"REVIEWED"

CLOUD-SEEDING EFFECT ON WATER STRESS OF MAIZE IN ZIMBABWE

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ABSTRACT

Results of experimental cloud-seeding in Zimbabwe indicate that silver iodide treatment enhances rainfall if cloud-tops are colder than -10°C. Still higher increases result if tops are colder than -13°C. By comparing distribution functions fitted to seeded and to non-seeded clouds, tentative relationships were built up between natural and seeded rainfalls.

A cloud-seeding season in north-east Zimbabwe was stimulated by a model in which 1 000 showers were distributed at random within a rectangular area, enabling total extra rainfall to be computed at every km grid-point. Less than half the area received any additional rainfall. A soil-water balance rountine was then used to relate the apparently increased rainfall to changes in maize yield.

In approximately half of all rainy seasons in northern Zimbabwe natural rainfall appears to be adequate so that cloud-seeding is of negligible benefit to maize. In poor or modest rainy seasons most places probably receive less than 10 mm from a cloud-seeding operation, but this can eliminate one, occasionally two, post-flowering stress-days during maize growth. However, planting dates can hardly ever be brought forward as a result of artificial rain stimulation. Results suggest that cloud-seeding operations more than pay for themselves.

1. INTRODUCTION

Numerous trials have been conducted in various countries to determine whether additional rain can sometimes be made artificially. By dropping dry ice pellets into a layer of alto-cumulus and photographing the "hole" produced by the fall-out of snow, Schaefer (1946) demonstrated conclusively that man could interfere with and change certain clouds. Subsequently, most experimenters preferred silver iodide for seeding, because it is more economical in terms of mass. However, attempts to compare quantitatively the rainfall yielded by seeded and by non-seeded clouds have led to varying results, some positive, some negative, and others inconclusive. A number of workers have presented evidence that seeding might induce a marked increase in rainfall in some circumstances with a nil or possibly a slight negative effect in others (Gabriel, 1966; Smith, 1967; Neyman, Scott and Wells, 1969; Smith, Veitch, Shaw and Miller, 1979).

Potential rainclouds, whether seeded or not, may produce heavy rain, or may yield no rain at all. This is the source of difficulty in evaluating the results of cloud-seeding, i.e. to distinguish any effect seeding might have from chance variations. The task becomes a little easier when smaller experimental units are used, so that reports of successful seedings of discrete cumuliform cloud systems (Bethwaite, et al., 1966; Simpson, 1972) are more common than successful experiments involving large areas.

Trials in Zimbabwe with isolated cumulus have given promising results (McNaughton, 1970, 1974, 1975). Table 1 compares the yield of seeded with that of natural clouds in three temperature categories. The best response came from clouds with top temperatures of -13°C or colder, which is consistent with findings in other countries (Grant and Elliot, 1974). Significance tests indicated that the increases in rainfall were genuine, particularly with colder cloud-tops when the calculations excluded rain that fell less than 30 minutes after seeding (McNaughton, 1975, 1978).

Table 2 lists the total rainfall yielded by each experimental cloud whose top was -10°C or colder. The distributions of seeded and non-seeded values in Table 2 were similar to those obtained in the Florida experiments (Simpson, 1972) and in Australia (Bethwaite, et al., 1966). Following Simpson (1972), fourth root gamma distributions were fitted to the seeded and non-seeded shower

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populations (McNaughton, 1978, 1980); these distributions are represented by the two curves of Fig. 1. A comparison of their corresponding percentile points gave a tentative estimate of the increases in rainfall amounts which might be expected from cloud-seeding in Zimbabwe (Table 3). The large increases given at the top of this Table were comparatively rare, and must be regarded with caution. However, Table 3 is consistent with indications in other countries that cloud-seeding might occasionally give really good results, with smaller, often insignificant yields on most occasions (Gabriel, 1966; Neyman, et al., 1969).

In another exercise, populations were built up of ground-level grid-point rainfalls beneath experimental showers, assuming (Fig. 2) that the area of wetted ground was elliptical in shape, and that the variation of rain intensity through any section of a shower could be represented by a parabolic function (McNaughton, 1970, 1978, 1980). A comparison of corresponding percentiles in the seeded and non- seeded distributions then suggested a relationship

$$R^s = 1.8 R^n + 3$$

where R^s denotes seeded and R^n natural rain in mm.

Most rainfall amounts in these populations were small; approximately 70 percent of natural falls were 5 mm or less, which, according to the above formula would have yielded increases of up to only 7 mm. The rainfall at the center of the heaviest non-seeded shower was 20,5 mm.

2. MODEL TO ASSESS CLOUD-SEEDING BENEFITS

To investigate whether rainfall increases of the order of 7 mm are too small to be of value, their contributions to the daily soil-water balance were computed to evaluate their effect, if any, in reducing the stress suffered during dry weather by maize (Zea mays L), one of the most important crops grown in Zimbabwe. Nationwide cloud-seeding operations have been conducted in Zimbabwe since 1972. A computerized model which could simulate an operation was used to calculate the effect on maize yield, on the assumption that operations produce benefits similar to those indicated by the experiments.

Robins and Domingo (1953) and Denmead and Shaw (1960) found that depleting soil moisture to the wilting point significantly decreased the yield of maize, particularly during tasselling. Working in Zimbabwe with maize (cv. SR52, the variety most widely used), Wilson (1968) concluded that wilting days after flowering were particularly detrimental to yield. Also in Zimbabwe, Carew (1973) and Wilson and Williams (1974) developed soil-water balance models, using rainfall records to calculate daily changes and correlating stress-days (wilting) with decreased maize yield. In the hope of improving upon their results, a computerized, more complex water balance routine was constructed to assess cloud-seeding effects.

Two types of soil were considered: a heavy clay capable of holding 150 mm of available water in the maize rooting zone (assumed to be 1.5 m deep), and a sand with an available water capacity of only 75 mm.

TABLE 1.

