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CROP DAMAGE-HAILPAD PARAMETER STUDY IN ILLINOIS

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Final Report for
Contract -- U.S. NCAR NSF S-5015

ILLINOIS STATE WATER SURVEY
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I. INTRODUCTION

Suppression of hail is under investigation in various parts of the world, primarily motivated by the effects of hall on agriculture. Hail can cause disastrous damage to property, but it is less severe and infrequent than crop-hail damage. In economic terms, crop-loss to hail exceeds other types of damage about tenfold, at least in the United States (Changnon, et al., 1976).

Scientists and others are proposing to reduce hail by various means so as to reduce the loss of crops. In some cases it is claimed that hail can be eliminated entirely and at will. In others the claim is that some modification to the hail can be brought about which will reduce its damage potential to crops. Some such changes might be:

1. reduction of accumulated mass of hail (per unit area);
2. reduction of the total kinetic energy of the hall;
3. changing of a few large hailstones into many smaller ones; and
4. changing many small stones into a very few large ones.

The effect of such proposed hall changes on crops has been assumed beneficial in all cases. It is not totally obvious that this is so and questions on how to change hail to reduce crop (and property) loss have arisen. One could imagine any of the above changes leading to increased crop damage, at least in certain cases. One of the sources of confusion in this question is a lack of knowledge about just what determines the crop damage resulting from a given hailfall.

Thus, determination of the relationship between these hailfall parameters and damage to crops is very important for clarifying the dialogue between weather modification researchers and practitioners on the one hand and agricultural interests on the other, as well as between the researchers and the practitioners. The scientist reasons in terms of changes he might bring about in the numerical and physical parameters of the hailfall. The agriculturalist thinks in terms of net effect, reduction in damage. Practitioners of hail suppression tend to frame their operational rationale in scientific or technical, terms but describe expected results in terms of damage reduction. Attempts to evaluate their efforts are usually done in such terms and the actual change in hailfall parameters is not measured or recorded because it is a difficult and expensive endeavor.

Without some knowledge of how hail damages crops, or better, what reduction in damage will result from a given alteration in the hailfall, clarity of communication is difficult and seeding hypotheses can not be properly established. At the present time, a statement such as "hail suppression is 50% effective" calls forth the question. "Fifty percent of what?, hail mass? kinetic energy? or crop damage?".

This study is part of an attempt to illuminate the relationship between hail and crop-loss for cases of hail on the two major Midwestern crops, corn and soybeans. Data largely from a concentrated field effort in 1975 were collected to address this problem.

II. HAIL DAMAGE TO CROPS

Hail damages crops because hailstones are hard, heavy, and move fast. Each hailstone is a missile which has some degree of potential for puncturing or removing leaves, breaking stems and branches, crushing stalk fibers, and smashing fruit. The damage potential depends on the hail itself (mass, shape, hardness, speed); the plant which is exposed to it (type of plant, stage of growth, mode of planting, condition, aspect); and on other factors which affect these (wind, for example, affects the speed of the hailstones and many aspects of the plants).

A hailfall is a very complex phenomenon and one hailfall can differ from another in a bewildering number of ways. Some of the factors are:

1) characteristics of individual hailstones
    a. internal structure (crystal structure, contaminants)
    b. shape (not always, or even generally, spherical)
    c. hardness (can vary from slushy to very hard)
    d. density
    e. size (maximum dimension, weight or others)
    f. velocity (vertical and horizontal components)
2) characteristics of hail events
    a. time of onset
    b. duration of event
    c. characteristics of the ensemble of individual stones which strike a representative area.

At our present level of understanding, and for the purpose of studying the relationship between hailfall measurements and crop damage, not all of these factors are available or even of interest. Many of the complications of hail measurement with hailpads are removed by making certain assumptions:

1. all stones which dent hailpads are of equal but unknown hardness;
2. all stones are spherical with density 0.9 g/cm^3;
3. all stones fall at their terminal velocities $v_t \propto D^{1/2}$ and move horizontally at the speed of wind;
4. each stone strikes the hailpad only once;
5. timing (onset and duration) is unimportant to the damage process;

6. the collective effect of the individual hailstones in the damage process can be derived from the "spectrum" of the hailfall, N(D), the numbers of hailstones of diameters D to D + 6D. Use is also made of a cumulative form of the spectrum, C(D), the numbers of stones of diameters greater than D. These are related by

$$N(D)\ \delta D = \delta C(D)$$

The principal problem faced in this type of study is the determination of the dependence of crop damage on a function or functions of the hailstone size distribution. Ordinarily, crop damage means the percent loss of yield due to hail. This figure is really a prediction based on estimates of certain types of physical damage observed after the hailfall.

For corn, the basic loss estimates made are 1) direct damage (percent of plants which are totally lost [knocked down, ears damaged]) and 2) indirect damage (percent defoliation). Direct damage can be directly expressed as a loss of yield while the defoliation must be converted to loss of yield by means of empirical transfer functions determined from field experiments. At certain stages of growth, heavy defoliation leads to drastic loss of yield, whereas at others, the effect on yield is minor.

For soybeans, the types of physical damage estimates are called direct loss and indirect damage (plant damage). Again, plant damage must be converted to loss of yield through transfer functions.

In this study, the heaviest emphasis was placed on the physical damage estimates. These are considered as being more appropriately dependent on the hailfall characteristics than the loss of yield.

Relating hail parameters to crop-loss is thus an extremely complex endeavor. Some straightforward attempts at it have, however, produced very encouraging results. Changnon (1971) studied corn, wheat, and soybean losses as a function of two hail parameters and found useful relationships. The parameters studied were a) the number per square foot of stones of diameter ≥ 0.25 in, and b) the hail impact energy (the sum of the kinetic energies of all the stones striking the hailpad). Quite recently, Garcia, et al. (1976) have studied these and other hailfall parameters for relating damage to wheat and corn in the NHRE region (Colorado) and found good correlations. Both the above studies were based on rather small samples. Wojtiw and Renick (1973) acquired a large sample of 2,042 reports from volunteer observers with which they examined the effects of hail and wind on crop damage (what such observations lack in precision they make up for in numbers). They found that the variables most highly correlated with crop damage were the total (with wind) and vertical impact energies, the maximum and modal hailstone sizes, and the wind speed.

III. EXPERIMENTAL DESIGN

A. Overview

A serious need exists for large samples of hailpad measurements coupled with crop-loss estimates. These are hard to acquire due to the high variability, small areal scale, and low point frequency of hailfalls that cause significant crop damage. Several data collection approaches are open, none of them entirely satisfactory. One approach would be to put out many instruments in a small area and patiently wait for hail to fall. This would yield many measurements from a few events. The sample so acquired would be strongly biased toward the properties of these few events (season, crop stage, damage level, etc.). Another approach, the one adopted for this study, is to put out a very large number (over 600) of instruments over a large area (over 600 mi), for a single season during which a dozen or so hail events of varying sizes can be expected (in Illinois). This will produce several hundred hailpad measurements in a reasonably short time. The risk is that the particular season (year) will not reach expectations in terms of frequency and severity of hail. The study consisted of operating a large, dense hailpad network for the collection of objective measures of hailfall parameters, and following up occurrences of hail at the hailpad stations with detailed assessments of crop damage in the adjacent fields.

The hailpad network deemed adequate for the data collection was to have a density of approximately one hailpad per square mile over an area of about 600 square miles. This was achieved by bringing the 625-square-mile Eastern Illinois Network (EIN) (Changnon and Morgan, 1976) up to the required density by adding 561 new stations to the existing 81. The hailpads used were 12 inches (30 cm) square by 1 inch (2.5 cm) thick stryrofoam boards wrapped with .0015 inch thick aluminum foil which was fastened to the boards with staples. The new hailpad stands required for this expansion were of a new type, constructed entirely of aluminum. These new stands are much lighter in weight and easier to construct than the older, iron and plywood type. Loss of hailpads and stands to vandalism was so high that 853 hailstands (approximately $5 each) had to be built before the data collection was completed.

The crop-loss assessments were performed by an experienced (15 years) crop-hail insurance adjuster, retained fulltime for the data collection period.

B. Sources of Error

There are a number of sources of error to be contended with in attempting to relate hailfall parameters to crop-hail damage. These are:

1) hailfall sampling error ~ we do not know well enough the variability of hailfall at scales of a few meters or tens of meters, or, stated otherwise the representativeness of a hailpad measurement (1 ft sensing area) of the hailfall in its immediate neighborhood. The coherence of patterns of hailpad parameters in small networks with grid spacings of several hundred feet (Morgan and Towery, 1975) suggests that the measurements are reasonably representative. Some attempts have been made to sample hailfall with sixteen hailpads spaced 3 feet apart in a square array, but not enough data have been gathered for an evaluation. In the absence of measurements it is probably reasonable to assume as others have done for hail and rain (Atlas, unpublished ms.; Sasyo, 1965; Joss and Waldvogel, 1969) that the statistics of hailstone numbers are those of a Poisson distribution.

2) lack of measurements of the wind-caused horizontal hail fluxes and energies. When hail is windblown, damage can increase enormously. This is a *very* important subject which will be discussed elsewhere in this report.

3) lack of information on crop conditions or crop varieties (due to fertilizers, soils, etc.). This is thought to be a very minor source of error due to the great uniformity of cropping practice in the study area.

4) separation between the hailpad location and the point at which the damage assessment is made. Hailpads were located in the open near road intersections. Crop damage assessments were made some distance inside the cropped field to minimize edge-of-field effects. This will be discussed elsewhere in this report.

5) errors in the assessment of the crop damage. This combines the problems of the representativeness of the plants chosen for estimation, and errors in the estimation. This could amount to an expected error of 5%.

It is not at the moment possible to place a variance estimate on each of these sources of error, but their number and some intuition about their magnitude suggest that the noise level in this study can be expected to be rather high.

Figure 1 provides a visualization of the overall noisiness of the data sample. It shows kinetic energy as a function of defoliation (percent) for the "later" corn stages. Figure 2, showing even greater scatter in the data, is for plant damage to late (reproductive stages) soybeans.

