about by steepening of channel gradients through diastrophic action. Any type of doming, warping, or tilting of the earth's crust, however, would involve a directional orientation along which grades would be increased and an orientation in the opposite direction in which grades would be decreased. Warping that would produce increased cutting in southward-flowing streams should produce aggradation in those flowing toward the north in the same area. Vertical uplift or doming would produce a steepening of gradient of streams flowing radially outward from the uplifted area.

No evidence of recent drainage changes of these kinds has been found in the Polacca or elsewhere in the Southwest. Observation of the growth of continuous gullies from short discontinuous ones (p. 92) further suggests that acceleration of erosion has been brought about by changes on and above the earth's surface rather than within the crust.

AGRICULTURE

Where cultivation of the land entails complete removal of natural vegetation and for part of the year leaves the surface entirely bare, the hazard of soil erosion varies with the farm calendar and with the seasonal variations in climate. In the Navajo and Hopi reservations agriculture is well adapted to the climatic conditions and is far less likely to induce serious erosion than are the usual agricultural practices of farmers in somewhat more humid lands.

Few of the Indian fields of northeastern Arizona are ever plowed. Corn, the major crop, is planted in individual holes made with a planting stick. Most of the fields are in sandy areas which retain much of the scant rainfall and therefore do not wash badly. Sand blowing rather than gullying is the major difficulty to be combatted on these fields, and windbreaks of reed, brush, or stones are commonly used. Fields on alluvial fans or on flood plains of arroyos are more subject to gullying. Even here, however, the usual Indian agriculture does little to increase the hazard. Stewart (*100, p. 329*) reports that flood-water irrigation as practiced by the Hopis and the Zunis today is a highly effective means of preventing gullying. The result of land abandonment may be seen on a field that went out of tribal control when boundaries of the Zuni Reservation were realigned about 35 years ago. The flat-bottomed stream which was formerly used to provide floodwater irrigation for the field has now cut a channel approximately 75 feet wide by 20 to 30 feet deep.

Diversion dams and distribution ditches to irrigate the fields are reported to have been very numerous in the past (*82, 100*), and if properly maintained must have acted to prevent rather than induce accelerated erosion. Abandonment of these works, as Reagan (*82*) has suggested, may have been a contributing factor in starting accelerated channel cutting. Bryan [20] believes there were fewer dams than Reagan indicates and that their effect on alluviation and erosion was small. It seems certain, however, that in the areas most intensively cultivated the water-control structures of these early farmers were highly effective in retarding run-off and in causing alluviation.

Little is known of the number of inhabitants in northeastern Arizona before the coming of the Spaniards. Espejo in 1583 estimated the number of the Moquis at 50,000, but this is thought to have been far too high (*43, p. 15; 48, p. 661*). In 1776 the engineer Miguel Costanso [21] made an estimate of 7,494 (*43, p. 15*). This figure, which is also given by Escalante, agrees well with other estimates of that period. In 1780, however, after 3 years without rain, Governor Anza gave the population as 798 and the deaths as 6,698. Whipple in 1853 noted the population as 6,720 (*111, p. 13*), the Eleventh Census in 1890 as 1,996 (*43, p. 49*), and the Indian Service in 1939 as 3,339, including 114 Hopis residing off of the reservation (*109, table 3*).

Considering that the Hopi population probably has never exceeded 8,000 and that the Navajos have gradually risen to their present 48,235 (*109, table 2*) from a start of about 8,000 in 1868, it is improbable that the Indian lands have ever been much more intensively farmed than they are today.

In recent years only about 38,000 acres on the Navajo and Hopi reservations have been under cultivation, exclusive of a small area around Gallup, N. Mex., and of acreage operated by the Indian Service. The cultivated acreage, less than 60 square miles, is approximately 0.25 percent of the two reservations excluding the Gallup area, or an average of 1.6 cultivated acres per square mile.[22] The

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[20] See footnote 18, p. 102.

[21] CONSTANSO, MIGUEL. DICTAMEN . . . SOBRE DISTANCIAS DEL NUEVO MEXICO A SONORA, Y A MONTERREY. [Ms.] Arch. Gen. y Pub. de la Nac., Prov. Int., v. 169, item 2. Mar. 18, 1776. Mexico City.

[22] U. S. SOIL CONSERVATION SERVICE. STATISTICAL SUMMARY HUMAN DEPENDENCY SURVEY, NAVAJO AND HOPI RESERVATIONS. 41 tables and map. Albuquerque, N. Mex. Rev. 1939. [Mimeographed.] (See tables 1 and 24.)

proportion in the Hopi country is higher, 7.6 acres per square mile in 1936, but above and below the Hopi lands on the Polacca and adjoining drainage basins cultivated land falls to less than the average for the reservations. Considering the small amount of land cultivated it seems impossible that agriculture could have been a significant cause of the acceleration of erosion.

CLIMATE

Many of those who have considered the acceleration of erosion in the Southwest have concluded that it has been brought on by a change of climate. The exact mechanism operative or the amount of change necessary to produce the accelerated cutting are not stated, but references to progressive desiccation, decreased rainfall, or greater relative aridity are common. Huntington (*65, 66, 67*), Gregory (*51*), Visher (*110*), and Bryan (*23, 28*) have suggested such a change as the cause of recent channel trenching (pp. 45–46).

RELATION OF CLIMATE TO NORMAL AND ACCELERATED EROSION

The possible effects of change of climate on rate of erosion are many and varied. Increase or decrease of precipitation are the changes most prone to affect run-off and are therefore of greatest significance in the problem.

Decrease of precipitation in an arid or semiarid land reduces the vigor of plant growth. The less hardy specimens die, the survivors are reduced in size or strength, and there is a general shift toward a more xerophytic vegetation. With decreasing precipitation there is also less water to flow off the lands. Three results are possible: (1) If the effect of vegetal depletion is less than that of reduction in precipitation, run-off will be less destructive and the hypothetical change of climate will bring less erosion than formerly; (2) vegetal depletion may balance decrease in precipitation and erosion conditions may remain the same as before; (3) depletion of vegetation may be more effective than the decrease in precipitation and, particularly if individual storm intensity remains the same, run-off and erosion will be accelerated.

Moderate increase of precipitation may have the opposite of any of these three effects. In an arid or semiarid land moderate increase should improve the vegetal cover on slopes. A great increase in precipitation is likely to cause degrading of stream valleys temporarily, until vegetal protection can adjust fully to the new climatic conditions. There is a question, then, in any area whether increase or decrease of annual precipitation would be most likely to cause acceleration of erosion. It has been assumed by most of the proponents of the climatic-change hypothesis, that a decrease in precipitation, by lowering the resistance offered by vegetation to run-off has brought about the increase in erosive activity in the Southwest. Huntington (*66, p. 32*) stresses the complimentary process. He points out that depletion of vegetation because of decreased precipitation so increases the amount of debris removed from the slopes that streams are overloaded and must aggrade rather than degrade their valleys. It must be kept in mind that processes are different in upstream and downstream parts of the same drainageway. In arid drainages that do not run through to a major stream all material eroded from the headwaters must be deposited at least temporarily in the lower course. The boundary between the eroding and the depositing zones migrates upstream or downstream with each period of run-off.

Possible results of a lowering of precipitation would depend in large part on the specific meteorological changes. In northern Arizona, for example, a reduction in winter rains would have a different effect from reduction in summer rains. Bailey has pointed out that a change in intensity would be important even if there were no change in total precipitation (*13, p. 337*). A meteorological shift that would lessen the frequency and intensity of summer thundershowers and of the occasional tropical cyclones in the Southwest, while maintaining the same annual total, might increase the protection afforded by the plant cover to the ground surface. A shift that would delay the inception of the summer rains by only a few weeks, however, would seriously damage the vegetation, thus favoring acceleration of erosion.

In a land of abundant rain an increase rather than any slight decrease of precipitation would be needed to cause acceleration of erosion.