RESULTS OF ZIMBABWEAN CLOUD-SEEDING EXPERIMENTS, SHOWING VARIATION IN RAINFALL YIELD ACCORDING TO CLOUD-TOP TEMPERATURE

Temperature at cloud-top*	Number and treatment	Av. Rainfall (10^3 m^3)
Warmer than -10°C	7 seeded	41
	9 control	33
-10°C to -13°C	12 seeded	82
	7 control	66
-13°C or colder	17 seeded	297
	12 control	96

*Cloud-top temperature is the coldest attained when selected or during the 10-minute period following.

FIG. 1. FREQUENCY DISTRIBUTIONS OF RAINWATER TOTALS FROM EXPERIMENTAL CLOUDS.

Corresponding non-seed/seeded values lie on the same abscissa; e.g. the horizontal bar indicates that a 16-kilocume shower is, on average, increased by seeding to 42 kilocumes. This method should be applied with caution to the broken sections of the curves, because of sparsity of experimental data there.

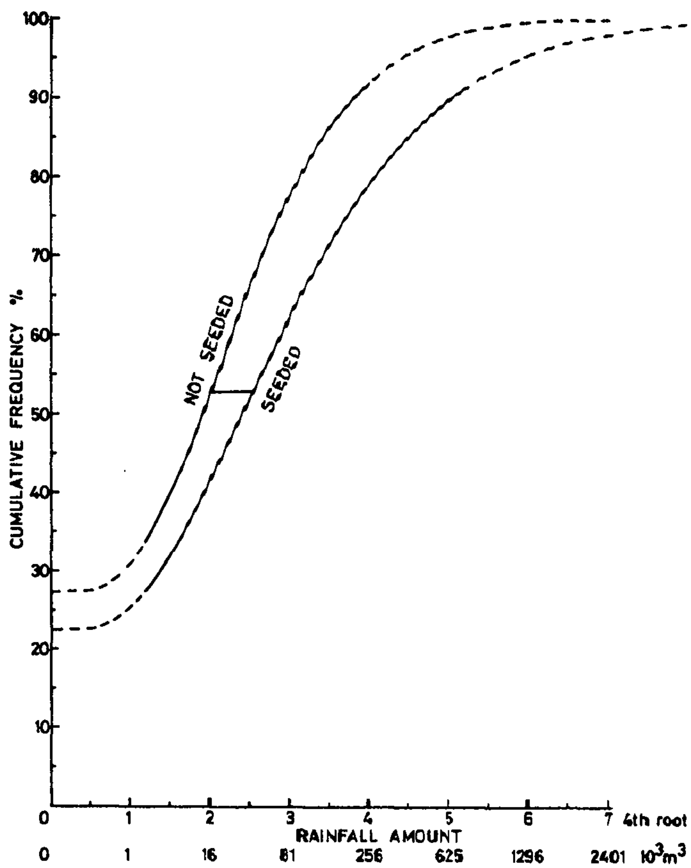


TABLE 2

RAINFALL FROM EXPERIMENTAL CLOUDS WITH TOPS OF -10°C OR COLDER, 1968/69, 1973/74, AND 1974/75

All rain (including 1968/69) fell more than 10 minutes after cloud selection. Calculations assume 40 percent evaporation loss between cloud-base and ground.

NON-SEEDED			SEEDED		
Total rain at cloud-base (10^3 m^3)	Area of wetted ground (km^2)	Average rain at ground level (mm)	Total rain at cloud-base (10^3 m^3)	Area of wetted ground (km^2)	Average rain at ground level (mm)
630	36,8	10,3	1792	77,2	13,9
127	19,7	3,9	1211	33,3	21,8
122	11,9	6,2	640	28,3	13,6
99,7	24,6	2,4	555	30,6	10,9
95,2	11,4	5,0	526	61,2	5,2
79,5	14,2	3,4	438	42,3	6,2
74,3	15,0	3,0	314	29,2	6,5
73,6	12,7	3,5	224	31,3	4,3
56,9	11,8	2,9	204	7,0	17,5
29,1	17,0	1,0	187	36,0	3,1
19,0	13,1	0,9	157	20,9	4,5
12,0	6,6	1,1	142	13,7	6,2
6,4	13,0	0,3	98,8	37,9	1,6
5,8	7,7	0,5	95,4	14,0	4,1
2,0	3,3	0,4	80,1	21,5	2,2
0,6	2,9	0,1	76,9	12,5	3,7
			63,4	31,0	1,2
			61,0	8,1	4,5
			60,4	17,5	2,1
			45,3	15,2	1,8
			27,1	11,5	1,4
			17,6	4,2	2,5
			14,4	11,6	0,7
			9,7	10,9	0,5
			3,9	3,1	0,8
			3,1	4,6	0,4
			1,2	4,7	0,2
			0,5	6,9	Trace

Available water is held in the soil at comparatively low tensions, and can be withdrawn easily by plants; water remaining in the soil below the wilting percentage is regarded as "unavailable". Unavailable water capacities in the root-zone were taken as 300 mm in clay and 50 mm in sand (Tillett and Saunder, 1959; Metelerkamp, 1972).

At the beginning of the rainy season (1 October), available water was assumed to be zero. In addition the plough zone (150 mm deep) was considered to be completely air-dry (Willatt, 1967). Deeper layers in the soil, on the other hand, were treated in the calculations as if the water held at high tensions had not been lost during the dry season (May to September), because these layers are largely undisturbed by ploughing.

Rainwater entering dry soil was considered to fill the uppermost portion of the root-zone to field capacity, distributing itself between the available and unavailable stores. The model kept a daily check on the depth of this wetted layer until it reached 1,5m; in poor rainy seasons this value was never attained.

The run-off routine was similar to that used by Fitzpatrick, et al., (1967) and by Wilson and Williams (1974), except that before and for a period after planting, allowance was made for the antecedent soil-water content in the wetted layer. The procedure adopted is portrayed graphically in Fig. 3, where the three alternative paths are

TABLE 3

CALCULATED CHANGE IN TOTAL WATER AT CLOUD-BASE PRODUCED BY SEEDING A CLOUD

Natural rain (10^3 m^3)	Percentile*	Enhanced rain (10^3 m^3)
625	97	2 134
256	92	810
81	78	233
39	66	107
16	53	42
5	40	14
1	31	4

*Percentile in the distribution of fourth root values.