C. Network Servicing Procedures

All hailpads were routinely serviced (changed) every two weeks. The network servicing was set up as an 8-day routine (Saturdays and Sundays excluded) of approximately 80 pads per day. Raingage servicing, maintenance, and other duties occupied the remaining 2-3 days. The servicing routine generally involved driving around the network perimeter for 5 days, gradually reducing the network size, and permitting a daily sampling from the entire network. The final two days were spent in servicing the network core.

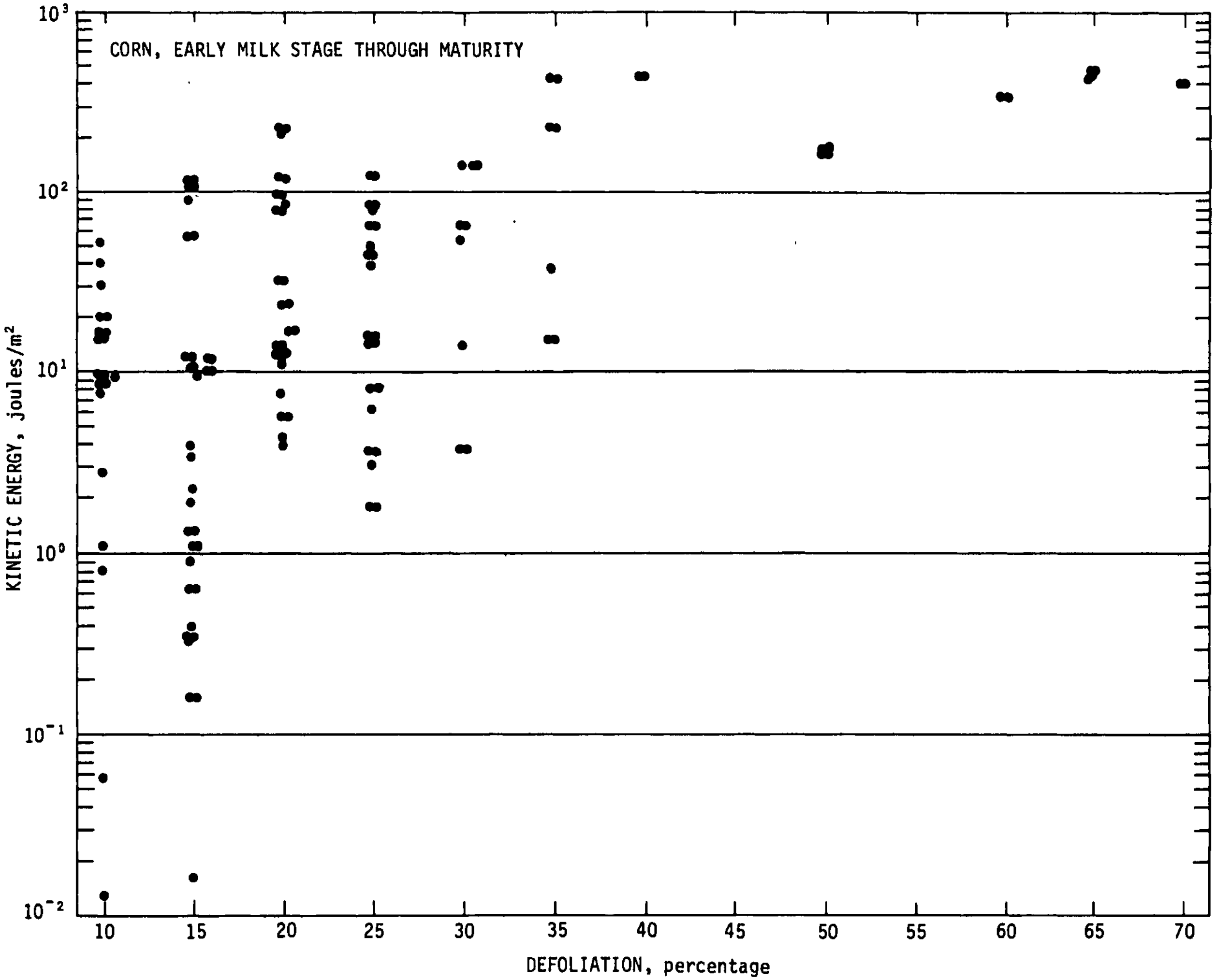

Figure 1. Kinetic energy versus defoliation for late corn.

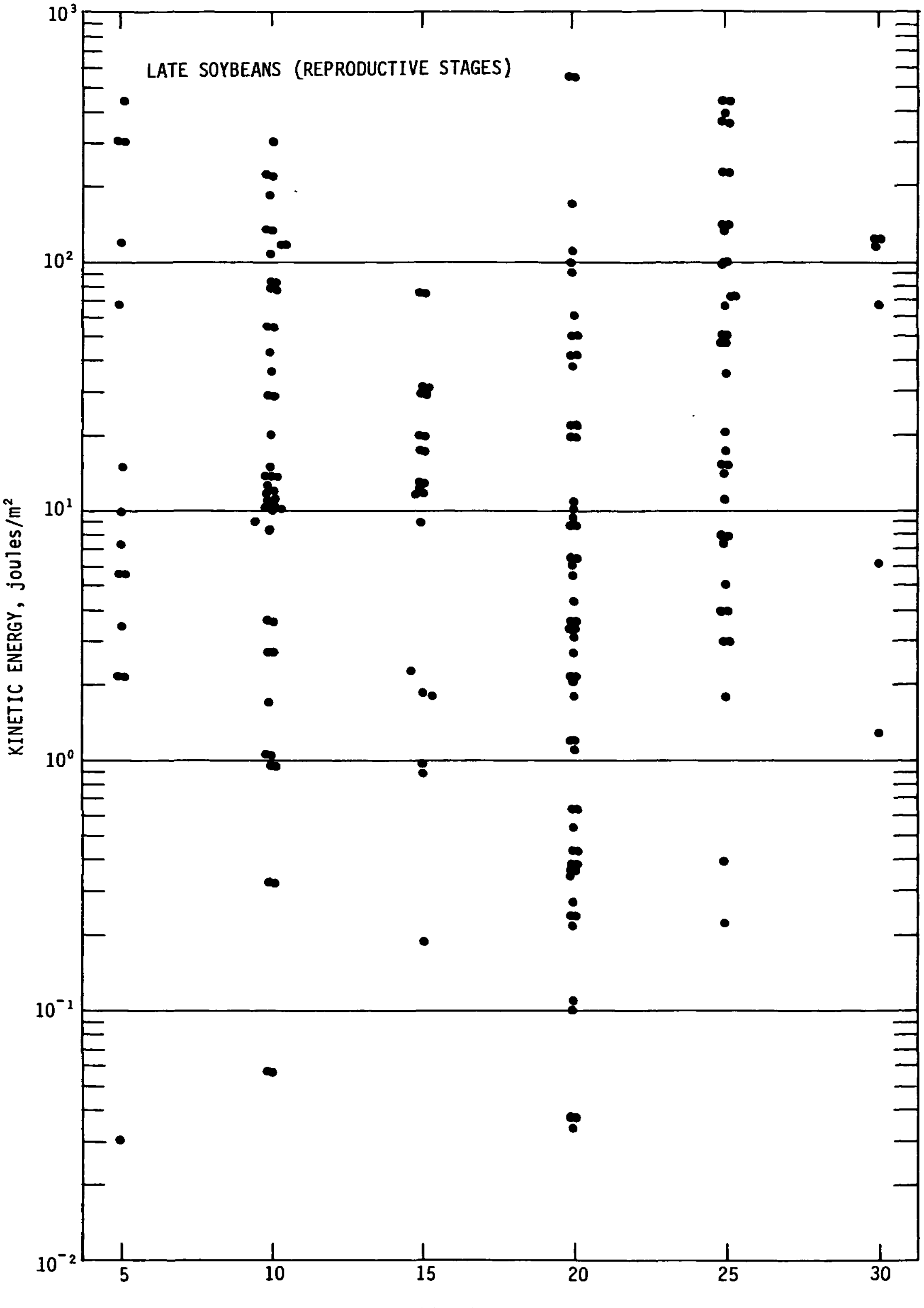

Figure 2. Kinetic energy versus plant damage for late soybeans.

Approximately 1300 miles of driving were required to perform one complete network servicing.

Allowing time to drive to and from the network, loading and unloading hailpads, fueling, and other routine necessities, approximately 4 minutes were required to service each hailpad station. This included driving from location to location, trimming the vegetation, replacing the pad, and record keeping. This was only possible by having two persons on the service team. One person drove and did the trimming (the most time consuming chore) while the second assisted with navigation, kept records and changed the hailpads.

IV. RESULTS

A. Preliminary Data Examination

Each day's collection of hailpads was quickly inspected for the occurrence of hail. This inspection and review process was necessary so that the crop adjuster's time could be most efficiently used. In general, locations with very small (largest stone $\leq$ 1/4 inch) and very few (less than 10 stones/ft^2) were not visited by the adjuster. Also considered in this review process was the general crop sensitivity. That is, as the crops reached the more sensitive stages, the review process became more conservative. It is quite likely that some damage occurred that went unadjusted; however, this is expected to have been minimal. If sufficient hail occurred at a hailpad site to warrant inspection of the crops there, the crop adjuster would visit the hailpad location and make an estimate of the damage to the crops near the hailpad. There could be as many as four different crops at each hailpad site, one on each corner of the road intersection. The information was recorded on a data form (Fig, 3) which included a map showing the crop locations relative to the hailpad and spaces for information about the damage to the crops located around the pad. Information obtained about each crop included 1) the distance from the pad to the location of the loss assessment, 2) row width, 3) row orientation, 4) crop stage at inspection, and 5) crop stage at time of loss. The actual damage Information for soybeans included the amount of 1) direct loss (plants completely broken over), 2) the percent of plant damage, 3) the loss of yield from plant damage, 4) shatter loss (beans shattered from pods), and 5) the total predicted loss of yield. The damage Information for corn included 1) loss of stand (plants completely lost), 2) percent defoliation, 3) percent loss of yield from defoliation, 4) stalk damage, 5) ear damage and 6) total loss of yield.