It has been pointed out in the discussion of the distribution and intensity of precipitation in the Southwest and in the Polacca drainage in particular that summer conditions are markedly different from those of winter (pp. 8–11, 47–48). The silent differences and their effects on the operation of normal and accelerated erosion are summarized in table 13.

TABLE 13.—*Relation of summer and winter precipitation to normal and accelerated erosion in the Navajo country*

Seasonal elements of erosion	Normal erosion	Accelerated erosion
Summer:		
Vegetal cover at maximum	Natural cover retards run-off and promotes rapid infiltration and transpiration.	Depleted cover of slight effect in retarding run-off and in removing water by transpiration. Infiltration decreased.
Storms of high intensity but small areal extent and short duration.	Owing to natural vegetal protection, new channels can be eroded only in small areas visited by storms of exceptional intensity.	Owing to depletion of vegetal protection, new channels may form from storms of lower intensity, hence more areas are channeled.
No snow		
Low cloudiness; high evaporation rate; rapid surface drying.	Run-off beyond the storm area rapidly diminished by absorption and evaporation.	Run-off beyond the storm area rapidly diminished by absorption and evaporation.
	Few channels formed, mostly discontinuous.	Many channels formed, mostly discontinuous.
Winter:		
Vegetal cover at minimum	Natural cover offers limited obstruction to run-off; infiltration low; transpiration inoperative.	Depleted cover provides little obstruction to run-off; infiltration decreased; transpiration inoperative.
Storms of low intensity but large areal extent; may be of long duration.	Although natural vegetal protection is low at this season, rains are generally of too low intensity to carve new channels.	Combination of seasonal lowness of vegetal protection and depletion of natural cover may allow carving of new channels locally.
Snow		
High cloudiness; low evaporation rate; slow surface drying.	Run-off beyond the storm area little diminished by absorption and evaporation; flow from protracted storms may travel great distances.	Run-off beyond the storm area little diminished by absorption and evaporation; flow from protracted storms may travel great distances.
	Few channels formed, some of the existing channels cleared out and enlarged by confined flow.	Limited number of new channels formed; many existing channels cleared out and enlarged by confined flow; extensive continuous gully systems result.

Under normal conditions the vegetal cover of the Navajo country in summer gave adequate protection against all but the most intense rains. Carving of new channels took place largely where storms of unusually high intensity centered over areas where the vegetal cover was locally impoverished or destroyed by fire or other causes or where steep slopes allowed very rapid run-off. Most of the storms covered areas of less than 30 square miles and had low total precipitation and durations of less than an hour. High temperatures and almost continuous wind movement caused rapid evaporation outside the immediate storm area and only slightly slower evaporation within. Infiltration into the soil and transpiration from the natural plant cover were higher than they are today and were at their peak in the summer months.

Outside of the highly localized storm center the run-off rapidly diminished in volume, owing to losses from infiltration and from evaporation and transpiration, usually termed "evapo-transpiration" by hydrologists. Erosion and transporting power decreased as the volume of flow lessened, and the material washed from the storm area was deposited at no great distance.

Summer conditions tend to retard run-off and localize the effect of each storm. As a result the arroyos that were formed in summer under normal conditions were mostly short and unconnected and characteristically terminated in alluvial fans. Longitudinal alluvial fans, representing in part at least deposition at the lower end of discontinuous arroyo channels in the period of normal erosion, are present on the surface of the upper Polacca Wash.

In contrast to the intense summer storms, winter storms are characteristically of low intensity, may last for several days, and are of wide areal extent (table 13). These storms are accompanied by widespread cloudiness and low evaporation; winter vegetal cover is light and transpiration therefore ineffective. Under these conditions the widespread winter storm, although less able to initiate new channels locally, may cause run-off throughout the entire area. Especially if coalescence of tributary drainage brings together considerable flows of water, winter run-off, whether from rain or melting snow, tends to clear out channels and enlarge discontinuous arroyos lying within the drainageways.

With normal plant cover, the lands recovered quickly from the effects of heavy storms. Vegetation crept back into the newly carved channels and aided in trapping sediment. Vegetation on the surrounding area prevented rapid run-off from average rains and permitted healing of the storm-cut channels.

Depleted plant cover is much less effective than the natural cover in retarding run-off and removing water by transpiration. It is also less effective in aiding infiltration. In areas subject to accelerated erosion the effect of depletion is shown in several ways. Summer storms of an intensity of precipitation insufficient to cause cutting of new channels on a landscape clothed with natural vegetal cover can initiate channels in areas of depleted vegetation. Thus in a region having natural cover, only the area affected by the intense central part, or eye, of the typical summer storm would be subject to initiation of new channels, whereas in a region of depleted cover a much larger part of the storm might cause destructive erosion. Similarly, where the ground retains its natural cover, a rain of given intensity would carve channels only on steeper slopes and where drainage was concentrated in sags or draws. Where ground cover is depleted, a storm of the same intensity could initiate channeling on gentler slopes and on surfaces outside of draws and sags, hence subjecting a much larger part of the area to accelerated erosion.

Plant cover offers much less protection against erosion in winter than in summer. Mechanical obstruction to run-off is slight, especially where the cover has been depleted, and transpiration in winter is essentially inoperative. It is fortunate indeed that rains in the Southwest are characteristically of low intensity during this season of poorest vegetal protection.

Channel initiation is inactive in the winter months except along some of the major drainageways. Instead, the run-off from the slow, protracted, widespread rains and melting snows increases the size of channels already formed. Owing to the high proportion of cloudiness and the lowered rate of evaporation during the winter, in addition to a more sparse vegetal cover, run-off can travel a considerable distance little diminished by absorption or evaporation.

Channel clearing and headward growth of gullies lead to integration of the discontinuous gullies formed by summer rains and convert small separate channels into parts of one great continuous drainage system. This development of long, continuous channels through which water is rapidly drained from the region is one of the most serious consequences of accelerated erosion in the Navajo country today.

INCIDENCE AND EFFECTS OF INTENSE PRECIPITATION

A plant cover sufficient to protect the ground from the average storm, or even from the 5-year or 10-year storm, may be quite inadequate to protect against the 50-, 500-, or 1,000-year storms. The timing of rains and the conditions immediately preceding intense rains also weight their effectiveness. Vegetation impoverished by a long period of drought (pp. 31–35) is much less able to withstand a heavy rain than is a plant cover brought to bountiful growth by a succession of well-spaced rains of low intensity.

The effects of heavy rains are amply shown in the gullies and gullied channels, so nearly universal in the Southwest today, and in the floods, wash-outs, and cave-ins that have caused destruction of life and valuable property. Heavy rains are not new to the Southwest. They are an essential part of the meteorological regimen that has characterized this region at least since the readjustments that followed the close of the Ice Age (*91*). Run-off from heavy rains here as well as in other parts of the country, however, is now more rapid than it was before white settlement (*103*). From the earliest records to the present there has been an ever-increasing cry that floods are getting higher upstream, channels are cutting more deeply, downstream reaches are aggrading, and the vegetal cover is not so good as it once was.

The occurrence of destructive rains in the latter half of the last century is amply shown by newspaper accounts, journal entries, and official correspondence. Representative storms and their effects are described below.

The Arizona Miner (*1*) for August 8, 1868, reported:

> About 9 o'clock Sunday morning last there occurred, in Yuma county, in this Territory, one of those dreadful catastrophies in Nature, known as a "water spout," which * * * is without a parallel in similar phenomena. Mr. James Grant, mail contractor on the La Paz and Prescott route * * * left La Paz Sunday morning, and proceeded about 14 miles when he beheld a tremendous black cloud to the eastward, moving toward him from the direction of Granite Wash. Nothing daunted, he kept on his journey until arriving at the big ravine, 14 miles this side of Tyson's Well, now Rovert's Station--where he found the freight trains of Miller Brothers and Campbell & Buffum, of Prescott, in a badly demoralized condition. While the wagons, or a part of them, were crossing the ravine or wash, a flood of water, which came very near destroying the whole train rushed upon them * * *.