FIG. 2. AN ELLIPSO-PARABOLOID MODEL OF A RAINSHOWER.

Column heights represent rainfalls at four selected points.

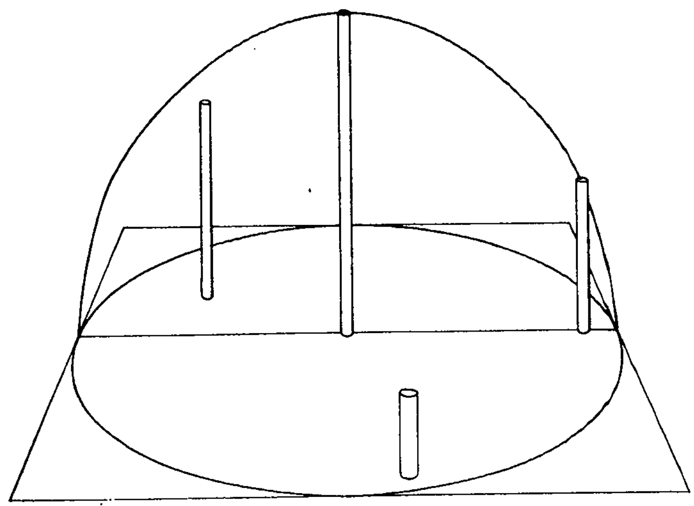
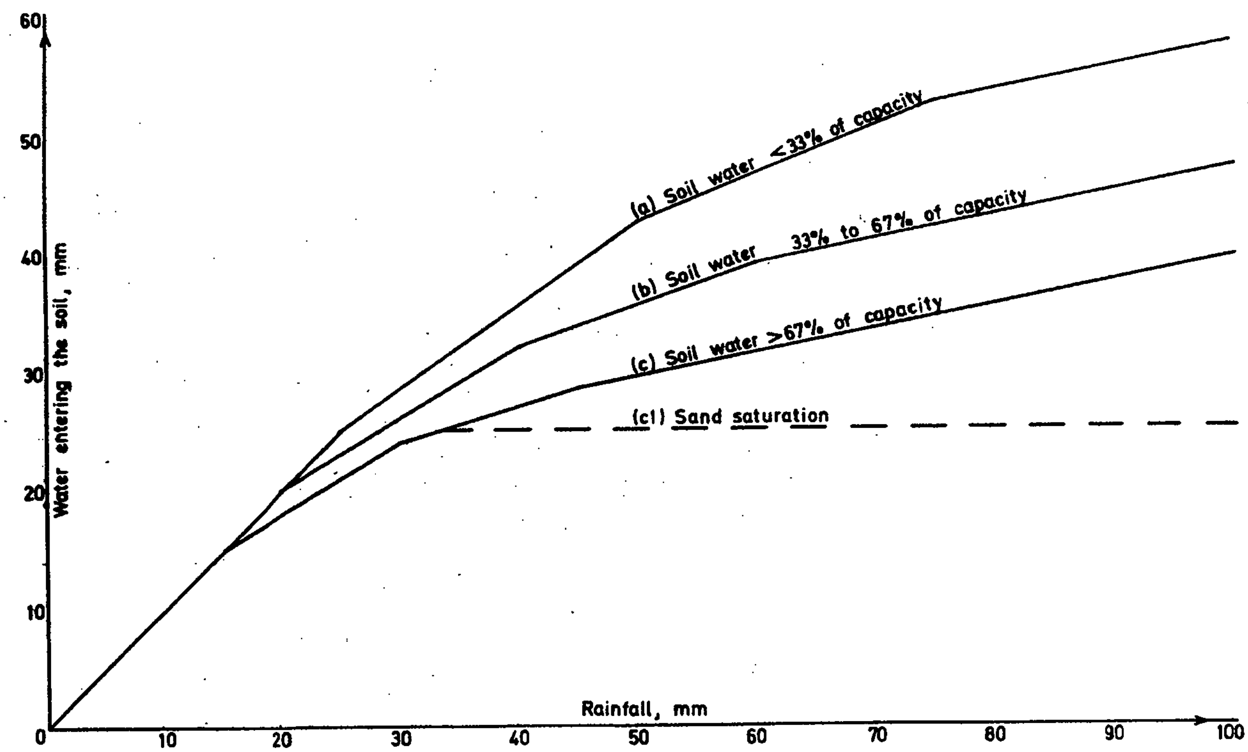


FIG. 3. RELATIONS BETWEEN INCIDENT RAINFALL AND WATER ENTERING THE SOIL.



shown by solid lines. In this diagram, sand in category (c) (available water more than 2/3 of capacity) always reaches saturation at or below the broken line cl.

After eight weeks of plant growth (when full ground-cover is attained) run-off was always determined by the middle solid line (b) of Fig. 3, regardless of antecedent soil-water content. An alternative model, using instead the lowest solid line (c) of Fig. 3 to determine run-off (McNaughton, 1980), gave results similar to those from the first model.

Pre-planting rainfalls of less than 5 mm on dry ground were assumed to evaporate rapidly, and were disregarded. Daily soil-water loss was calculated from Weather Bureau class "A" pan evaporation measurements, adjusted by a factor according to plant age and by another depending on the percentage of available moisture in the wetted layer. Only the available water store was considered to release moisture during the rainy season.

Bare soil was assumed to lose water at 30 percent of the potential evaporation rate (Denmead and Shaw, 1959; Cackett and Metelerkamp, 1964). When adequate water was available, the transpiration rate was steadily increased after planting until it reached the free-water value after eight weeks. As long as available water in the wetted layer remained above 60 percent of capacity, evapotranspiration losses were not reduced due to soil dryness. This 60 percent level corresponds to a point of inflexion on a curve derived by de Jager and Mallett (1972). Below 60 percent the dryness factor modified the daily water loss, which gradually declined to zero along with the prevailing available soil moisture content.