B. Data Summary

The 2-week cycle of servicing of the hailpads did not allow for individual storm identification, thus, the data have been grouped by the hailpad servicing in which the hail occurred. Table 1 gives a summary of information related to the hail occurrence for each servicing.

A total of 391 pads from the first servicing had hail. Very little crop damage occurred because crops were very small, or not even out of the ground, and not very susceptible to damage. A total of 122 sites were visited, 13 sites had damage, and 21 of 29 crops at the sties had some measurable loss of yield.

Location #	Storm Date	Inspection Date

Field Map:

SOYBEANS

Pt. No.	Distnce Pad/Pt.	Row Width	Row Direction	Stage @ Inspection	Stage @ Loss	Direct Damage	Plant Damage		Shatter Loss	Total Loss
							% Dmg.	% loss		
1.										
2.										
3.										
4.										

CORN

Pt. No.	Distnce Pad/Pt.	Row Width	Row Direction	Stage @ Inspection	Stage @ Loss	Loss of Stand	Defoliation		Stalk Damage	Ear Damage	Total Loss
							% dfl.	% loss			
1.											
2.											
3.											
4.											

Figure 3. Sample worksheet of crop adjuster.

Table 1. Summary information for each hailpad servicing

Serv. #	No. Pads with Hail	No. Sites Visited by Adjustor	No. Sites with Crop Loss	Number of crops at sites visited				Number of crops damaged at sites visited			
				Beans	Corn	Other	Total	Beans	Corn	Other	Total
1	391	122	13	16	11	2	29	14	7	0	21
2	352	34	8	3	16	3	22	3	16	0	19
3	201	164	40	50	41	0	91	50	25	0	75
4	247	57	33	45	48	0	93	45	32	0	77
5	140	98	73	89	89	0	178	89	76	0	165
6	149	55	33	24	45	0	69	24	45	0	69
7	69	12	0	0	0	0	0	0	0	0	0
Totals	1549	542	200	227	250	5	482	225	201	0	426

The second servicing produced 352 pads with hail. The hail was very small and measurable damage occurred at only 8 of the 34 sites visited by the adjuster. Only 19 of the 22 crops at those 8 sites had a measurable loss of yield. Again, one of the reasons for this was that the crops were young and not susceptible to hail damage.

The third, fourth and fifth servicings produced most of the damage data. A total of 588 pads detected hail. The adjuster visited 319 sites and found damage to 317 of the 362 crops at 146 sites.

Fifty-five of the 149 sites were visited by the adjuster after the sixth servicing and 33 of the 55 sites had damage to adjacent crops. All 69 available crops sustained damage.

No measurable loss of yield was produced by the hail from the seventh servicing. The hail was generally light and crops were almost mature and not sensitive to damage.

A total of 1549 hailpads detected hail in the 4-month period. Figure 4 is a plot of the number of occurrences of hail at each location. Some locations had no hail. Most locations had 1, 2, or 3 occurrences, and some locations had more than 4 occurrences. The maximum number of occurrences at one location was 6.

The area of crop damage (corn, beans, or other) is shown in Figure 5. The total damage area is 173 square miles of the 600-square mile network.

Figure 6 shows a plot of the corn losses with an iso-percentile analysis for losses greater than 5 percent. Figure 7 shows a similar analysis for the soybean losses. The damage for both crops is widespread; however, there were three areas where the heaviest damage was concentrated — north of Farmer City, southeast of Heyworth, and near Maroa.

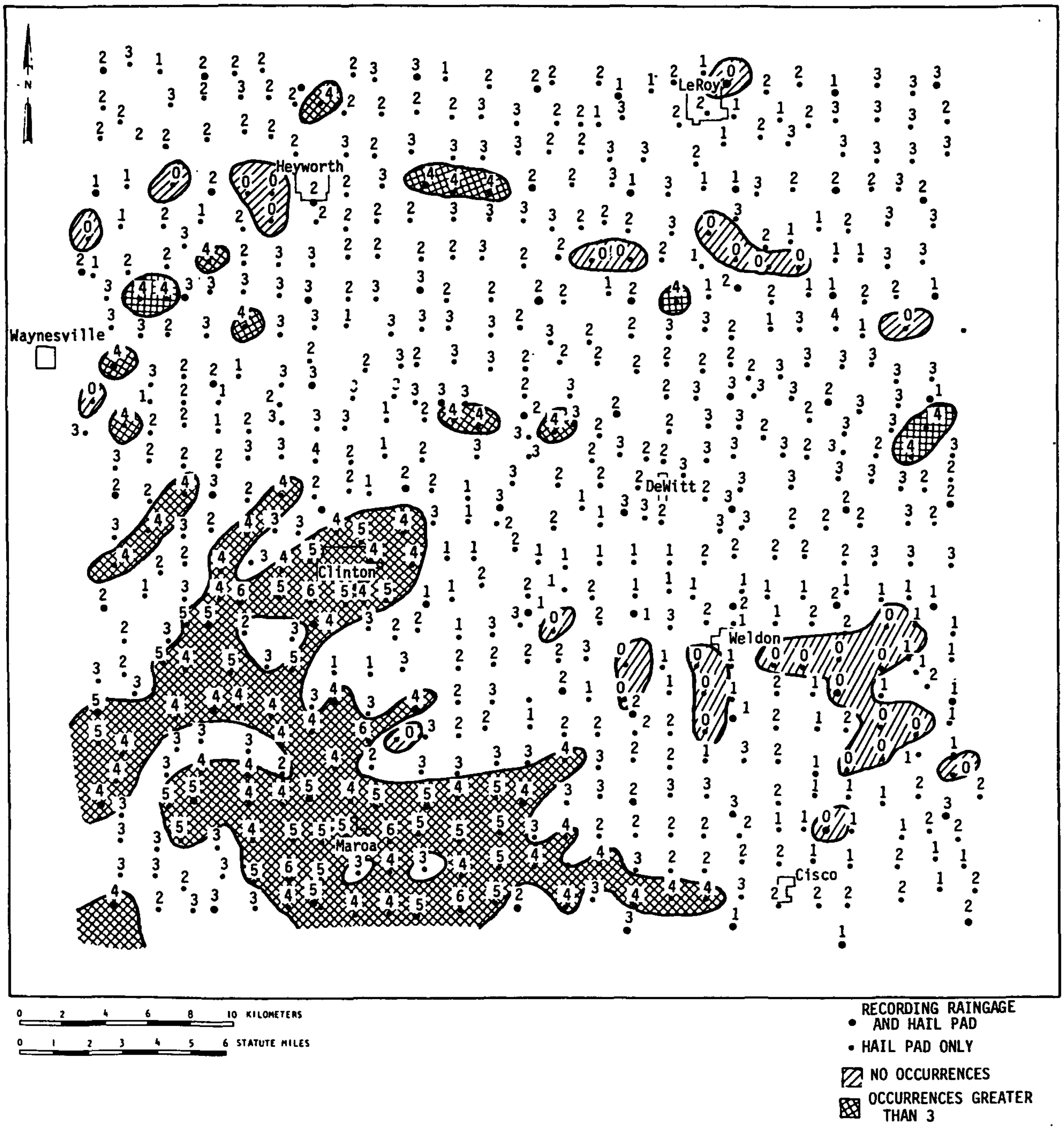

Figure 4. Number of occurrences of hail at each hailpad location.

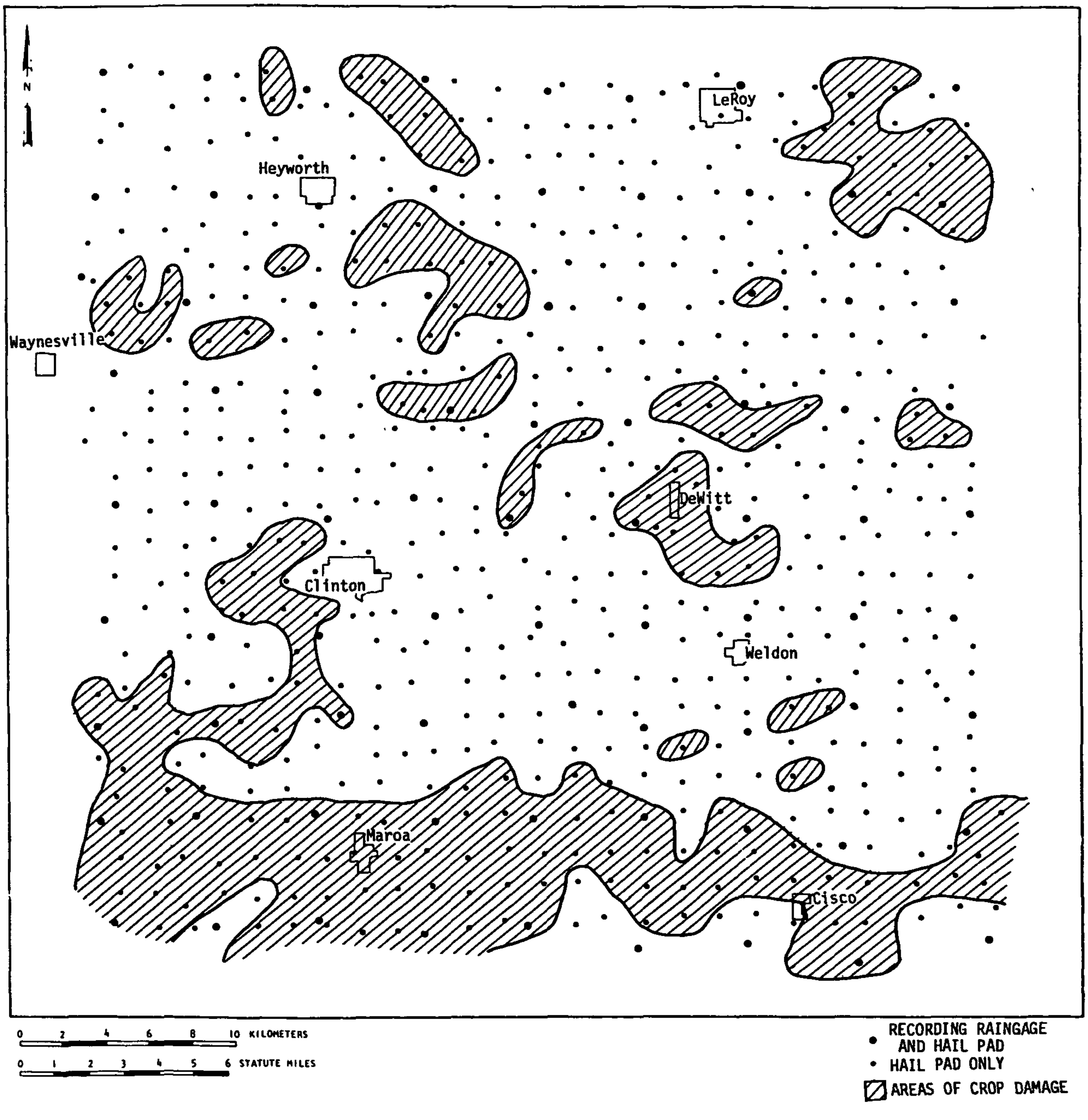

Figure 5. Areas with measureable crop damage in 1975.