On the 31st of August, 1872, the Arizona Miner (*98*) published a delayed letter from Camp McDowell, stating:

> On the 9th inst., we had the greatest flood in this section that has ever been witnessed here, 3 60-100 inches of water fell (by the hospital guage,) in less than two hours, and nearly 7 inches fell in less than 12 hours. The damage is immense. The Government ditch is nearly all washed away. We lost over $5,000 worth of hay.

A few years later, in 1880, the Indian Agent on the Navajo Reservation commented (*16, p. 132*).

> The effect of the heavy winds and rains has been to destroy in many localities the entire crops of wheat and corn. The rains were unusually severe this season, more so than for four or five years past. The dam at the agency, about completed, was carried away by one of those extraordinary floods in about half an hour's time, and rocks weighing tons carried a distance of several hundred yards.

Bourke, a keen observer of natural phenomena, described (*17, pp. 5–6*) many of the storms his party encountered in Arizona and New Mexico in the summer of 1881.

> Those who are not familiar with the fearful type of thunder-storms which arise in the Trans-Missouri region can form no conception of the havoc wrought by those which assailed the vicinity of Santa Fé in the first week of August 1881, and taxed to the utmost the engineering ability of the managers of the Topeka and Santa Fé Railroad to keep their trains running with anything like regularity. The worst storm of the series (that of the early morning of August 2), although spasmodic in its nature, was phenomenal in the amount of water falling during the time it lasted. * * *
>
> Consequently we were not astonished to learn, as we did at breakfast, that the railroad track had been washed away, and that there was no probability of trains running on schedule time for several days.

Constant storms forced Bourke and his party to remain at Keam's ranch in Keams Canyon from August 13–15, 1881. He says (*17, pp. 276–277, 280–281*):

> The first evening after our arrival, as the sun was setting, the mist thickened suddenly, and a fearful cloud-burst broke upon us; in less time than it takes to write these lines it had flooded the creek-bed, raised the water to a depth of three inches on the level ground around the house, carried away the dam, which was built of ponderous sandstone slabs two feet on a side, and then subsided as quickly as it had come.
>
> Inside of half an hour the whole tempest had come and gone. Eight to ten feet of water had swept like a solid wall down the narrow channel of the creek, and the stars were again shining!
>
> * * * * * * *
>
> No description could do justice to one of these Arizona cloud-bursts. Mr. Keam's house lies in a narrow gorge only 100 yards wide, and the receptacle of every drop of water falling within an area of ten miles square. It does

> not take much calculation to show the power of one of the storms prevailing here during the rainy season.

Following the trail southward through the Hopi Butte country to the Mormon settlement of Sunset, on the Little Colorado River, Bourke's party reached the Breaks of the Little Colorado in the afternoon of August 21, 1881 (*17, p. 347*).

> Here could be made out the grade of what must at one time have been a very respectable piece of engineering, a road down into the valley below, or rather down to the lower bench.
>
> * * * * * * *
>
> Whoever had done the work had done it well, but fruitlessly. A fearful cloud-burst must have swept over this place lately, and with immense power had hurled great cubes of rock from their positions or gnawed out awful gaps 5 and 6 feet deep and 8 and 10 feet wide in the path we were to descend.

The destructive power of some of the storms of a single month in 1881 is well shown by Bourke's accounts. Then, as now, railroad tracks were washed out, substantial rock dams were carried away, and roads were made impassable by gullying. Other summer storms in northeastern Arizona led the Indian Agent (*80, p. 190*) to report, September 1, 1888:

> Some of the dams constructed last year have washed out; in fact it would be difficult to make a dam in this country to withstand the terrible floods during the rainy season, without a great outlay of expense. For this reason the construction of dams, except for temporary uses, should be abandoned and the work directed to reservoirs, ditches, and the developing of springs.

The heavy rains of 1880–1890 are of particular interest because of the evidence that acceleration of erosion first became apparent in many of the valleys of the Southwest during that period (pp. 104). Among the excessive and destructive storms of the 1880's General Greely (*47, pp. 14, 17*) in a report on the climate of the arid regions of the Southwest listed for Arizona and New Mexico.[23]

> *September*, 1880.—The rainfall of the 21st, measuring 2.80 inches, caused a flood at Silver City, [N. Mex.] which damaged buildings and drowned a boy.
>
> *August*, 1881.—Three floods visited Silver City during the month, on the 7th, the 15th, and the 20th, of which the second did considerable damage.
>
> *August*, 1881.—Near Wickenburgh, Ariz., a cloud burst, causing the Hassayampa River from being perfectly dry at sunset, August 6, 1881, to be a stream a mile wide at 11 p. m., and from 2 to 15 feet deep; in 13 hours the river was again dry. On the 17th a flood interrupted communication and did much damage in the Salt River Valley near Phoenix.
>
> *October*, 1881.—Great damage was done to the Atchison, Topeka and Santa Fé Railway on the 6th, and all traffic was suspended south of Las Vegas. In the Rio Grande and Galisteo valleys there were numerous heavy washouts, and in many places the road bed was covered with great heaps of sand.
>
> *August*, 1882.—Serious washouts occurred on the 24th between Casa Grande and Yuma.
>
> *March*, 1884.—At Florence on the 7th a cloud-burst flooded the streets 4 feet deep. On the 10th several miles of track were washed away east of Yuma. On the 11th the Gila broke through its levees and flooded Yuma.
>
> *July*, 1884.—The flooded Colorado washed away parts of the railway bridge at Yuma on the 1st and 3d.
>
> *April*, 1886.—Heavy rain on the 19th and 20th caused Santa Fé Creek to assume the proportions of a river. Telegraph communication was interrupted, railroad bridges were washed away, and several miles of track destroyed.
>
> *June*, 1886.—High water in the Rio Grande, in the Valverde, completely overflowed the towns of Chamberino, Launeen, and Nombre de Dios, this on

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[23] The data on Arizona and New Mexico quoted from Greely have been rearranged chronologically.

the 2d and 3d of the month. Between the 7th and 10th the freshet having moved downstream washed away houses and railway tracks, destroyed bridges, and submerged three towns in the Mesilla Valley.

August, 1886.—This was a month of floods at Yuma. On the 1st, light rain fell during the greater part of the day. Seventy-five miles west of Yuma the rain was heavy, causing a washout on the railway and delaying trains. On the 15th there was a thunderstorm measuring 1.57 inches, of which 0.80 fell in 20 minutes; the railway was washed out both east and west of Yuma, causing a complete suspension of traffic for several days. On the 27th, heavy rain in the mountains washed out the track east of Yuma and delayed trains.

September, 1886.—Between the 11th and 13th, heavy rains fell between Socorro and Albuquerque, washing away several miles of track, a bridge over the Salida was rendered insecure, and several houses were destroyed in Socorro and San Marcial.

July, 1887.—On the 7th a remarkably heavy rain fell at Nogales, flooding streets, destroying bridges, and washing away railway tracks. During the prevalence of a thunderstorm on the afternoon of the 8th, a cloud-burst occurred on the east fork of the White River in the mountains east of Fort Apache. A volume of water 3 feet deep came down the cañon, which subsided in two hours. On the afternoon of the 13th another heavy rain occurred at Nogales in connection with which there was reported a cloud-burst in the mountains southeast of Sonora. Railway traffic was stopped for nearly a month.

September, 1887.—Heavy freshets came down the Santa Cruz and Rillito on the 9th, destroying several miles of track and some bridges near Pantano. On the 12th, 5 miles of track and three bridges were washed away on the Sonora railroad. Near Dragoon a railway embankment 50 feet high was washed out for a distance of 8 miles.