Thus, free-water evaporation was usually multiplied by both the plant-age factor and the dryness factor to calculate actual daily loss. An exception was made with bare clay, from which moisture evaporates comparatively quickly because a given rainfall wets a shallower depth of clay than of sand. Thus, bare clay was assumed to dry out at 30 percent of the potential evaporation rate regardless of its prevailing water content (McNaughton, 1980).

3. REGRESSION COMPUTATIONS

Stress-days were identified as those when available soil moisture in the wetted layer fell below a particular threshold. Three thresholds were examined, corresponding to water contents of 10, 25, and 40 percent of capacity respectively. Stress-days were logged both before and after mid-silk, considered to occur 47 percent of the way through the maize growth period (Wilson and Williams, 1974.) Eleven seasons of weather records at Salisbury Research Station (whose root-zone available water capacity is 130 mm) were processed through the soil-water balance model; stress-day totals were then compared with corresponding maize (cv. SR 52) yield data at this station. With the 10 percent stress criterion, the correlation between yield (Y) and number of stress-days after flowering (N) was -0,90; the regression, expressing yield in tonnes per hectare, was

$$Y = 11.5 - 0.17 N$$

Table 4 compares actual with predicted maize yields in each season.

No significant correlation was found between yield and stress incurred before flowering. Similarly, the correlation was negligible when stress-days were defined in terms of water content below 40 percent or 25 percent of capacity (McNaughton, 1980).

Fifteen years of daily rainfall and evaporation data from a network of six stations in Mashonaland (north-east Zimbabwe) were run through the model, using the "10 percent water" criterion to identify stress-days. Each station's data were processed with both sand and clay, regardless of the soil texture at the station concerned, so as to obtain a broadly based assessment of the effect of any particular season on maize throughout Mashonaland.

When running the model, planting dates were initially selected on the basis of total rainfall received during a three-day period, 18 mm being required for sand and 35 mm for clay (because in clay more water is lost to the unavailable store and through evaporation). Following Carew (1973),

TABLE 4

MAIZE YIELD AT SALISBURY PREDICTED BY REGRESSION WITH POST-FLOWERING STRESS-DAYS

Season	65/66	66/67	67/68	68/69	69/70	70/71	71/72	72/73	73/74	74/75	75/76
Stress-days	0	16	33	0	8	5	0	12	0	0	0
Yield (t/ha)											
Predicted	11.5	8.8	5.9	11.5	10.1	10.6	11.5	9.5	11.5	11.5	11.5
Actual	10.9	10.3	5.8	12.5	10.3	9.7	11.4	8.0	11.0	12.4	11.3

TABLE 5

NUMBER OF POST-FLOWERING STRESS-DAYS ON CLAY (CL) AND SAND (SA) AT SIX STATIONS

	KAROI		MT. DARWIN		GATOOMA		HENDERSON		SALISBURY		MARANDELLAS		AVERAGE	
Growth period, days	158		150		153		160		165		170		159	
	CL	SA	CL	SA	CL	SA	CL	SA	CL	SA	CL	SA	CL	SA
1962/63	0	0	0	15	0	12	0*	0*	0	0	0	0	0	5
1963/64	12	27	49	61	32	18	>10*	> 5*	37	35	40	40	>30	>31
1964/65	3	20	6	17	32	15	> 5*	>20*	34	21	30	57	>18	>25
1965/66	0	0	#	54	0	8	0	0	0	0	0	0	0	10
1966/67	0	0	0*	0*	9	6	0	0	0	7	0	23	2	6
1967/68	7	6	54	16	46	29	52	37	25	27	42	41	38	26
1968/69	0	0	0	0	0	3	0	0	0	0	0	0	0	1
1969/70	8	21	49	66	37	43	19	32	4	12	16	34	22	35
1970/71	0	14	0	20	25	29	1	25	0	18	11	31	6	23
1971/72	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972/73	#	9	2	20	62	60	6	8	16	18	39	33	25	25
1973/74	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1974/75	0	6	0	7	3	18	0	0	0	0	0	10	1	7
1975/76	0	0	0*	0*	0	0	0	0	0	0	0	3	0	1
1976/77	0	0	0	0	0	1	0	0	0	0	0	0	0	0

*Value estimated by comparison with other stations (McNaughton, 1980).
#No crop because planting rain insufficient.

seedlings were deemed to have survived if, according to the calculations, at least 10 stress-free days followed planting; if this was not fulfilled then a later planting date was used (McNaughton, 1980).

The numbers of post-flowering stress-days calculated by the model for the various stations and seasons are presented in Table 5. Zero entries constituted approximately half of the total; on these occasions maize in Mashonaland would apparently have benefited little from cloud-seeding.

Data from these same seasons and stations were also run through the soil-water balance model constructed by Wilson and Williams (1974), which has been tested successfully against maize trials from 15 stations. Maize yields predicted by this model were similar to those obtained from the present, more complex model (McNaughton, 1980).

4. RANDOM DISTRIBUTIONS OF MODEL RAINSHOWERS IN MASHONALAND

Most maize in Zimbabwe is grown within an approximately rectangular region bounded by parallels 17°S and 18°30'S and meridians 30°E and 32°E. Its dimensions are about 211 km by 166 km, giving it an area of 35 000 km^2, of which roughly 1 500 km^2 are devoted to maize. To simulate a season's cloud-seeding operation, 1 000 showers were distributed at random over this rectangle, so that the effects of seeding their parent clouds could be estimated and subsequently applied to the maize crop grown there.

The figure 1 000 was chosen to represent a poor or modest rainy season, based on actual cloud-seeding operations carried out in Zimbabwe. Numbers of clouds seeded in the above area were: 729 in 1972/73 (when operations did not commence until a third of the way through the season); 979 in 1976/77 (even though this operation was terminated two months early); 880 in 1978/79 (together with 215 others slightly further north); and 1 130 in 1979/80 (Reports on National Cloud-Seeding Operations, Dept. of Meteor. Services, Zimbabwe. Three have been reprinted in J. Weather Mod. 6 (1974), 8 (1976), and 10 (1978).).