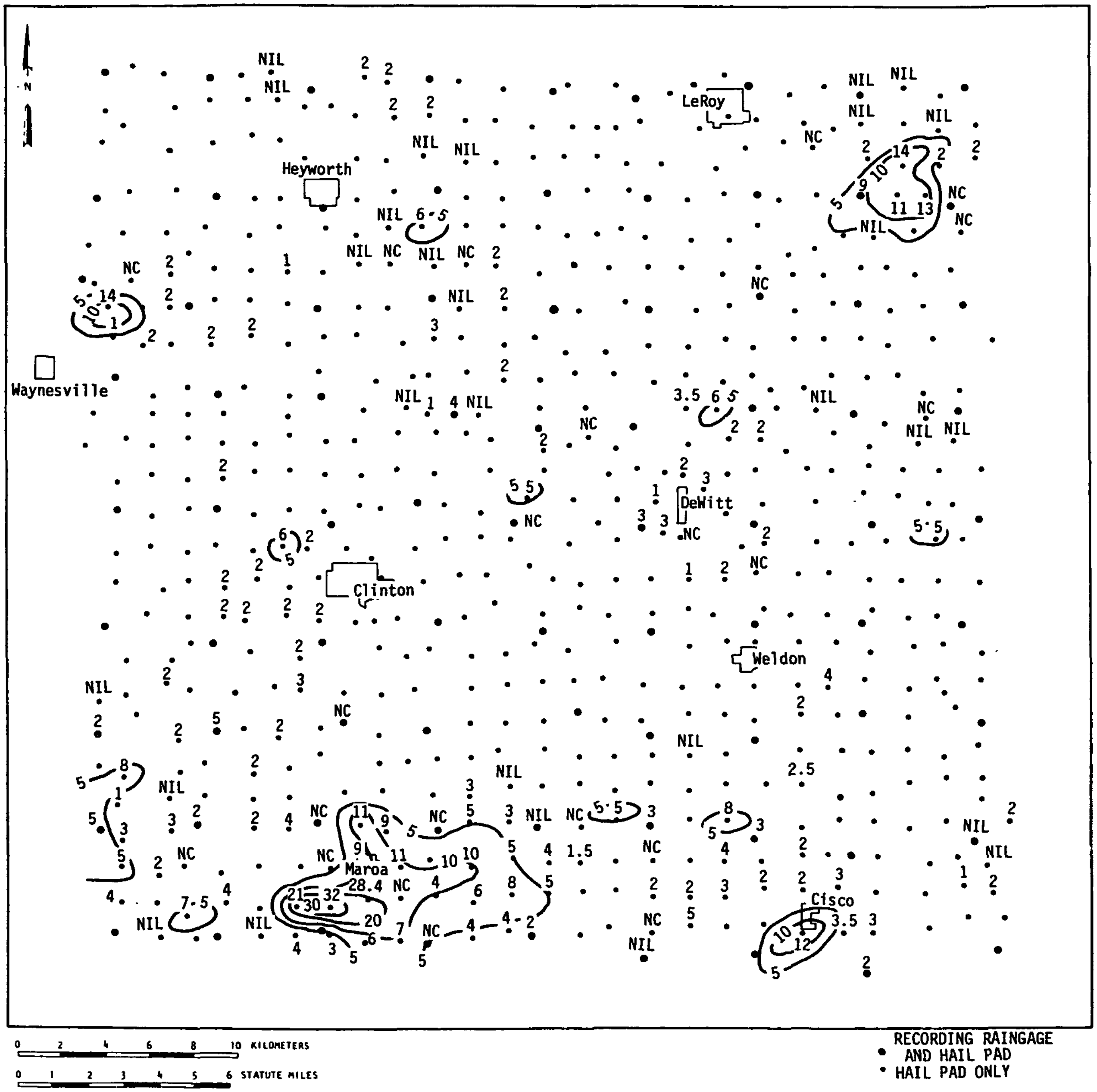

Figure 6. Average loss of yield to corn crops at locations with crop damage.

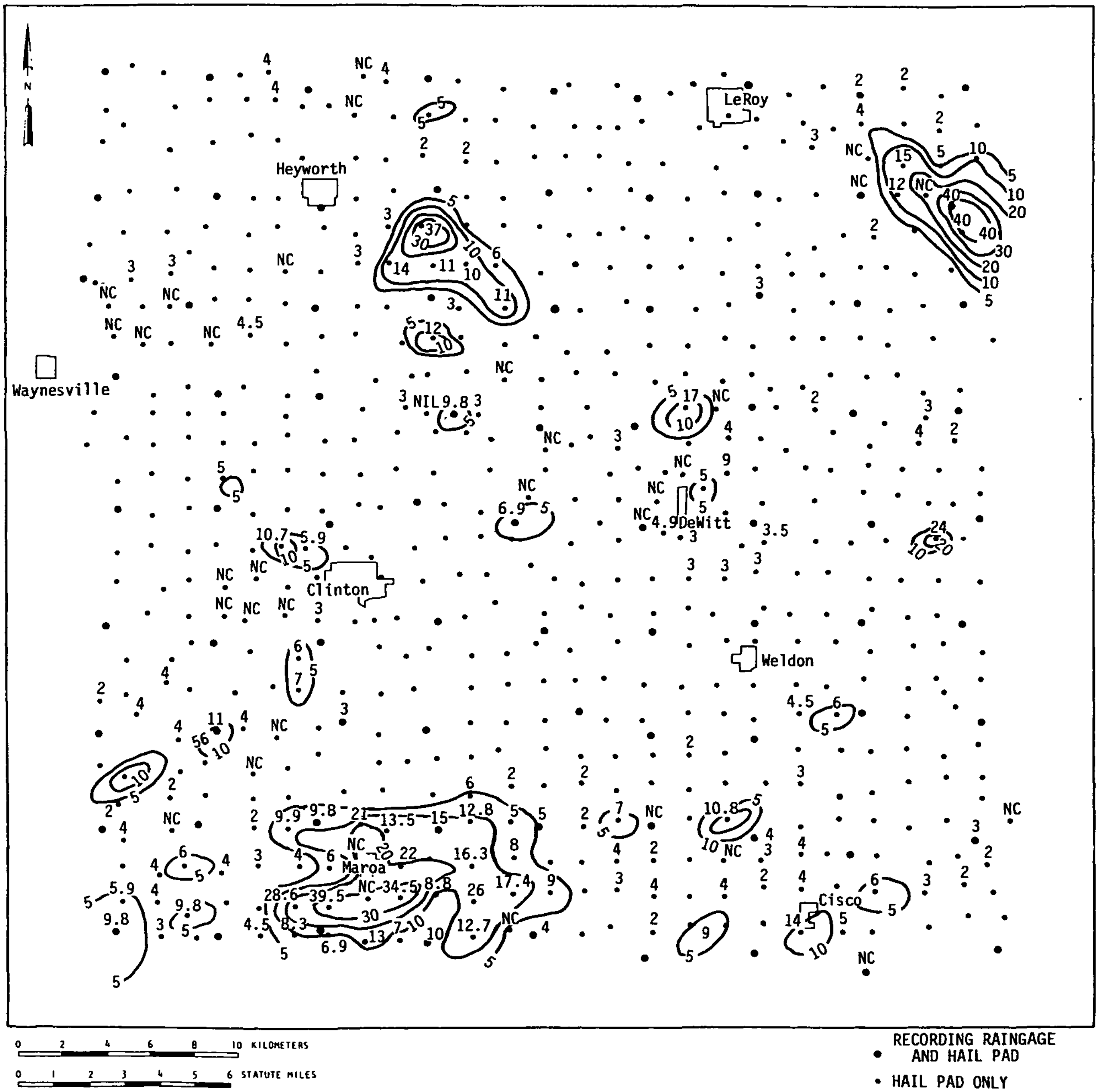

Figure 7. Average loss of yield to soybean crops at locations with crop damage.

The timing of the heavier damage and storms was such that a large percentage of the damage data was concentrated into a few crop stages, Figure 8 is a plot of the number of loss assessments versus the various crop stages as they occur in growth for corn. Corn stages range from 5 to 21 leaf then tassle through maturity. There are no assessments for some stages and the bulk of our data falls within the pre-blister to soft dough stage. This stage occurs after the sensitive, tassle stage. A total of 64 assessments were obtained in the leaf stages and 194 assessments were in the ear development stages.

A similar situation occurred with the bean stages. Figure 9 is a plot of loss assessments versus stages of growth for soybeans. Soybean stages are classified as vegetative (V) or reproductive (R) and range from V-1 to V-9 and R-5 through R-11 (maturity). The major portion of our data is in the R-5 to R-9 stage. Soybeans in the R-7 to R-9 stage are more sensitive to hail than other stages. A total of 33 assessments occurred in the vegetative stages and 196 assessments were in the reproductive stages.

As noted earlier, the distance from the pad location to the point loss assessment was recorded. This was done because hailpads were typically located at road intersections and crops could be located at any of the four corners. Variability in crop damage and hailfall parameters over short distances has been documented (Morgan and Towery, 1975). Figure 10 is a plot of the percentage occurrence of loss assessments against distance from the hailpad for corn and beans. Almost 3/4 of the loss assessments were within 100 feet of the pad.