The nineties and the early years of the next decade were not without intense storms. 1905, however, stands out as a particularly wet year (pp. 18–21): in January, February, March, April, and November precipitation was far more than normal at many stations, but the summer months were drier than usual. Because the rains were mostly of the winter type, characterized by large total precipitation rather than high intensity, many widespread floods resulted. Records of a few of the rains of 1905 and their effects in damage to property and loss of life, as published by the Arizona Republican, of Phoenix, are listed below:

[January 11] From authentic sources it was learned that while [it was] the heaviest rain for seven years in Central Arizona, the losses to the railroads comprised nothing but minor washouts * * *. The situation was much better than would have been the case if the precipitation had been of the midsummer, torrential character. [See *2, p. 1.*]

[February 6] Mr. Green had 100 acres of barley and some alfalfa * * *. It was all rooted up but about ten acres, and that was badly damaged. There is no sign of the young alfalfa. If it had been older something might have been expected of it yet, but this crop was removed by the roots, the surface of the ground being sheared off or cut full of miniature arroyas. [See *3, p. 1.*]

[February 20] The worst that was feared has happened and for the third time this year the Gila bridge is wrecked. At least 400 feet of it was taken away by the flood waters Saturday night and Sunday and by this time the break may be still larger. [See *4, p. 5.*]

[March 15] A Mr. Brown * * * said that one farm under the Arlington canal had been taken bodily and another of 160 acres adjoining it was more than half gone, and a part of the property of the Arlington Land and Cattle company had been swallowed up by the river.

The river has at no time overflowed its banks in that immediate neighborhood but has risen almost to the top of the banks. The water runs with terrible swiftness and the banks melt away, whole acres at a time. The erosion is increased by heavy drift wood which the water hurls against the loose soil. [See *5, p. 6.*]

[March 17] Tempe and the surrounding country was visited by the worst rain and hail storm so far yet this season yesterday afternoon. * * * Mr. Simmons * * * reported that in forty-five minutes the precipitation amounted to 1.42 inches and it seemed from that place to be raining as hard or harder on all sides.

* * * * * * *

About 500 feet of the M. & P. track went out * * *. [See *6*, *p. 7*.]

[April 16] J. T. Hord who has lived for some years on a farm near the river at the south end of the Novinger road [near Phoenix, Ariz.], has moved to town. * * * Of the sixty-five acres he had title to a week ago only twenty-five acres are left and with the forty acres that were swept away in the flood, went his honey extractor, the building it was in, various outbuildings, an outside cellar, nearly all the mesquite and shade trees on the farm and all of his back yard. The water had undermined his main house so bad it was no longer safe to stay in it and one-half of it is sticking out over the angry stream, or was yesterday. [See *7*, *p. 4*.]

[April 26] Gallup, N. M., April 25.—The flood situation on the Atchison, Topeka and Santa Fe railway was practically unchanged tonight and it is regarded as very doubtful if any trains can be moved before late tomorrow if then.

* * * * * * *

Bridge No. 90, over the Rio San Jose, just at the west switch at Horace, is in a very dangerous condition and may go out at any moment. The snow is very deep in the mountains and all the streams are running bank full in some places overflowing the lowlands. [See *8*, *p. 1*.]

[November 30] All other flood news now takes a back seat and the Maricopa & Phoenix railroad bridge over the Gila river again steps into the limelight. As was feared Tuesday night, disaster overtook it and yesterday morning it was learned that four hundred feet of the long structure had been swept away and fears are entertained that the breach will be further widened before this morning. The bridge is somewhere between 1500 and 2000 feet long * * *. [See *9*, *p. 3*.]

Heavy floods on the lower Colorado River in the spring of 1905 enlarged the intake to the irrigation canals of the Imperial Valley, and the river cut a new channel 75 miles across southern California to the Salton Sink. This basin had been dry when first explored by the Spanish in 1774 and remained dry almost continuously until the Salton Sea was formed in 1905.

Protracted winter, spring, and fall rains such as caused the extensive flooding in 1905 are very effective in clearing out and widening channels and in bringing about integration of gully systems. There is little information available on the effects of the 1905 rains on soil erosion. However, as the heavy winter and spring rains produced a good vegetal cover, it is to be expected that erosion would have been felt much more in enlargement of channels already started than in the cutting of new gullies down vegetated slopes.

The tropical storms that moved up the California coast in September 1939 (pp. 13-14) caused extensive damage in Arizona and in the southern part of California. The storm of September 4–7 brought the heaviest rain Phoenix, Ariz., had experienced in 28 years. Canal banks broke, traffic was interrupted, fields and homes were inundated, and gullies were carved on agricultural land. Traffic on the Atchison, Topeka & Santa Fe Railroad was interrupted for several days by wash-outs between Valentine, Ariz., and Goffs, Calif. Before the damage from the storm of September 4–7 could be fully repaired, rain from the second tropical cyclone reached the area. Many of the reconstructed sections of track were washed out again, and other sections untouched by the first storm were badly damaged. Bridges, culverts, bulkheads, and embankments were most seriously affected. Thousand-foot sections of track were undercut or removed in at least six locations. Several of the breaks were nearer 2,000 feet in length.

In a few areas additional damage was done by other storms coming still later in September.[24]

The Southern Pacific Co. had no more than average storm damage to the Arizona portion of its lines in September 1939. In southeastern California the storm apparently was heavier, and in the two States damage to the railroad right-of-way approximated $175,000.[25] The Arizona Highway Department reports that in its opinion this was the heaviest storm experienced in northwestern Arizona in the past 50 years. Traffic was delayed on U. S. Highway No. 66 between Kingman and Topock and on U. S. Highway No. 80 between Hassayampa and Yuma because of run-off in the dips. A stretch of about 10 miles of U. S. Highway No. 93 between Kingman and Boulder Dam was so badly damaged that it will have to be rebuilt. The cost is estimated at $150,000. A timber bridge some 300 feet long across Detrital Wash was carried away bodily and will have to be replaced.[26]

Destructive floods from the abnormal September rains swept down the lower Colorado River Valley in California and Arizona early in the month. Property along the river was damaged extensively and canals and lands of the Yuma irrigation project and the Imperial Irrigation District were affected by wash-outs, gullying, and silting (*46, p. 754*).

> Imperial and Coachella valleys suffered the greatest damage. Nearly every wash and water course ran full and many (with the exception of Alamo and New rivers) exceeded their previous maximum records. In a number of instances the channels were insufficient to carry all the water, and the runoff flowed as a sheet over the adjoining land cutting numerous gulleys varying in depth from inches to several feet. * * *
>
> Truck gardens in many places were covered with several inches of sand and silt, leaving the fields perfectly flat, but eroded by large gulleys.
>
> The Imperial district's canal system suffered probably the worst damage since the disastrous floods of 1905–06–07. Many of the canals were obliterated, others became uncontrolled flood channels, and miles of laterals were so devastated that it will be necessary to reconstruct them.

Less precipitation fell in the Navajo Country in the northeastern part of the State, but even if storms had been as heavy there accounts of the damage would be few. Records of destructive rains in the Navajo country come largely from reports of Indian Agents, as storms seldom receive notice in the public press unless they happen to disrupt highway or rail travel or damage irrigation or water-supply works.

Many storms have contributed to the cutting of the present large gully in Keams Canyon, on the Polacca drainage. Bourke's description of the heavy rains he observed there in 1881 (p. 113) shows the power of flash run-off.

In 1911, the Annual Report of the Moqui Agency, Keams Canyon, Ariz., stated that buildings of both the agency and the school were being injured by the constant cracking of the walls. This was believed to be due to the gradual slipping of the soil toward a large arroyo in front of the grounds. The arroyo, it was noted, was con-

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[24] Letter to C. W. Thornthwaite from M. C. Blanchard, chief engineer, Coast Lines, Atchison, Topeka and Santa Fe Railway Co., Los Angeles, Calif. March 15, 1940.

[25] Letter to C. W. Thornthwaite from W. H. Kirkbride, chief engineer, Southern Pacific Co., San Francisco, Calif. March 19, 1940.