Using the distribution of non-seeded values portrayed in Fig. 1, a spectrum of sizes was assigned to 1 000 natural showers (McNaughton, 1980), presented in Table 6. Corresponding seeded values were obtained by matching percentile points in the two distributions of Fig. 1.

The rectangular area representing Mashonaland was regarded as a grid with a 1-km mesh. A random number generator assigned a center to each of the 730 non-zero natural showers in succession. Rainwater was distributed around each center following the ellipso-paraboloid model of Fig. 2, with the heaviest rain occurring at the center, gradually decreasing to zero towards the perimeter. From the data of Table 2, an area-rain regression was constructed in which a 0,4-kilocume shower produced rain at only three points in the 1-km grid, while a 789-kilocume shower extended over about 50 points (McNaughton, 1980). When a shower center fell near the boundary of the rectangle, that part of its rain falling outside was ignored. (A kilocume is a cubic dekameter = 1,000 m^3 = 0.8107 acre-feet.)

After a natural rainshower had been assigned in this manner, the corresponding seeded shower was treated in the same way, with its heavier rainfall distributed over an ellipse concentric with, but larger than the non-seeded one. The extra rainfall due to seeding at every place affected was obtained by subtracting the natural from the seeded rain at each 1-km grid-point. This process was repeated for each of the 1 000 showers in turn (apart form those with nil rainfall), with their respective sizes following the pattern portrayed in Table 6. Table 7 gives a typical example of the distribution of these showers within the rectangular area during the course of a simulated rainy season.

Finally, each of the 35 026 grid-points was examined to see how many seeded showers had affected it during the modelled rainy season, and what additional rainfall had been received at each point. Table 8 gives the results of six simulated seasonal operations; the patterns produced in every case were similar. During each "season" less than 40 percent of grid-points showed any benefit from cloud-seeding, while only about 8 percent of points experience two or more seeded showers.

TABLE 6

RAINFALL SPECTRUM OF 1 000 SHOWERS FOR DISTRIBUTION IN GRID

Number of clouds	Natural	Seeded
273	Nil	Nil
37	Trace	3
91	3	9
130	9	25
134	26	69
113	53	148
84	105	308
57	187	578
36	311	1 000
48	789	2 750

TABLE 7

TYPICAL DISTRIBUTION OF SHOWER CENTERS IN A SIMULATED RAINY SEASON, NUMBERS OF SHOWERS OCCURRING IN EACH 12 km BY 12 km SQUARE WITHIN THE RECTANGULAR GRID REPRESENTING MASHONALAND. (From season no. 1 in Table 8)

3	1	4	1	2	5	2	0	3	10	2	3	1	2	3	4	4	2
2	2	1	4	5	1	4	8	1	1	4	2	3	3	6	0	4	4
4	1	3	5	2	5	4	0	2	2	1	4	7	1	1	3	2	1
2	4	1	2	1	6	2	4	2	2	2	3	0	5	4	1	1	3
4	2	4	2	1	5	1	3	4	1	3	0	5	3	2	3	4	1
3	4	5	3	5	4	3	5	0	1	0	1	4	2	6	3	4	1
5	4	3	6	2	1	3	6	0	3	4	5	2	2	3	5	7	1
5	4	2	0	4	2	2	1	2	4	1	1	2	2	3	1	5	3
5	0	4	0	3	3	3	4	1	1	3	6	2	3	5	5	4	5
2	6	7	0	4	1	4	3	2	1	2	2	1	3	4	2	6	1
4	2	1	5	5	1	2	2	2	1	4	3	6	2	1	3	6	2
4	5	3	2	4	4	2	1	2	6	2	3	1	6	2	6	3	0
1	3	3	6	4	2	3	5	3	0	5	3	1	5	5	4	3	0
3	2	6	1	2	6	4	3	3	1	0	4	3	0	4	1	6	1

TABLE 8

NUMBER OF GRID-POINTS IN VARIOUS RAIN INCREASE CATEGORIES

Additional rainfall from seeding (mm):	<5	5-10	10-20	20-30	30-40	>40	Points with 5 or 6 showers
Representative rainfall increment:	2	7	14	24	34	44	
Season							
1	6 675	2 770	2 300	1 335	113	71	9
2	6 828	2 830	2 250	1 321	109	65	0
3	6 628	2 674	2 178	1 386	148	102	22
4	6 910	2 795	2 391	1 425	77	31	2
5	6 540	2 782	2 118	1 348	197	59	17
6	6 691	2 945	2 247	1 448	132	28	13
Mean:	6 712	2 799	2 247	1 377	129	59	10.5
Standard error:	55	36	39	21	17	11	--

5. MAIZE STRESS REDUCTION FROM EXTRA RAIN

After the soil-water balance routine had run with actual rainfall data from a station, it was re-run with a rainfall increment to represent the effect of cloud-seeding. Using the categories of Table 8, increments were 2 mm, 7 mm, 14 mm, 24 mm, 34 mm, 44 mm in turn. For the first re-run the respective increment was inserted on 9 November, and its effect on post-flowering stress-days (and thus on maize yield) was computed; for the next re-run it was introduced on 24 November, and the computations repeated; it was then inserted and re-run on each of 10 further dates 15 days apart, extending until 23 April.

Allowing for fewer cloud-seeding oppportunities in November and April than in wetter months (McNaughton, 1980), a mean stress-reducing effect of each incremental amount was calculated from its effect at each of the 12 individual dates; Table 9 presents over-all averages, based on the six stations and 15 seasons of Table 5. Standard errors are also included in Table 9. "Mashonaland" values are 2:1 weighted means between sand and clay, reflecting the distribution of maize between the different soil types.