C. Data Reduction

All of the dents in the hailpad were measured, counted, and entered onto punchcards and various hailpad parameters calculated. The

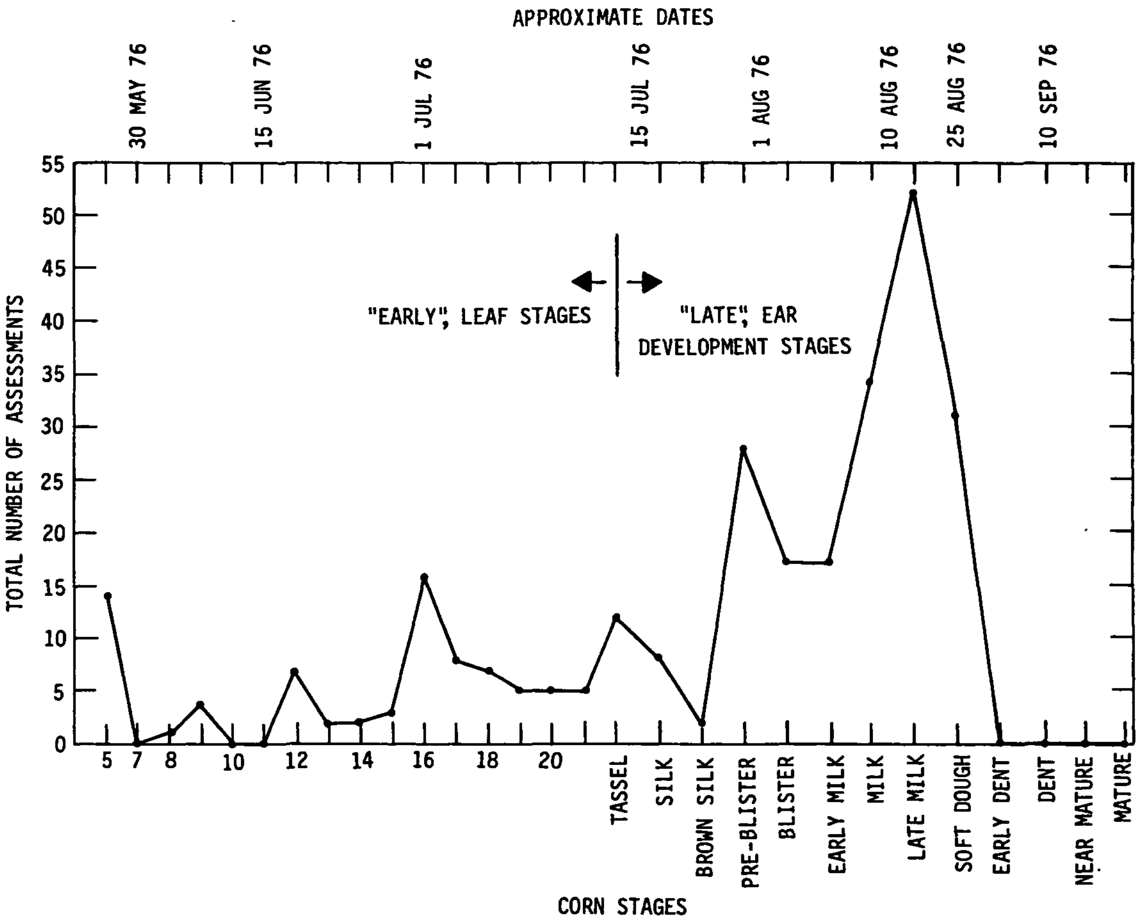

Figure 8. Number of loss assessments versus stage of growth for corn.

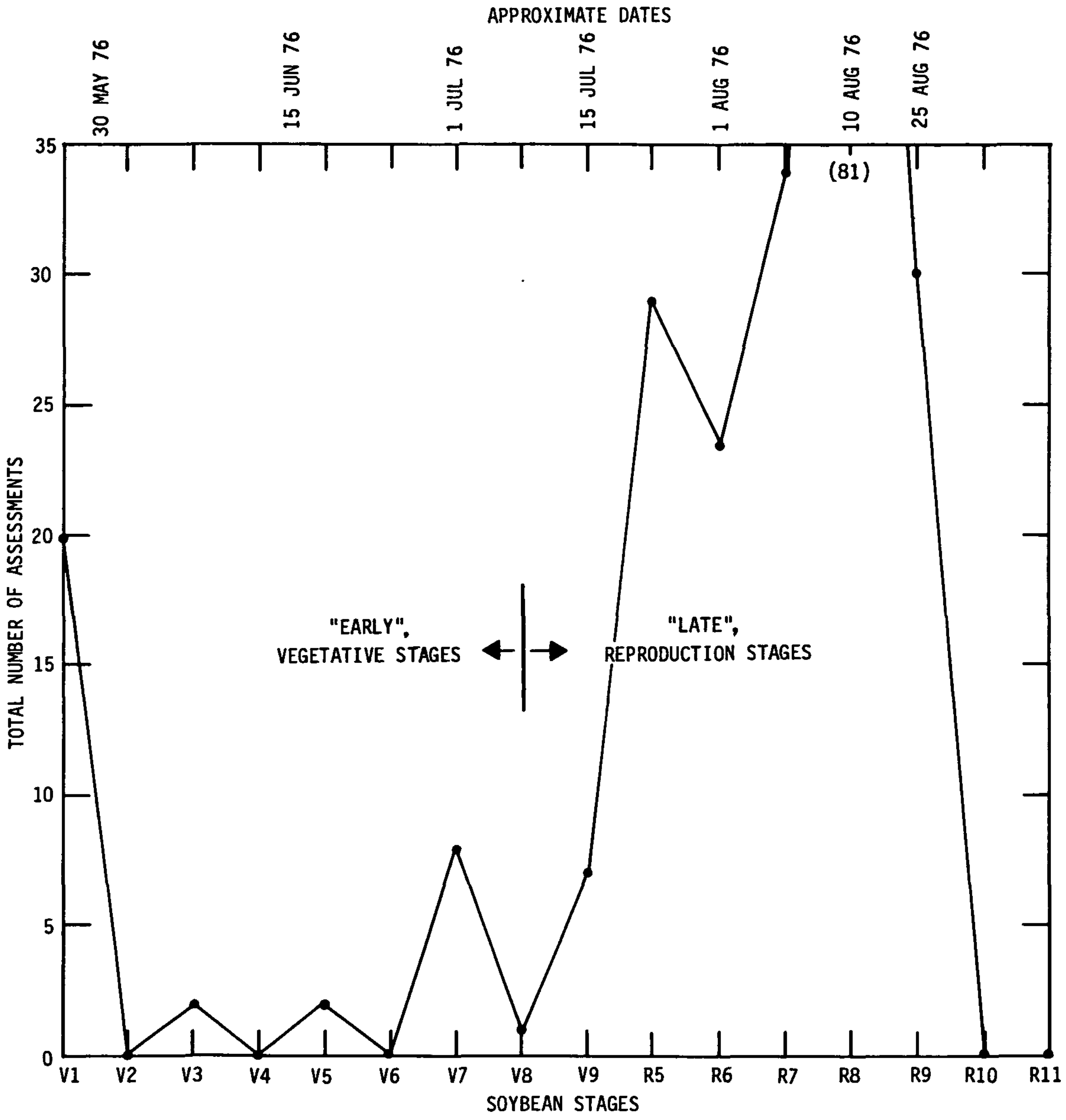

Figure 9. Number of loss assessments versus stage of growth for soybeans.

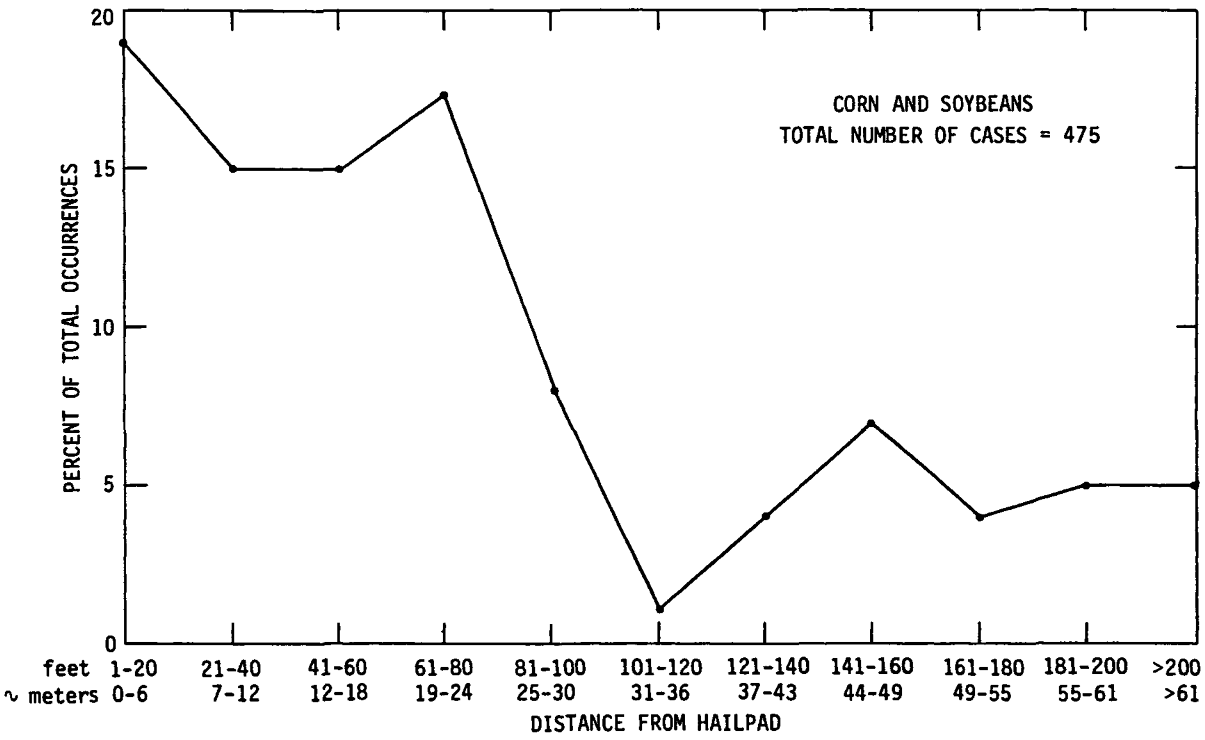

Figure 10. Percentage of occurrence of loss assessments versus distance from hailpad for corn and soybeans.

parameters calculated were the number of stones, energy, mass, and momentum for 0.25 cm diameter classes. The totals of the above parameters were also calculated for each pad. The crop loss data have also been entered onto punchcards for use in analysis.