[26] Letter to C. W. Thornthwaite from F. N. Grant, deputy State highway engineer, Arizona Highway Department, Phoenix, Ariz. April 6, 1940.

stantly becoming larger by reason of the heavy rains in July and August of each year.[27] The report for the same agency in 1913 shows a picture of the arroyo in Keams Canyon "within one mile of its beginning, where the canyon is narrow. Depth approximately fifty feet." The caption notes further that 10 years before there had been no evidence of such an arroyo.[28]

The annual report[29] for the next year states that the first days of July were rainy and that on Sunday, July 5, 1914 0.7 inch of water fell in 15 minutes. Great damage resulted. Rains between August 26 and September 3, 1915, in the vicinity of Keams Canyon destroyed roads and rendered communication exceedingly difficult.

In 1919 the Superintendent[30] of the Moqui Agency reported: "On July 15th, 1919, in Keams Canyon, one inch of rain fell in thirty minutes. This was a flood that caused one to wish he had an Ark."

Only 2 years later, on August 4, a cloudburst washed out the retaining walls at the Keams Canyon agency and destroyed roads, crossings, and bridges, cutting off all communication with the schools.[31]

It is apparent from the foregoing descriptions and from that by Hoover (p. 106) that the major gullying in Keams Canyon probably started between 1903 and 1911 but that the gully did not approach its present size until about 1915 or 1920. The part played by the occasional intense rains in the cutting of this gullied channel is clearly indicated by the above accounts.

Intense rains have caused accelerated cutting and serious property damage in many other parts of the Navajo country. A cloudburst on the evening of July 24, 1921, near Fort Defiance Agency rushed down Bonito Creek 10 feet deep destroying protective works that had stood for 16 years. A road and 200 feet of pipe line were washed away, cutting off the water supply. Damage was estimated at $10,000 to $12,500.[32] [33]

Superintendent Kneale[34] of the San Juan Agency at Shiprock, N. Mex., reported on September 19, 1925:

> I have to report a cloud burst yesterday P.M., about 3:00, lasting practically one half hour. The water flowed over the highway near the athletic field to a depth of three feet; the ware house, jail, and all cottages were surrounded by water to a depth of one feet or more; water flowed down the highway leading toward Farmington to a depth of one foot. Some of our crops are buried under many inches of ooze and some are washed away; fences were destroyed; ditches filled and obliterated; bridges and roads washed out; the basement at the Mesa School was partially filled with mud and water. However there was no accident or loss of life.
>
> There have been numerous such storms, during the past six weeks, on all sides of us, keeping the arroyas full and the roads for the most part impassable, but this one hit Shiprock squarely.

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[27] LAWSHE, A. L. ANNUAL REPORT FOR THE FISCAL YEAR, 1911, OF THE MOQUI INDIAN SCHOOL, ARIZONA. [Ms., Nat. Arch.]

[28] CRANE, LEO. ANNUAL REPORT OF THE SUPERINTENDENT, MOQUI INDIAN RESERVATION, ARIZONA [FOR 1913]. PICTORIAL SECTION. [Ms., Nat. Arch.]

[29] CRANE, LEO. ANNUAL REPORT OF THE SUPERINTENDENT, MOQUI INDIAN RESERVATION, ARIZONA [FOR 1914]. NARRATIVE SECTION. [Ms., Nat. Arch.]

[30] CRANE, LEO. EIGHTH ANNUAL REPORT [1919] OF THE SUPERINTENDENT FOR THE MOQUI INDIAN RESERVATION KEAMS CANYON, ARIZONA. NARRATIVE SECTION. [Ms., Nat. Arch.]

[31] DANIEL, [R. E.] Telegram to the Indian Office, Washington, D. C., from Moqui Agency, Keams Canyon, Aug. 4, 1921. [Ms., Nat. Arch.]

[32] PAQUETTE, [PETER]. Telegram to the Indian Office, Washington, D. C., from Fort Defiance, Ariz., July 25, 1921. [Ms., Nat. Arch.]

[33] ——— Letter to Commissioner of Indian Affairs, Washington, D. C., from Fort Defiance, Ariz., July 26, 1921. [Ms., Nat. Arch.]

[34] KNEALE, A. H. Letter to Commissioner of Indian Affairs, Washington, D. C., from the San Juan Agency, Shiprock, N. Mex., Sept. 19, 1925. [Ms., Nat. Arch.]

If records of heavy rains and resulting erosion damage in the Navajo country were more complete, a much more detailed picture should be available of the close relation between storms and erosion suggested by these scattered accounts of the cutting of Keams Canyon Gully and the damaging erosion near Fort Defiance and at Shiprock Agency.

As there is no indication that there has been either an increase or a decrease in the average annual amounts of precipitation in the past 2,000 years or that heavy storms are now any more frequent or more severe than they have been in the past (pp. 43–46), the explanation of the increased erosion by run-off and the heightened floods must be sought outside of the field of meteorology.

GRAZING

Evaluation of the role of overgrazing in bringing about accelerated erosion in the Southwest can be based in part on correlation of the time of starting of heavy grazing and the date of gully cutting in various valleys. As the Southwest developed primarily as a cattle country, it is only natural that the introduction of large herds took place as early as or earlier than the establishment of permanent white settlements. Herds grew in size rapidly, and the grazing load increased until in many areas it soon exceeded the safe range capacity. In humid years when the vegetal cover was at its best the large load could be carried. With the coming of a dry year or a succession of dry years, however, the cover was far from sufficient for the livestock. It was inadequate also to protect the land from erosion.

The facts are clear that acceleration of erosion followed close on the heels of the introduction of heavy grazing. Considering the large number of valleys throughout the Southwest where this is found to be true, the relation can hardly be fortuitous.

Rillito Creek, near Tucson, began cutting after the opening of the Army post at Fort Lowell in 1872. According to Smith (*96, p. 98*) the valley was first settled in 1858, and at that time was an unbroken forest, principally of mesquite, with a good stand of grama grass and other grasses between the trees. When the Army post was opened hay was needed in large quantities. A few years of cutting hay killed much of the grass, and cattle introduced during the seventies further destroyed the forage and developed trails, which soon eroded to gullies.

According to a rancher (*53, p. 12*), the San Pedro Valley, Ariz., had a luxuriant growth of vegetation in 1870. He continues:

> There were fully 50,000 head of stock at the head of Sulphur Spring Valley and the valley of the Aravipa in 1890. In 1900 there were not more than one-half that number and they were doing poorly.

Another rancher (*53, pp. 13–14*) on the San Pedro said in 1900:

> Of the rich grama grasses that originally covered the country so little now remains that no account can be taken of them.
>
> *   *   *   *   *   *   *
>
> Twelve years ago 40,000 cattle grew fat along a certain portion of the San Pedro Valley where now 3,000 can not find sufficient forage for proper growth and development. If instead of 40,000 head 10,000 had been kept on this range, it would in all probability be furnishing good pasture for the same number to-day. Very few of these cattle were sold or removed from the

> range. They were simply left there until the pasture was destroyed and the stock then perished by starvation.

Hoover states (*61, p. 45*) that the changed behavior of the Gila River is generally attributed to overgrazing and the cutting of timber in the upper basin.

> Before 1870 there were few cattle, but they increased rapidly after the settlement of the Apache Indian troubles that year. During the eighties there was a series of wet years with abundance of natural forage. The ranges built up rapidly, and overgrazing resulted. During the same period the mountains of the Upper Basin in southeastern Arizona were being rapidly stripped of their timber for use in the mines. The hills were barer than now, because with the advent of the railways better mine timber was brought in from the outside; but the cutting for fuel continued. At the end of this series of wet years came the disastrous flood of 1891. Before this, flood waters of the Gila merely spread out over the flats and irrigated them. Now with the banks of the river unprotected by brush and grass, the channel suddenly widened, and many good ranches along the river were cut out. Smaller branches of the river in the upper basin cut channels as much as twelve feet deep. On the desert deep channels appeared in what had been grassy swales.