Similar results were obtained when a rainfall increment was treated as the sum of two separate falls, with the second one introduced on a later date than the first (McNaughton, 1980); thus Table 9 also depicts the effects of split increments. As rainfalls become larger their relative efficiency in eliminating stress decreases; e.g. 44 mm was not quite three times as effective as 14 mm, because proportionately more water was lost from larger falls through run-off and drainage.

For the two most important increments of Tables 8 and 9, namely 7 mm and 14 mm, Table 10 presents a frequency breakdown of the distributions which led to Table 9 (based, as before, on a 2:1 sand:clay weighting). Table 10 indicates that these modest amounts of additional rain can eliminate one, occasionally two, post-flowering stress-days during maize growth.

In the previous paragraphs rainfall increments were introduced on fixed dates regardless of prevailing weather. As a check on these results, potentially seedable rainfalls were identified from synoptic charts and records. On autographic raingauge charts a shower from cumuliform cloud was distinguished by a sudden steep rise in the trace, compared to slow, gradual climb of nimbo-stratus

TABLE 9

AVERAGE NUMBER OF POST-FLOWERING STRESS-DAYS
ELIMINATED BY VARIOUS ARTIFICIALLY INSERTED RAINFALLS

Rainfall increment: (mm)	2	7	14	24	34	44
Clay:	0,2±0,04	0,8±0,1	1,4±0,1	2,3±0,1	3,0±0,2	3,5±0,3
Sand:	0,2±0,02	0,7±0,1	1,2±0,1	1,9±0,2	2,4±0,2	2,8±0,2
Mashonaland:	0,2±0,03	0,7±0,1	1,3±0,1	2,0±0,2	2,6±0,2	3,0±0,2

TABLE 10

FREQUENCIES (%) OF POST-FLOWERING STRESS-DAYS REMOVED BY 7 mm AND 14 mm

Mean effect of introducing these rainfall increments on various dates distributed throughout the rainy season, based on 2:1 weighted means, sand:clay

Stress-days removed:	>3,5	2,5-3,5	1,5-2,5	0,5-1,5	<0,5
Rainfall increment (mm)					
7	0	0	6	59	35
14	1	5	29	57	9

rain. Corresponding cloud and sunshine records then indicated whether the cloud formations were too congested to permit airborne seeding. If rainfall appeared to be seedable, an increase was assumed to be governed by the relation discussed earlier:

$$R^s = 1.8 R^n + 3$$

where R^s denotes seeded and R^n natural rain in mm. To conform with experimental criteria, rainfalls did not qualify for increases based on seedability if they exceeded 20 mm.

Table 11 presents results of re-running the soil-water model after adding these seeded increments to the daily rainfall data of various stations and seasons. A few entries represent planting dates later than those used for Table 5, when earlier ones gave completely stress-free seasons at the station concerned. In 1974/75, seeding calculations were confined to the latter portion of the season, because its rainfall was more than adequate until early February.

Table 11 represents the computed results of operations with aircraft always available to seed every suitable cloud over the respective stations, which is impossible (cf. Table 8). However, the results of Table 11 are consistent with those of Table 9, especially because the higher rainfall increments leading to Table 11 were relatively less efficient in eliminating maize stress, (each stress-day in Table 11 corresponded, on average, to 15 or 20 mm.) In other words, even if maximum possible cloud-seeding were feasible, some of it would be wasted.

Greatest wetted depths attained in Table 11 could be taken as representing root depths. Judging by these calculations, areas which enjoy near-maximum possible cloud-seeding could have their maize root lengths extended by 200 or 250 mm, during a poor season like 1972/73.

The early part of the Zimbabwe rainy season varies between hot, dry cloudless weather and violent thunderstorms or hailstorms, usually unsuitable for seeding. According to Table 8, the majority of rainfall increases produced by cloud-seeding are relatively small, such that the prospects of using then to bring forward a planting date appear poor.

Synoptic weather records for the two clay entries in Table 5 with insufficient planting rain (Mount Darwin 1965/66 and Karoi 1972/73) show that none of their raindays in November or December were seedable according to the criteria associated with Table 11. In addition, in the water balance model re-runs leading to this Table, numbers of stress-free days following planting were not altered significantly by the introduction of seeded rainfall increments (McNaughton, 1980).

6. ECONOMICS OF CLOUD-SEEDING

For Table 12, the shower frequencies of Table 8 are applied to Table 9, estimating improved maize yield from its regression coefficient, i.e. 0.17 t/ha per stress-day removed. Thus, in Table 12, extra moisture days multiplied by 0.17 gave extra yield. Number of grid-points multiplied by extra

TABLE 11

COMPUTED EFFECTS OF CLOUD-SEEDING ON RAINFALL, MAIZE STRESS, AND WETTED SOIL DEPTH, USING DATA FROM SUITABLE CONVECTIVE DAYS
N denotes non-seeded, and S seeded.

		RAINFALL			POST-FLOWERING STRESS-DAYS						GREATEST WETTED DEPTH (%)			
					CLAY			SAND			CLAY		SAND	
Station	Season	Natural* total (mm)	No. of seedable falls	Seeded increase, % of total	N	S	N-S	N	S	N-S	N	S	N	S
Karoi		821,2	14	7,9	5	2	3	14	4	10	100	100	100	100
Mt. Darwin		739,5	12	7,7	4	2	2	20	18	2	100	100	100	100
Gatooma		561,1	21	16,1	25	7	18	29	19	10	84,3	99,7	100	100
Henderson	1970/71	865,0	19	13,3	8	6	2	25	22	3	100	100	100	100
Kutsaga #		771,4	26	21,1	10	3	7	20	14	6	100	100	100	100
Marandellas		745,2	26	15,4	11	3	8	31	16	15	100	100	100	100
Henderson		588,4	15	17,6	6	0	6	8	4	4	64,3	90,1	100	100
Kutsaga		473,5	13	14,4	-	-	-	12	5	7	-	-	79,3	89,6
Kutsaga	1972/73	474,6	13	14,4	33	24	9	31	24	7	41,1	50,7	85,2	100
Gwebi		449,7	18	18,7	38	31	7	23	14	9	33,1	40,7	63,1	72,1
Belvedere		485,0	15	14,5	16	12	4	15	8	7	65,4	69,1	100	100
Karoi		670,8	1	0,6	0	0	0	6	4	2	100	100	100	100
Mt. Darwin	1974/75	745,0	2	1,5	0	0	0	7	6	1	100	100	100	100
Gatooma		847,3	9	6,6	3	0	3	18	15	3	100	100	100	100
Marandellas		1016,9	6	2,0	0	0	0	10	4	6	100	100	100	100

TABLE 12

"REVIEWED"

EFFECT OF CLOUD-SEEDING ON MAIZE YIELD IN MASHONALAND
Extra moisture days (column 2) are "stress-days removed", taken from Table 9; number of grid-points (column 4) is taken from Table 8.