The limited range of crop-loss experienced in the network during the data collection period points out the problem of monitoring a variable phenomenon such as hail over a single summer. The general hail experience in Illinois in 1975 was worse than normal. Major hailstorms occurred around and near, but not in, the network. An insurance company which sells roughly half of the crop-hail insurance in Illinois, paid out $19 million in losses, well above the average. During the following sunnier, 1976, a disastrous hailstorm occurred in the area previously occupied by the network. That is the nature of hailfall.

D. Wind and Hail

Many assessments of the effectiveness of hail suppression have been based on crop damage (Changnon, 1973). The relationship between hail and the damage 1t produces to crops is very complex and depends strongly on the wind which accompanies the hail. The effect of wind is an important element not yet adequately taken into consideration in any study of the relationship between hail and crop damage. A *very* impressive fall of hail can do little or no crop damage (depending on crop type) if the wind is calm, whereas a lesser fall of hail can completely destroy a crop if accompanied by a strong enough wind.

These facts are known to all farmers and all hail insurance adjusters but to relatively few weather modification researchers. They are an important reason for including crop-hail damage values as a measure of the effectiveness of suppression efforts.

Very little or no attention has been given to the surface wind factor in the design and evaluation of weather modification projects. A major reason for this is the difficulty of acquiring measurements of the wind at places where it hails on crops.

A view of the effects of wind on hail damage can be had from the studies of Wojtiw and Renick (1973) and Towery et al (1976). The contribution of wind to the energy fluxes of hailfall is discussed by Morgan and Towery (1976) and Vento and Morgan (1976), based on use of a simple device, the hailcube, which makes possible the measurement of various effects of the wind on hail.

Some statements can be made about the dependence of damage on stone size, wind and crop factors.

If the crop be of depth ℓ and a hailstone be of diameter d, the time for the stone to transit the crop depth if unimpeded is

$$t = \ell / v_t$$

where v. is the terminal fall speed of the stone.

In the same time, t, the hailstone, if moving at horizontal speed (which is typically assumed to be the wind speed) V_h, will move a horizontal distance

$$\delta = V_h t = V_h \, \ell / v_t$$

from its point of entry. Its path through the crop layer will be

$$r = (\ell^2 + \delta^2)^{1/2} = \ell \, (1 + V_h{}^2 / v_t{}^2)^{1/2}.$$

It will sweep out a volume

$$V_s = \pi/4\ D^2 r = \pi/4\ D^2\ \ell\ (1 + V_h^2/v_t^2)^{1/2}.$$

Thus, if the crop consists of a volumetric distribution of entities (assumed points) which are subject to damage (such as fruit in a tree, or pods on a soybean plant) with a density of σ such entities per unit volume, an average hailstone would, if undeviated, contact (and presumably damage) a number of them equal to

$$\begin{aligned} n &= V_s\ \sigma \\ &= \pi/4\ D^2\ \ell\ (1 + V_h^2/v_t^2)^{1/2}\ \sigma. \end{aligned}$$

If the crop (or the portion of it of interest) is rod-like (such as corn stalks, and considering only the potential for damage to stalks) the analogous number of intercepted entities would be more likely to depend on the horizontally projected area, A , swept out by the hailstone in falling through the depth, ℓ, of the crop (in which there are x stalks per unit area).

$$\begin{aligned} n = A_s\ x &\ \dot{\sim}\ x\ (\pi/4\ D^2 + D\delta) \\ &\ \dot{\sim}\ x\ (\pi/4\ D^2 + D\ V_h/v_t \ell) \end{aligned}$$

where, for typical values of V., the second term in parentheses is by far the larger.

Another effect of the wind is due to the increase of the kinetic energy (or momentum) of the individual hailstones. If there is a threshold diameter (as specifying energy or momentum in the no-wind case) below which the hailstones have no potential for the type of damage under consideration in the absence of wind, the wind will move this threshold toward smaller diameters. In general, the number of stones per unit volume or area decreases with increasing diameters so that lowering the threshold diameter may increase markedly the number of stones having potential for damage. The magnitude of this potentially large effect will depend on both the wind and the shape of the hailstone size spectrum.

In summary, the above extremely crude considerations indicate that the crop damage from a hailfall depends inextricably on the crop characteristics, the type of damage being considered, amount of hail, the characteristics of the hailstone size distribution, and the wind which accompanies the haifall. The effect of the wind will:

1) increase the energies or momenta of the hailstones,
2) increase the number of stones having potential for damage,
3) increase the path (length, area, or volume) of the stones through the crop and hence the probability of a given stone's encountering a damageable entity.

It is not unreasonable to state that the wind is as important as the hail itself in determining the amount of hail damage to the crops.

Complicating the wind-hail interaction are the shielding effects of the crops which depend upon the manner in which the crops are planted (row spacing, row orientation, etc.). Difficult to assess are the effects of alteration in the aspect and condition of the plants by the wind on their vulnerability to the hail. For example, strong winds may rend a plant so that more of its stalk area is perpendicular to the direction of stone arrival.

It is unfortunate that provision was not made in this project for recording the horizontal, wind-caused components of hailfall parameters.

Hailcubes would have been at least feasible for this purpose and were initially considered. Their use, however, would have increased the project budget significantly (3200 hailpads would have been required, rather than 640, and the required field personnel would have increased two- or three-fold).

It is recommended that any future studies of this sort be designed to consider wind effects.

The following points are worth setting out at this time:

1. Wind with hail must be considered in designing weather modification projects.
2. It is not unreasonable to investigate the possible increase of wind due to seeding. Several hail suppression projects report increasing rainfall (Changnon and Morgan, 1976b). Cold air production is related to precipitation and is the cause of the strong thunderstorm winds. Such a wind increase with seeding would be very serious indeed as it could limit the attainable damage reduction or even cause a *net increase in damage.*
3. Even if it can be demonstrated that there is no wind alteration due to seeding, a reduction in hailfall could be negated by random effects due to the winds. The farmers would not perceive the hail reduction.
4. There is, thus, a need to establish the joint probability distributions of hail energy and winds and test this as part of the randomized project.
5. The only instrument presently available for inexpensively estimating wind effects with the occurrence of hail is the hailcube.

E. Crop-Damage Functions

The damage cases from 1975 for each of the two crops, corn and soybeans, were divided into two groups: 1) the leaf stages (64 cases), and 2) the ear development stages for corn (194 cases); and 1) the vegetative (33 cases), and 2) reproductive stages (196 cases) for soybeans. These are referred to here as "early" (leaf for corn and vegetative for beans) and "late" (ear development for corn and reproductive for beans). A finer division of the sample by stages would have been impractical, given the overall sample size.

Simple regressions and correlations were determined in which the predicted (dependent) variables were the three basic types of damage: direct damage; defoliation (corn) or plant damage (soybeans); and total loss of yield. The independent variables chosen were:

1) the number of stones (m^{-3}) of all sizes;
2) the number of stones (m^{-3}) of diameter $\geq$0.25 cm;
3) the number of stones (m^{-3}) of diameter $\geq$0.50 cm;
4) the number of stones (m^{-3}) of diameter $\geq$0.75 cm;
5) the number of stones (m^{-3}) of diameter $\geq$1.00 cm;
6) the number of stones (m^{-3}) of diameter $\geq$1.50 cm;
7) the total mass of hail ($g\ m^{-2}$);
8) the total hail momentum ($g\ cm\ sec^{-1}\ m^{-2}$);
9) the total hail kinetic energy ($joules\ m^{-2}$).

The regressions (slopes, intercepts, correlation coefficients and t ratios) are presented in tabular form in Tables 2a through 2b.

Some rather tedious preliminary analyses which will not be described here suggested that another class of parameters, the nth-ranked stone diameter,

Table 2a. Results of regression analyses for stone frequency and spectrum integral predictor types

EARLY SOYBEANS -- SAMPLE SIZE = 38

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
DIRECT DAMAGE (Sample Average 5.9%)	No. of stones:				
	All sizes	$.15 \times 10^{-2}$	.031	.51	3.6
	≥ 0.25 cm	$.51 \times 10^{-2}$	.39	.68	5.6
	≥ 0.50 cm	$.51 \times 10^{-2}$	.42	.68	5.6
	≥ 0.75 cm	$.55 \times 10^{-2}$	.90	.67	5.4
	≥ 1.00 cm	$.77 \times 10^{-2}$	1.6	.66	5.3
	≥ 1.50 cm	$.18 \times 10^{-1}$	2.6	.64	4.9
	mass/m^2	$.30 \times 10^{-2}$	2.1	.66	5.2
	momentum/m^2	$.14 \times 10^{-5}$	2.5	.64	4.9
	kinetic energy/m^2	$.13 \times 10^{-1}$	2.8	.61	4.6
PLANT DAMAGE (Sample Average 9.6%)	All sizes	$-.31 \times 10^{-2}$	21.7	-.76	-7.0
	≥ 0.25 cm	$-.79 \times 10^{-2}$	18.2	-.77	-7.2
	≥ 0.50 cm	$-.79 \times 10^{-2}$	18.2	-.77	-7.2
	≥ 0.75 cm	$-.83 \times 10^{-2}$	17.1	-.73	-6.3
	≥ 1.00 cm	$-.10 \times 10^{-1}$	15.4	-.65	-5.1
	≥ 1.50 cm	$-.21 \times 10^{-1}$	13.6	-.55	-4.0
	mass/m^2	$-.38 \times 10^{-2}$	14.4	-.60	-4.5
	momentum/m^2	$-.18 \times 10^{-5}$	13.8	-.57	-4.1
	kinetic energy/m^2	$-.16 \times 10^{-1}$	13.4	-.54	-3.8
TOTAL LOSS OF YIELDS (Sample Average 6.9%)	All sizes	$.11 \times 10^{-2}$	2.4	.43	2.8
	≥ 0.25 cm	$.42 \times 10^{-2}$	2.3	.61	4.7
	≥ 0.50 cm	$.42 \times 10^{-2}$	2.4	.61	4.7
	≥ 0.75 cm	$.46 \times 10^{-2}$	2.7	.61	4.6
	≥ 1.00 cm	$.66 \times 10^{-2}$	3.3	.61	4.7
	≥ 1.50 cm	$.15 \times 10^{-2}$	4.1	.60	4.5
	mass/m^2	$.25 \times 10^{-2}$	3.7	.61	4.6
	momentum/m^2	$.12 \times 10^{-5}$	4.0	.59	4.4
	kinetic energy/m^2	$.11 \times 10^{-1}$	4.3	.57	4.2

Table 2b. Results of regression analyses for stone frequency and spectrum integral predictor types.