Diversion of water by irrigation projects farther up the Gila Valley and consequent reduction of flow is also thought to have contributed to the changes in the regimen of the river (*61, p. 45*).

The balance of grazing, vegetal cover, and climate can readily be upset. In a series of years with normal or greater than normal precipitation the range may have carried the grazing load with little detrimental effect. With the coming of a drier than normal season, year, or series of years the depletion of vegetation may have been so great as to adjust the grazing load automatically by starvation. Calvin[35] in a study of the history of the Upper Gila Region says:

> With an immense grass-covered range, then, in its virgin condition, and with the additional advantages of a mild climate, Arizona was obviously destined to develop almost overnight into an important stock-raising country.
>
> * * * * * * *
>
> When the two transcontinental railroads crossed Arizona about 1880, they gave still further impetus to the livestock industry along with others. A great part of the sudden influx of population took to ranching. * * * Many made fortunes at first, but competition naturally grew keener. By the middle eighties, every running stream and permanent spring had its settler. Ranch houses were built, and ranges stocked with cattle brought from every part of the west.
>
> In the fall of 1883, the first carload of pedigreed Herefords were unloaded in Arizona. * * *
>
> In the early eighties, there was a heavy demand for beef in the great mining camps of the Territory and another from the California markets. * * *
>
> Then about 1885 occurred a drastic deflation in the mining industry. * * * As a result, ranchmen turned for the first time to eastern markets and when a shipment of five hundred head brought the owner a gratifying price, a new trend in ranching practice developed. It became the custom for several years to retain the she stock on the range, and to hold the steers until three years old and sell them as feeders to the corn-growing states or to California.
>
> The retention of cattle on the range then began to assume great importance for the purposes of the present study. By 1891 it was conceded that the ranges were stocked, says Campbell, to the limit of their capacity. Then the drouth arrived. * * *
>
> Little effort was made by owners to sell or ship their stock, as they waited for the grass of the coming season. But 1892 was worse than its predecessor. By May cattle were dying. June, always a dry month in the Southwest, further dissipated the moisture which remained. The July rains did not come. The August rains did not come. Cattle were perishing everywhere.

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[35] CALVIN, ROSS. THE HISTORY OF THE UPPER GILA REGION IN ARIZONA AND NEW MEXICO. [Unpublished manuscript, September 1935.] Mr. Calvin was research assistant, Soil Conservation Service, Safford, Ariz.

> * * * Another year dragged onwards, and then in May, June, and July of 1893 occurred the worst losses of all. "All ranchmen concede," says Governor McCord, looking backwards in his Report of 1897, "that it (the loss) was no less than fifty per cent, and some insist that seventy-five per cent is not too great an estimate."
>
> * * * * * * *
>
> The first tragic half-cycle was complete, for the country had passed in twenty years from its virgin, grass-covered state to a parched, close-picked condition in which the last palatable leaf had temporarily been destroyed by starving animals. * * *
>
> Sufficient history has been cited to show extreme unwisdom in the practice of overstocking by the ranchmen. They estimated the carrying capacity of the range and stocked it, not according to its minimum but its average—which without a reserve of some kind has always proved fatal.

Other changes incident on settlement have been at least contributory causes for acceleration of erosion in some areas of the Southwest. When settlers cut a short drainage channel to confine flood waters of San Simon Creek near Solomonville in 1883 (*79, p. 79*), they started a gully that is now at least 60 miles long. The gully of the Rio de Flag, Ariz., was started partly by erosion along an old logging road used in 1886–87 (*20*). The San Vicente arroyo which formed down the main street of Silver City, N. Mex., has been mentioned on p. 103. Bare of vegetation but unpaved, the street lay in a natural drainageway. It began to erode, and the channel enlarged rapidly to its present depth of more than 50 feet. Lumbering, forest fires, and overgrazing, Calvin says, are the reasons for the increased rate of run-off from the watershed above Silver City (*31, p. 39*). Setting aside of the Gila Forest in 1908 gave nature a chance to revegetate the watershed, and Calvin reports that floods are now so much smaller and less frequent that there is a popular notion that the area no longer receives the big rains that formerly fell there, an impression not borne out by the records. Revetment work and gully-control dams installed by the United States Soil Conservation Service and the Civilian Conservation Corps have further protected the city from the possibility of recurrence of destructive floods (*32*).

In southern Colorado, according to Duce (*44*), ranchers are unanimous in stating that trenching of valleys has taken place within the 60 years preceding 1918. Development of the arroyos, he says, seems to have been contemporaneous with ranching. Duce notes that cattle often trail down the center of a canyon, and he believes that wearing of trails and destruction of vegetation by livestock were the causes of the accelerated erosion.

Additional evidence of the part played by heavy grazing was presented by Dodge in 1909 (*42*). He found in the Chinle Valley strong indication that the run-off from rains formerly flowed over gently sloping valley floors in sheets. The Navajos, he says, charge that sheep, first introduced to the area by the white man, have closely cropped the native grass. This and the traveling of sheep in droves, often in single file, have aided in loosening surface detritus and giving water opportunity to become concentrated in streams. Dodge notes (*42, p. 531*) that, at the time he wrote, the main Chinle Valley and its larger tributaries were barren and were cut by arroyos, but—

> one branch is grass-covered and flat-floored and supports willow trees. Water flows in sheets over the surface and is not concentrated in streams. This valley has never been occupied as a grazing area for sheep by the Navajos because of a superstition that it contains certain plants that are injurious to sheep.

The presence of dead willows in branches of the Chinle Valley that have been grazed and are now deeply dissected by arroyos suggests that moisture conditions and the valley floor were formerly like those of the one remaining branch that has escaped erosion.

In the Navajo country, grazing of domestic animals could not have been extensive before the founding of the reservation in 1868. By 1872 about 44,000 head of sheep and goats had been brought into the the reservation (*12, pp. 198–199*), and growth of the flocks had undoubtedly increased the number considerably. Compared with the number of sheep and goats on the reservation in recent years, this number is very small. It seems hardly likely, therefore, that the grazing load of the seventies would be heavy enough to introduce serious erosion. In the eighties or early nineties the critical grazing load may have been reached.

As the small vegetational surplus was consumed, overgrazing prepared the way for erosion. Where part of the vegetal cover had been removed, even light storms were able to produce erosion. Sheet wash and rilling came first, followed by the cutting of gullies, which enlarged in each succeeding period of run-off. Gullying of the main channels of the washes and integration into continuous gully systems followed. The headward growth of gullies and the starting of new ones have gone on year after year during the period in which the overgrazed condition of the ranges has become increasingly acute. Natural grasses have been displaced by less desirable vegetation, and locally vegetative depletion has gone so far that only scattered remnants of sod on bare rock surfaces give evidence of the former soil and grass cover.

Overgrazing has altered the plant association on the mesa areas of the Polacca Wash drainage and has so increased the run-off that all rains except those of very low intensity cause soil erosion. The run-off from the lighter storms is too slight to do much gully cutting near the divides and seldom becomes sufficiently concentrated through coalescing drainage to cause channeling on the mesa tops. Light rains, however, do soak the walls of preexisting gullies and induce caving.

In the pediment zone along the Polacca Wash the gentler slopes, and especially the back slopes of the asymmetric ridges formed by slumping (p. 79), were formerly well vegetated, and grasses as well as brush and trees were present in many parts of the area. Hogans were frequently built within or adjacent to this zone, and these gentle slopes were subjected to heavy grazing. Many of the slopes which formerly were soil covered are now bare, and gullies have been cut in the benches where alluvial material was once deposited. Most of the grass has been destroyed, and except for local abundance of piñon-juniper, brush and weeds now compose the sparse plant cover of this zone.

The vegetal cover of the alluvial fans and valley flats of the Polacca drainage has also been seriously depleted by heavy grazing. The extensive gullying of the fans and flats, though, is influenced not only by overgrazing within the canyons but by depletion of vegetative cover on the mesas, which causes accelerated washing over the cliffs and down into the canyons.