(1) Rainfall category (mm)	(2) Extra moisture days	(3) Extra yield (t/ha)	(4) No. of grid-points	(5) Total extra maize(t)
A. MEAN VALUES				
<5	0,2	0,03	6 712	(981)
5-10	0,7	0,12	2 799	1 456
10-20	1,3	0,21	2 247	2 068
20-30	2,0	0,35	1 377	2 055
30-40	2,6	0,45	129	247
>40	3,0	0,52	59	131
			Grand total:	5 957 (6 938)
B. MEANS MINUS STANDARD ERRORS: THREE PARAMETERS				
<5	0,2	0,02	6 657	(687)
5-10	0,6	0,09	2 763	1 069
10-20	1,2	0,16	2 208	1 557
20-30	1,8	0,26	1 356	1 504
30-40	2,4	0,34	112	162
>40	2,8	0,39	48	81
			Grand total:	4 373 (5 060)

yield (converted to t/km^2) and by 0.043 (proportion of Mashonaland under maize) then gave total extra maize. Summing for all sizes of rainfall, the grand total additional yield is shown without and, in brackets, with the falls of less than 5 mm, because despite the soil-water balance calculations it is questionable whether such small amounts contribute anything to maize production.

In constructing section B of Table 12, one standard error was subtracted from all values in columns 2 and 4 (in Table 12A), and from the stress-day coefficient, which became 0,14 t/ha per day.

Table 13 includes the cost of each season's national cloud-seeding operation since 1972 (taken from the Meteorological Department's annual cloud-seeding reports). Producer maize prices applicable to each season are also given in Table 13. In 1972/73 the additional value of 938 6 938 tonnes of grade 'A' maize (from Table 12A) would have been about Z.$ 264 800. This is substantially higher than the cost of the corresponding cloud-seeding operation, but that approximately half of all seasons appear to receive sufficient natural rainfall for cloud-seeding to be of little or no benefit to maize in Mashonaland (Table 5). This was why all calculated benefits in Table 13 were halved, so as to give a more realistic comparison with costs. Nevertheless, even on this basis the cloud-seeding benefit / cost ratio remained approximately 2:1 during the period 1972 to 1981.

Using instead the more pessimistic estimate of additional maize yield given in Table 12B, and also disregarding the effects of rainfalls less than 5 mm, the final column of Table 13 gives the halved values of 4 373 extra tonnes of maize; these figures are all larger than the corresponding costs of

TABLE 13

COMPARISONS OF COSTS OF CLOUD-SEEDING WITH CALCULATED BENEFITS TO MAIZE YIELD

Season	Cost of national cloud-seeding operation, Z.$	Producer price of maize, Z.$/t	Halved value of 6 938 t of maize	Halved value of 4 373 t of maize
1972/73	58 028	38.17	132 400	83,500
1973/74	84 455	43.51	150 900	95 100
1974/75	64 057	48.25	167 400	105 500
1975/76	82 873	48.00	166 500	105 000
1976/77	94 892	52.00	180 400	113 700
1977/78	90 129	53.00	183 900	115 900
1978/79	116 444	60.50	209 900	132 300
1979/80	147 358	85.00	294 900	185 900
1980/81	146 291	120.00	416 300	262 400

cloud-seeding. The means in three separate populations are not likely to have all been over-estimated by one standard error; thus that cloud-seeding operations apparently more than pay for themselves. Furthermore, the computed benefits were based only on maize grown in the Mashonaland rectangle; they did not take into account the contribution of cloud-seeding to other crops in this region or to other areas of Zimbabwe.

The model calculations indicate that cloud-seeding in Zimbabwe increases maize yield by more than enough to pay for itself. Because of the tentative nature of the assumed sizes of seeded rainfall increases, the most valuable portion of this study is probably its indication that modest amounts of rainfall, such as 7 mm, can reduce maize stress and benefit yield.

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REFERENCES

BETHWAITE, F. D., E. J. SMITH, J. A. WARBURTON, and K. J. HEFFERNAN, 1966. Effects of seeding isolated cumulus clouds with silver iodide. J. appl. Meteor. 5: 513-520.

CACKETT, K. E., and H. R. R. METELERKAMP, 1964. Evapotranspiration of maize in relation to open-pan evaporation and crop development. Rhodesia J. agric. Res. 2: 35-44.

CAREW, G. W. 1973. Droughts and maize yields in three Mashonaland Intensive Conservation Areas. Rhodesia agric. J. 70: 111-114.

DE JAGER, J. M., and J. B. MALLETT, 1972. Effect of moisture stress upon maize production and its economic significance. S. Afr. J. Sci. 68: 182-186.

DENMEAD, O. T., and R. H. SHAW, 1959. Evapotranspiration in relation to the development of the corn crop. Agron. J. 51: 725-726.

_______, and ______, 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J. 52: 272-274.

_______, and ______, 1962. Availability of soil water to plants as affected by soil moisture content and meteorological conditions. Agron. J. 54: 385-390.

FITZPATRICK, E. A., R. O. SLATYER, and A. I. KRISHNAN, 1967. Incidence and duration of periods of plant growth in central Australia as estimated from climatic data. Agric. Meteor. 4: 389-404.