LATE SOYBEANS -- SAMPLE SIZE = 167

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
	No. of stones:				
DIRECT DAMAGE (Sample Average 1.9%)	All sizes	$.41 \times 10^{-3}$	.53	.28	3.8
	≥ 0.25 cm	$.34 \times 10^{-2}$	-.49	.56	8.7
	≥ 0.50 cm	$.34 \times 10^{-2}$	-.48	.56	8.7
	≥ 0.75 cm	$.39 \times 10^{-2}$	-.38	.56	8.8
	v 1.00 cm	$.66 \times 10^{-2}$	+.043	.55	8.5
	≥ 1.50 cm	$.23 \times 10^{-1}$	.68	.49	7.2
	mass/m^2	$.41 \times 10^{-2}$	.058	.54	8.2
	momentum/m^2	$.23 \times 10^{-5}$	.20	.52	7.9
	kinetic energy/m^2	$.26 \times 10^{-1}$	.33	.51	7.6
PLANT DAMAGE (Sample Average 16.6%)	All sizes	$.32 \times 10^{-3}$	15.5	.18	2.3
	≥ 0.25 cm	$.13 \times 10^{-2}$	15.6	.18	2.4
	≥ 0.50 cm	$.13 \times 10^{-2}$	15.6	.18	2.4
	≥ 0.75 cm	$.14 \times 10^{-2}$	15.8	.16	2.1
	≥ 1.00 cm	$.17 \times 10^{-2}$	16.1	.11	1.5
	≥ 1.50 cm	$.23 \times 10^{-2}$	16.5	.04	.53
	mass/m^2	$.11 \times 10^{-2}$	16.1	.12	1.6
	momentum/m^2	$.61 \times 10^{-6}$	16.1	.11	1.4
	kinetic energy/m^2	$.66 \times 10^{-2}$	16.2	.10	1.4
TOTAL LOSS OF YIELD (Sample Average 5.6%)	All sizes	$.53 \times 10^{-3}$	3.9	.34	4.6
	≥ 0.25 cm	$.40 \times 10^{-2}$	2.8	.61	10.0
	≥ 0.50 cm	$.40 \times 10^{-2}$	2.8	.61	10.0
	≥ 0.75 cm	$.46 \times 10^{-2}$	3.0	.61	10.0
	≥ 1.00 cm	$.75 \times 10^{-2}$	3.5	.58	9.1
	≥ 1.50 cm	$.24 \times 10^{-1}$	4.3	.48	7.1
	mass/m^2	$.46 \times 10^{-2}$	3.6	.56	8.7
	momentum/m^2	$.26 \times 10^{-5}$	3.7	.54	8.3
	kinetic energy/m^2	$.29 \times 10^{-1}$	3.9	.53	7.9

Table 2c. Results of regression analyses for stone frequency and spectrum integral predictor types.

ALL SOYBEANS -- SAMPLE SIZE = 205

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
DIRECT DAMAGE (Sample Average 2.6%)	No. of stones:				
	All sizes	$.55 \times 10^{-3}$	.77	.32	4.8
	$\geq$ 0.25 cm	$.39 \times 10^{-2}$	-.40	.60	10.8
	$\geq$ 0.50 cm	$.39 \times 10^{-2}$	-.38	.60	10.7
	$\geq$ 0.75 cm	$.44 \times 10^{-2}$	-.21	.60	10.8
	$\geq$ 1.00 cm	$.73 \times 10^{-2}$	+ .23	.61	10.8
	$\geq$ 1.50 cm	$.21 \times 10^{-1}$	1.0	.57	9.8
	mass/m^2	$.36 \times 10^{-2}$	.46	.60	10.7
	momentum/m^2	$.10 \times 10^{-5}$	.74	.58	10.1
	kinetic energy/m^2	$.17 \times 10^{-1}$	1.0	.55	9.4
PLANT DAMAGE (Sample Average 15.3%)	All sizes	$-.66 \times 10^{-4}$	15.5	-.03	-.42
	$\geq$ 0.25 cm.	$-.11 \times 10^{-2}$	16.2	-.13	-1.9
	$\geq$ 0.50 cm	$-.11 \times 10^{-2}$	16.1	-.13	-1.8
	$\geq$ 0.75 cm	$-.13 \times 10^{-2}$	16.1	-.13	-1.9
	$\geq$ 1.00 cm	$-.31 \times 10^{-2}$	16.3	-.20	-2.9
	$\geq$ 1.50 cm	$-.14 \times 10^{-1}$	16.4	-.30	-4.5
	mass/m^2	$-.22 \times 10^{-2}$	16.6	-.28	-4.1
	momentum/m^2	$-.12 \times 10^{-5}$	16.6	-.30	-4.4
	kinetic energy/m^2	$-.13 \times 10^{-1}$	16.5	-.31	-4.7
TOTAL LOSS OF YIELD (Sample Average 5.9%)	All sizes	$.60 \times 10^{-3}$	3.8	.35	5.3
	$\geq$ 0.25 cm	$.40 \times 10^{-2}$	2.7	.62	11.1
	$\geq$ 0.50 cm	$.40 \times 10^{-2}$	2.8	.62	11.1
	$\geq$ 0.75 cm	$.46 \times 10^{-2}$	2.9	.62	11.1
	$\geq$ 1.00 cm	$.71 \times 10^{-2}$	3.5	.59	10.4
	$\geq$ 1.50 cm	$.18 \times 10^{-1}$	4.4	.50	8.1
	mass/m^2	$.33 \times 10^{-2}$	3.9	.55	9.4
	momentum/m^2	$.16 \times 10^{-5}$	4.2	.52	8.6
	kinetic energy/m^2	$.15 \times 10^{-1}$	4.5	.48	7.8

Table 2d. Results of regression analyses for stone frequency and spectrum integral predictor types.

EARLY CORN -- SAMPLE SIZE = 61

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
	no. of stones:				
DIRECT DAMAGE (Sample Average .19%)	All sizes	$.42 \times 10^{-4}$	.051	.16	1.2
	$\geq$ 0.25 cm	$.48 \times 10^{-3}$	-.16	.44	3.7
	$\geq$ 0.50 cm	$.48 \times 10^{-3}$	-.16	.44	3.7
	$\geq$ 0.75 cm	$.58 \times 10^{-3}$	-.14	.46	4.0
	$\geq$ 1.00 cm	$.11 \times 10^{-2}$	-.15	.55	5.1
	$\geq$ 1.50 cm	$.26 \times 10^{-2}$	-.074	.59	5.6
	mass/m^2	$.44 \times 10^{-3}$	-.12	.59	5.6
	momentum/m^2	$.26 \times 10^{-6}$	-.093	.58	5.4
	kinetic energy/m^2	$.20 \times 10^{-2}$	-.063	.56	5.3
PLANT DAMAGE (Sample Average 14.4%)	All sizes	$.11 \times 10^{-2}$	10.5	.25	2.0
	$\geq$00.25 cm	$.47 \times 10^{-2}$	11.0	.25	2.0
	$\geq$ 0.50 cm	$.46 \times 10^{-2}$	11.0	.25	2.0
	$\geq$ 0.75 cm	$.40 \times 10^{-2}$	12.1	.19	1.4
	$\geq$ 1.00 cm	$.31 \times 10^{-2}$	13.4	.10	.75
	$\geq$ 1.50 cm	$.22 \times 10^{-2}$	14.2	.03	.23
	mass/m^2	$.94 \times 10^{-3}$	13.7	.07	.57
	momentum/m^2	$.34 \times 10^{-6}$	13.9	.05	.42
	kinetic energy/m^2	$.24 \times 10^{-2}$	14.1	.04	.31
TOTAL LOSS OF YIELD (Sample Average 2.0%)	All sizes	$.19 \times 10^{-3}$	1.28	.29	2.37
	$\geq$ 0.25 cm	$.10 \times 10^{-2}$	1.20	.37	3.05
	$\geq$ 0.50 cm	$.10 \times 10^{-2}$	1.21	.37	3.04
	$\geq$ 0.75 cm	$.11 \times 10^{-2}$	1.30	.35	2.86
	$\geq$ 1.00 cm	$.14 \times 10^{-2}$	1.48	.30	2.40
	$\geq$ 1.50 cm	$.22 \times 10^{-2}$	1.72	.20	1.57
	mass/m^2	$.47 \times 10^{-3}$	1.61	.25	1.96
	momentum/m^2	$.21 \times 10^{-6}$	1.67	.22	1.75
	kinetic energy/m^2	$.17 \times 10^{-2}$	1.72	.20	1.56

Table 2e. Results of regression analyses for stone frequency and spectrum integral predictor types.