The situation on the Navajo lands is like that in parts of Africa having similar climate. It is said that the overgrazed native pastures are today the most seriously eroding areas within East Africa. Pastures near the water holes are so badly overgrazed and trampled that water can no longer penetrate into the soil. Cattle trails develop into gullies radiating from the water holes, and the overgrazing spreads outwards so far that cattle may have to travel 20 miles for water.[36] Where pasturage is too poor for cattle, sheep and goats are substituted. When goats have devoured the ground vegetation they browse the lower parts of trees and shrubs up to a height of 5 or 6 feet (*33, pp. 130–139*).

In the Union of South Africa it has long been the native custom to drive livestock daily to and from a kraal, or enclosure. This practice closely resembles that of the Navajos, who use a corral until the surrounding area is grazed out and then move on. The development of centers of serious overgrazing and trampling is common in both areas and has led the Drought Investigation Commission of South Africa to state that the abolition of kraaling is their most pressing and necessary change in farm methods (*99*).

It has been held for many years by Bryan and others that overgrazing is not the basic cause of the acceleration of erosion in the Southwest. Part of the reasoning behind this stand is that the buried channels and filled washes within the present main valleys give evidence of at least three alternations of cutting and filling. Bryan says (*28, p. 281*), speaking especially of the Rio Puerco in New Mexico:

> It appears inherently most probable that the cyclic changes have a common, and doubtless a climatic, cause. The introduction of livestock and the ensuing overgrazing should be regarded as a mere trigger pull which timed a change about to take place.

From Bryan's viewpoint it might logically be concluded that anything man can do to reduce grazing and other surface irritations will in all probability be inadequate to prevent the continuance of accelerated soil erosion in the Southwest. If this view is in error, and the erosion has been the direct result of man's use of the land, there is every reason to believe that by judicious reorganization and restriction of land use the damage can eventually be checked. Expressing Bryan's hypothesis in another way, change of climate might be regarded as the debilitating agency that had lowered the resistance of the land—overgrazing as the germ or infection that had touched off the epidemic of accelerated erosion. Even if the present severe destruction could be checked, the general run-down condition would continue and a full cure would hardly be possible.

The other view, that held by the authors of this bulletin and by many others interested in actively combatting the soil destruction in the Southwest, is that overgrazing by livestock introduced by the white man has reduced the resistance of the land to erosion and that intense storm precipitation has been the germ or infection that caused the outbreaks of accelerated erosion. In this view, lessening of the grazing load would so build up the vegetal cover and the resistance of

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[36] MAHER, COLIN. SOME ASPECTS OF SOIL EROSION IN THE NATIVE RESERVES OF KENYA COLONY. [1938.] [Unpublished manuscript.]

the soil to erosion that only storms of extreme intensities would be able to cause serious erosion. The latter view is the more attractive in that it offers hope of continued use of the lands through wise control. Fortunately the evidence points strongly to the validity of this interpretation.

As has been seen in the discussions of the climate of the Southwest and of the possibility of climatic change (p. 38–46), meteorologic and climatologic considerations show no trend toward a more arid climate in the Southwest in the past few thousands of years and no evidence of any present day trend either toward more arid or more humid climate.

The large storm of high intensity and heavy fall of precipitation rather than a general climatic trend explains the accelerated erosion of the arid and semiarid lands. Large storms have always occurred. Before overgrazing lowered the resistance of the surface only the greatest rains could carve arroyos and enlarge wash channels. The lands recovered rapidly, moreover, and discontinuous channels had little opportunity to join with others to form long continuous waterways. Perhaps only the 100-year rain cut new channels on the naturally vegetated surface, perhaps only the 500-year rain. Big storms have been and always will be unpredictable. None may occur for many years, or two or more may take place a few days apart. Big storms, especially if grouped and if coming at a dry season or after a long drought, have always been able to cut channels and start a subcycle of accelerated erosion. Many of the periods of channel cutting before the coming of the white man to the Southwest may have been brought on in that way. Arroyos observed by Dellenbaugh (*40*) in places where he says there were no cattle and never had been may also have been cut by occasional storms of extreme intensity. Buried channels found in the valley fills of the Southwest doubtless resulted from earlier 100-year or 500-year rains, possibly some following the "great drought" of the last quarter of the thirteenth century A. D.

Big storms will continue to visit the Southwest. The lands can never be protected against the greatest of these storms, but much can be done to avert damage from the average summer storm or even from the 1-year or the 5-year storm. In the present state of the lands all these storms cause damage.

Various means can be used. Control of grazing and lessening of the grazing load are paramount. The plant cover must be increased. Water conserving measures such as pasture furrows will aid. Dams and other gully-control structures and water spreading devices will offer protection against all but the greatest storms. Structures must be carefully designed and be well suited to the peculiar foundations provided for them by the valley fills. They should be built to withstand the 25-year or 50-year rain, with the knowledge that a rain of greater intensity may destroy them. As grazing practices are improved and vegetation spreads to take a firmer hold on the soil, reduction of run-off will lessen the load imposed on control structures.

Confirmation of the view that overgrazing rather than climatic change has brought on the accelerated erosion in the Southwest is found in the vegetation on protected plots. Cooperrider and Hendricks report that a conservatively grazed fenced area near Albuquerque has approximately twice as much cover as the surrounding range and hence probably somewhat more than twice the protection against erosion. Another plot, an old cemetery 2 miles southwest of Albuquerque, has a far higher percentage of grass than the surrounding overgrazed land and a total density of vegetation more than three times that outside the fence (*36, pp. 22–23*). The same trend is being shown on newly fenced areas in the Navajo Country where grazing is controlled and the number of livestock is limited. Not only is the vegetation better, but in the first year of the test the sheep within the enclosure weighed almost one-third more and grew about one-third more wool than those outside. The lamb crop in the controlled area was half again as large as that on the range outside (*87, pp. 38–39*). The management that was best for the land and was best adapted to protect the soil against accelerated erosion also yielded the most profits.

SUMMARY AND CONCLUSIONS

Local information, physiographic evidence, and comparisons of old and new surveys indicate that in the Polacca Wash, as in most other valleys of the Southwest, acceleration of erosion first became active 50 to 60 years ago. This acceleration, which was made apparent by the trenching of wash floors, was accompanied by a depletion of vegetation. It has commonly been attributed to a progressive desiccation of climate, but this explanation is not substantiated by available evidence, and study of the climate of the Southwest suggests other possible reasons for the changes in erosion.

Because of a more critical balance of climate and vegetation, climatic variation produces far greater differences in plant growth and erosion in dry regions than in humid lands. Variations in precipitation and temperature from year to year may result in marked shifts in the climatic pattern. Areas normally semiarid may be arid one year and subhumid the next. Differences between the precipitation for corresponding months in different years is even more striking. One year a given month may receive more than the average rainfall for an entire year. The next year the same month may receive none.

The diurnal and annual marches of temperature and precipitation, caused by the relation of the earth to the sun, are complicated by the invasion and interaction of the various air masses that enter the Southwest. These masses are cool and moist, cool and dry, warm and moist, or warm and dry, depending on the source region from which they come and the route they follow. They cause the variations in temperature and precipitation in the Southwest. The sum of the variations produced by the interactions of the different types of air masses which enter the Southwest determines the yearly departure of the climate from the normal.

Examination of evidence in tree rings, lake levels, cutting and filling of valleys, and in the development of pueblo peoples fails to reveal proof of any climatic change in the Southwest in the last 2,000 years. Climatic fluctuations of the magnitude experienced today have occurred, and intense storms and groups of intense storms have had their effect on the landscape, but if there has been any progressive change toward either a more humid or a more arid climate that trend is so slight as to be completely overshadowed by the shorter period fluctuations.