GABRIEL, K. R. 1966. The Israeli artificial rainfall stimulation experiment. Statistical evaluation for the period 1961-1965. Proc. 5 Berkeley Symp. Math. Stats. and Prob. 5: 91-114.

GRANT, L. O., and R. D. ELLIOT, 1974. The cloud-seeding temperature window. J. appl. Meteor. 13: 355-363.

MCNAUGHTON, D. L. 1970. Seeding single cumulus clouds in Rhodesia with silver iodide, 1968-69. Proc. Trans. Rhodesia Sci. Assoc. 54: 85-98. (Reprinted J. Weather Mod. 5: 88-102.)

__________, 1974. Seeding single clouds using pyrotechnic cartridges, 1973-74. Meteor. Notes no. A43. Dept. Meteor. Services, Salisbury, Zimbabwe; 13 pp. (Reprinted J. Weather Mod. 7: 4-16.)

__________, 1975. Cloud-seeding experimental programme, 1974-75. Meteor. Notes no. A45. Dept. Meteor. Services, Salisbury, Zimbabwe; 12 pp. (Reprinted J. Weather Mod. 9: 79-92.)

__________, 1978. Summary of three seasons' single cloud-seeding results in Rhodesia between 1968 and 1975. J. Weather Mod. 10: 21-34.

__________, 1980. Cloud-seeding in Zimbabwe, and some of its effects on SR52 maize growth. D. Phil. thesis, University of Zimbabwe, Salisbury; 116 pp. (Also available from NTIS, Springfield, Va.)

METELERKAMP, H. R. R. 1972. Effect of soil properties on water availability to crops. Rhodesia agric. J. Tech. Bull. 15: 57-65.

NEYMAN, J., E. L. SCOTT, and M. A. WELLS, 1969. Statistics in Meteorology. Rev. Int. Stats. Instit. 37: 119-148.

ROBINS, J. S. and C. E. DOMINGO, 1953. Some effects of severe soil moisture deficits at specific growth stages in corn. Agron. J. 45: 618-621.

SCHAEFER, V. J. 1946. The production of ice crystals in a cloud of supercooled water droplets. Science 104: 457-459.

SIMPSON, J. 1972. Use of the gamma distribution in single cloud rainfall analysis. Mon. Weather Rev. 100: 309-312.

SMITH, E. J. 1967. Cloud-seeding experiments in Australia. Proc. 5 Berkeley Symp. Math. Stats. and Prob. 5: 161-176.

__________, L. G. VEITCH, D. E. SHAW, and A. J. MILLER, 1979. A cloud-seeding experiment in Tasmania. J. appl. Meteor. 18: 804-815.

TILLETT, E. R. and D. H. SAUNDER 1959. Soil moisture relationships of some Rhodesian soils. Rhodesia agric. J. 56: 61-64.

WILLATT, S. T. 1967. Moisture status in Rhodesian soils prior to the rains. Rhodesia agric. J. 64: 1-4.

WILSON, J. H. 1968. Water relations of maize. Rhodesia J. agric. Res. 6: 103-108.

__________, and J. H. WILLIAMS 1974. Yields of maize related to rainfall in Rhodesia. Rhodesia agric. J. 71: 47-50.

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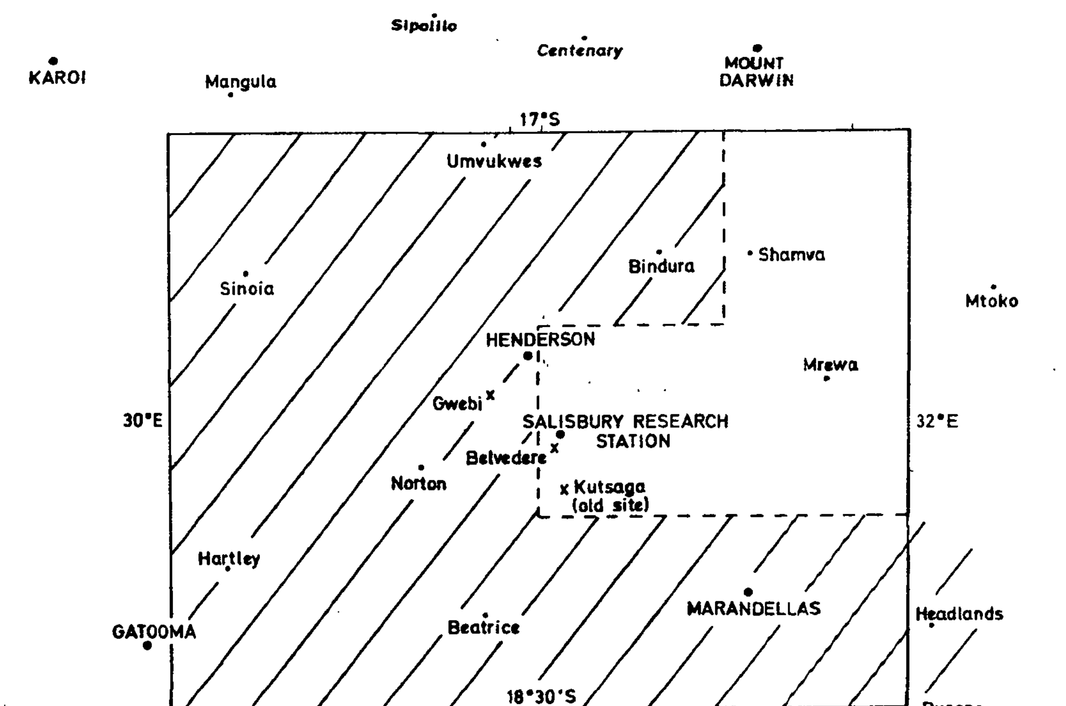

MASHONALAND RECTANGLE FOR MODEL CLOUD-SEEDING OPERATIONS

Hatched area averaged over 200 seeded clouds per degree square per season between 1973 and 1979