Under natural conditions, in the Polacca Wash drainage and through most of the Southwest, the plant cover protected the soil and retarded the flow of water off the lands. In the valleys, deposition exceeded removal. Discontinuous channels were developed locally as a result of heavy storms, but most of the channels or arroyos extended only short distances and ended down drainage in alluvial fans. There was no continuous deep channel running the full length of the Polacca Wash.

With acceleration of erosion, short discontinuous gullies became more numerous. As long as these were separate units, rain falling in one part of a drainage basin might be felt as run-off for a few miles or tens of miles down valley, but the flow seldom traveled much farther. All but the largest channels were ephemeral, shifting or disappearing after each rain.

As acceleration of erosion continued, more of the gullies lengthened until they joined other gullies farther along the wash. The water, confined within narrow channels, traveled longer distances, and gully cutting proceeded more rapidly. Integration of drainage by the joining of discontinuous gullies increased the rate of headward cutting and of downward scour. Gullying in the Polacca Wash is believed to have started with at least five large discontinuous gullies, which later joined to form a continuous gully channel reaching from the headwaters area to the Little Colorado River. Gullies in many of the tributary canyons form a part of this continuous system. Discontinuous gullies that do not reach the main axial channel but end in fans are abundant on the valley sides. More and more of these lateral slope gullies are now becoming continuous—permanent tributaries of the main channels.

Gully cutting is the most obvious and most destructive of the erosive processes at work in the Polacca drainage, but sheet erosion and wind erosion are also reducing the usefulness of the lands. Owing to sheet wash on the mesa surfaces bare rock now is exposed where once was grass-covered soil. On pediment slopes and alluvial fans, sheet wash is gradually removing the most valuable part of the soil cover. Wind erosion is destructive in certain parts of the area and has become of increasing severity within the memory of the native inhabitants. Shifting sands have forced the abandonment of fields and corrals and are now so widespread along the lower Polacca that they obscure the basic structure of pediment, fan, and valley fill. Wind erosion will become still more dominant in this part of the area unless vegetation is planted to anchor the shifting dunes. In the Painted Desert section of the Polacca Wash the shifting material includes not only sand but fine chocolate-colored silts from the flood plain of the Little Colorado River.

The work of the wind may be beneficial locally in helping to check erosion by running water. Blow sand, being porous, absorbs even fairly heavy rains. Where irregularly deposited it also tends to catch some of the precipitation in pockets and prevents its running off over the surface. Shifting sands, by filling or damming rills and larger channels, retard destructive run-off and protect both the immediate locality and the area downstream. Sandy lands are among the best areas in the Polacca drainage for raising crops or for growing a protective covering of vegetation.

There is no evidence of any appreciable uplift or tilting of the land or any change in base level that might explain the recent acceleration of erosion in the Southwest. The agricultural history of much of the area, particularly of the Navajo and Hopi Indian reservations, shows no extensive cultivation and no use of harmful practices that would cause the widespread accelerated erosion. No evidence has been found of any progressive climatic change that would explain the recent increase in the rate of erosion.

Owing to the delicate adjustment of vegetation to climate in the Southwest, a succession of even a few dry years may so impoverish the plant cover that rains of heavy, or even moderate, intensity can initiate a period of accelerated erosion. Climatic records and news reports show that from time to time parts of the region have been visited by storms of exceptional intensity (pp. 112–119). These are as characteristic of the Southwest as is its semiarid climate.

For all given climatic conditions there is a certain minimum plant cover needed to protect the land against destructive erosion. In arid lands with little or no vegetation and low precipitation there may never be sufficient vegetation to offer protection from the infrequent rains. The dryness of the ground and the lack of well-marked water channels may prevent rapid run-off, but a permanent inadequacy of cover is characteristic. In semiarid lands the plant cover may be barely adequate to resist the impact of the climatic elements. The margin of safety is slight, hence the amount of vegetation that can safely be grazed is small. In subhumid and humid lands, although storms are more frequent and more intense, the cover of vegetation is thicker and a larger amount can be grazed without causing soil wastage. The marked contrast of the humid and arid lands in adequacy of cover must be considered in evaluating the permissible grazing in any area. In the Polacca drainage and on range lands through most of the Southwest the permissible amount has long since been exceeded. Vegetation now is far from adequate to protect the surface against the erosive forces.

The Polacca drainage is now suffering the results of a grazing economy that was introduced to the Indians of the Southwest about 1540 and has been practiced with little change to the present time. The human and animal population was not heavily concentrated in this part of northeastern Arizona until after the Civil War. It appears to have taken 15 to 25 years for the increased grazing on this land to reduce the vegetal cover to such an extent that changes in erosion became recognizable to the human inhabitants. Serious gullying at most other localities in the Southwest correlates well with expansion of the cattle industry stimulated by the building of the railroads. Acceleration of erosion is reported to have begun in much of the region between 1880 and 1890, and in certain areas probably a decade or two earlier.

Although accelerated erosion has carved deep channels almost the entire length of many of the major washes in the Southwest and has carried away millions of tons of soil material, this does not necessarily mean that gullying need continue or that entire valley flats must be lost to productive use. If the removal of vegetation can be curbed and revegetation begun, it may be possible to check the accelerated cutting. If the vegetal cover can be improved until it is adequate to check further erosion, the damage can be stopped. There is always the possibility that natural stabilization may be achieved. But even if the stream cuts to bedrock and establishes a local base level of erosion, thereby greatly retarding down cutting, lateral swinging against the sides of the channel may continue to remove the valley fill. Natural stabilization without a reduction of grazing and an increase in the plant cover is unlikely.

In the Polacca drainage, as is general in the Southwest, the lowering of the ground-water level through the cutting of deep gully channels is more significant than the removal of soil by run-off. In most of the semiarid and arid regions the soil profile is imperfectly developed or immature, hence, the loss of a few inches from the ground surface is far less vital than a similar loss would be in a humid land. Water is of greater importance. It is essential that the run-off, instead of draining away immediately to deep gully channels, be kept on the lands. With increased water supply, vegetation can establish a more complete cover. The plants will not only help to hold back run-off by the mechanical obstruction they offer but by transpiration and by promoting infiltration they will diminish the amount of water to be carried away.

Changes in methods of herding are seriously needed. The Navajo practice of driving livestock regularly to and from the corral brings about a localized destruction of vegetation by trampling and grazing around corrals and watering places, a condition typical of native grazing on frontier lands in many parts of the world. The first step in preservation of the usefulness of the Navajo lands will be the abolition or modification of the corralling system. This must be accompanied by reduction in the number of animal units. A shift to a system of rotational pasturage in fenced enclosures would help greatly to reduce the damage from trampling and would make it possible to allow time for the worst ranges to recuperate. Vegetative plantings will probably be needed to aid in the reestablishment of a good plant cover composed of species valuable for grazing rather than the natural pioneers that characterize the margins of the present eroded surfaces.

Mechanical aids such as diversion dams, distribution ditches, and spreader structures, modernized since the days when they were applied to these areas by the Hopis and other agricultural Indians, can be used to keep water out of the gullies and spread it on the valley lands, where it can do more good. The major dependence, however, must be placed on a plant cover adequate to protect the soil against the occasional heavy rains.

The accelerated erosion that is damaging the lands in the Southwest appears to have been caused by man, and by proper methods man can check the erosion and reclaim the land for his use. Checking erosion will be more difficult in certain years than in others because some years will have greater than average precipitation, some less. Wet year may follow wet year or drought year may follow drought year in long series. Certain months will be exceptionally wet or dry, hot or cold. Occasional intense storms will deluge the land, and, depending on the completeness of the plant cover at the time, they may drain away with little erosive effect or may carve new channelways and enlarge old ones.

In spite of the large fluctuations that are characteristic of the climate of the Southwest, intelligent action to increase the protection and reduce the irritation to the surface and to reduce surface run-off and loss of water will go far toward controlling accelerated erosion and making possible the rehabilitation of the Southwest.

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