LATE CORN -- SAMPLE SIZE =142

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
DEFOLIATION (Sample Average 15.0%)	No. of stones:				
	All sizes	$.42 \times 10^{-3}$	13.3	.14	21.7
	$\geq$ 0.25 cm	$.79 \times 10^{-2}$	8.3	.66	10.3
	$\geq$ 0.50 cm	$.79 \times 10^{-2}$	8.3	.66	10.3
	$\geq$ 0.75 cm	$.87 \times 10^{-2}$	8.9	.65	10.2
	$\geq$ 1.00 cm	$.16 \times 10^{-1}$	9.6	.67	10.7
	$\geq$ 1.50 cm	$.69 \times 10^{-1}$	11.2	.58	8.4
	mass/m^2	$.11 \times 10^{-2}$	9.2	.66	10.5
	momentum/m^2	$.67 \times 10^{-5}$	9.5	.66	10.3
	kinetic energy/m^2	$.78 \times 10^{-1}$	9.7	.65	10.0
TOTAL LOSS OF YIELD (Sample Average 3.7%)	All sizes	$.27 \times 10^{-3}$	2.6	.22	2.7
	$\geq$ 0.25 cm	$.34 \times 10^{-2}$	.78	.71	11.8
	$\geq$ 0.50 cm	$.34 \times 10^{-2}$	.78	.71	11.8
	$\geq$ 0.75 cm	$.38 \times 10^{-2}$	1.00	.71	12.0
	$\geq$ 1.00 cm	$.69 \times 10^{-2}$	1.28	.74	13.0
	$\geq$ 1.50 cm	$.30 \times 10^{-1}$	2.00	.62	9.5
	mass/m^2	$.47 \times 10^{-2}$	1.16	.72	12.2
	momentum/m^2	$.29 \times 10^{-5}$	1.26	.71	11.9
	kinetic energy/m^2	$.34 \times 10^{-1}$	1.38	.70	11.4

Table 2f. Results of regression analyses for stone frequency and spectrum integral predictor types.

ALL CORN -- SAMPLE SIZE = 203

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
	No. of stones:				
DIRECT DAMAGE (Sample Average 0.06%)	All sizes	$.63 \times 10^{-5}$	.035	.06	.79
	≥ 0.25 cm	$.79 \times 10^{-4}$	-.005	.17	.4
	≥ 0.50 cm	$.79 \times 10^{-4}$	-.005	.17	2.4
	≥ 0.75 cm	$.89 \times 10^{-4}$	-.0007	.17	2.5
	≥ 1.00 cm	$.22 \times 10^{-3}$	-.015	.25	3.6
	≥ 1.50 cm	$.15 \times 10^{-2}$	-.048	.46	7.3
	mass/m^2	$.21 \times 10^{-3}$	-.064	.41	6.3
	momentum/m^2	$.13 \times 10^{-6}$	-.066	.45	7.1
	kinetic energy/m^2	$.14 \times 10^{-2}$	-.061	.48	7.8
DEFOLIATION (Sample Average 14.9)	All sizes	$.55 \times 10^{-3}$	12.7	.17	2.4
	≥ 0.25 cm	$.73 \times 10^{-2}$	8.8	.55	9.3
	≥ 0.50 cm	$.73 \times 10^{-2}$	8.9	.55	9.3
	≥ 0.75 cm	$.79 \times 10^{-2}$	9.5	.53	8.9
	≥ 1.00 cm	$.13 \times 10^{-1}$	10.4	.52	8.5
	≥ 1.50 cm	$.30 \times 10^{-1}$	12.7	.32	4.7
	mass/m^2	$.63 \times 10^{-2}$	11.1	.42	6.6
	momentum/m^2	$.30 \times 10^{-5}$	11.9	.37	5.7
	kinetic energy/m^2	$.26 \times 10^{-1}$	12.6	.31	4.7
TOTAL LOSS OF YIELD (Sample Average 3.1%)	All sizes	$.26 \times 10^{-3}$	2.1	.24	3.4
	≥ 0.25 cm	$.30 \times 10^{-2}$	.69	.66	12.4
	≥ 0.50 cm	$.30 \times 10^{-2}$	.70	.66	12.4
	≥ 0.75 cm	$.34 \times 10^{-2}$	.88	.66	12.6
	≥ 1.00 cm	$.58 \times 10^{-2}$	1.2	.66	12.6
	≥ 1.50 cm	$.13 \times 10^{-1}$	2.2	.40	6.2
	mass/m^2	$.27 \times 10^{-2}$	1.6	.53	8.8
	momentum/m^2	$.13. \times 10^{-5}$	1:9	.46	7.4
	kinetic energy/m^2	$.11 \times 10^{-1}$	2.2	.39	6.0

D_n, was worth examination. These also were used in the regression program, D is obtained by ranking all the stones (at a point) by order of size, counting off, starting from the largest, n stones and noting the diameter of the nth. The subscript n denotes the number of stones (ft) which are larger than D . This can be cast in metric terms (m^{-2}) by multiplying n by 10.75. The resulting regressions are shown in Tables 3a through 3f.

The strangeness of some of the regressions are obvious. To discuss them in detail would be to go over some of the earlier discussions and will be foregone. Certain results, for example, the negative slope for the regression giving plant damage for early soybeans, are clearly unacceptable.

Overall, the regression equations reflect the noisiness which was anticipated. There is, nevertheless, some reasonableness to the comparative values of the parameters. For example, in Table 2a, under direct damage, the correlation coefficients are all reasonably high, slightly higher for the smaller threshold sizes than for the larger. This corroborates one's prior understanding of the sensitivity of soybeans to hail damage; large stones and large energy values are not the key to the damageability of this rather delicate crop. For direct damage to early corn (Table 2d) the correlation coefficients are not as high but they do increase with increasing threshold stone diameter, supporting one's notion of the greater robustness of corn as compared to soybeans. For late corn (Table 2e) there was no direct damage observed. The very slight decrease of the correlation coefficients for defoliation with increasing threshold size is reasonable and suggests that all measurable stones contribute to

Table 3a. Results of regression analyses for nth ranked stone diameter predictor types.

EARLY SOYBEANS -- SAMPLE SIZE = 38

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
	No. of stones:				
DIRECT DAMAGE	D_{max}	4.5	-3.5	.68	5.5
	D_{20}	7.4	-1.2	.74	6.5
	D_{40}	8.7	-1.2	.71	6.0
	D_{60}	10.2	-1.2	.70	6.0
	D_{80}	10.6	-1.0	.70	5.9
	D_{100}	10.8	+ .28	.64	5.0
	D_{200}	14.1	2.3	.52	3.6
	median	4.5	5.1	.12	.70
PLANT DAMAGE	D_{max}	-6.8	23.8	-.73	-6.5
	D_{20}	-11.7	20.7	-.83	-8.9
	D_{40}	-14.4	21.4	-.85	-9.5
	D_{60}	-17.0	21.4	-.84	-9.3
	D_{80}	-17.0	20.8	-.81	-8.2
	D_{100}	-15.0	17.4	-.64	-5.0
	D_{200}	-15.5	13.6	-.41	-2.7
	median	-13.9	12.2	-.26	-1.6
TOTAL LOSS OF YIELD	D_{max}	3.8	-1.0	.62	4.7
	D_{20}	6.3	+1.0	.66	5.3
	D_{40}	7.2	1.1	.63	4.9
	D_{60}	8.4	1.0	.63	4.8
	D_{80}	8.8	2.1	.63	4.9
	D_{100}	9.3	3.8	.59	4.4
	D_{200}	12.4	6.4	.49	3.3
	median	3.0		.08	.50

Table 3b. Results of regression analyses for nth ranked stone diameter predictor types.

SOYBEANS — SAMPLE SIZE = 167

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
	No. of stones:				
DIRECT DAMAGE	D_{max}	3.1	-2.7	.36	5.0
	D_{20}	4.0	-.62	.38	5.3
	D_{40}	5.2	-.62	.45	6.6
	D_{60}	5.7	-.44	.44	6.2
	D_{80}	7.1	-.65	.50	7.4
	D_{100}	7.5	-.59	.49	7.2
	D_{200}	15.8	-1.3	.61	10.0
	median	-1.0	+2.1	-.03	-.37
PLANT DAMAGE	D_{max}	1.1	15.0	.10	1.3
	D_{20}	1.3	15.8	.10	1.3
	D_{40}	2.5	15.4	.18	2.3
	D_{60}	2.8	15.4	.18	2.3
	D_{80}	2.9	15.6	.17	2.2
	D_{100}	3.0	15.6	.16	2.1
	D_{200}	3.8	15.8	.12	1.5
	median	-0.28	16.6	-.01	-8.5
TOTAL LOSS OF YIELD	D_{max}	3.9	-.06	.42	5.9
	D_{20}	4.9	2.5	.44	6.2
	D_{40}	6.5	2.5	.52	7.9
	D_{60}	7.0	2.7	.50	7.4
	D_{80}	8.5	2.6	.56	8.6
	D_{100}	9.1	2.6	.55	8.4
	D_{200}	16.9	2.2	.61	9.8
	median	-1.2	5.8	-.03	-.42

Table 3c. Results of regression analyses for nth ranked stone diameter predictor types.

ALL STAGES SOYBEANS -- SAMPLE SIZE = 205

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
	No. of stones:				
DIRECT DAMAGE	D_{max}	3.9	-3.6	.51	8.5
	D_{20}	5.4	-1.1	.52	8.6
	D_{40}	6.5	-.89	.56	9.6
	D_{60}	7.2	-.73	.54	9.1
	D_{80}	8.4	-.86	.59	10.3
	D_{100}	8.8	-.59	.55	9.4
	D_{200}	15.8	-.72	.59	10.3
	median	.96	+2.5	.03	.37
PLANT DAMAGE	D_{max}	-3.0	20.0	-.30	-4.4
	D_{20}	-3.5	17.7	-.26	-3.8
	D_{40}	-3.2	17.0	-.21	-3.1
	D_{60}	-3.5	16.9	-.20	-2.9
	D_{80}	-4.0	17.0	-.21	-3.1
	D_{100}	-3.0	16.4	-.14	-2.0
	D_{200}	-2.6	15.8	-.07	-1.0
	median	-4.7	16.1	-.10	-1.4
TOTAL LOSS OF YIELD	D_{max}	3.7	+ .02	.47	7.7
	D_{20}	5.3	2.2	.50	8.3
	D_{40}	6.5	2.3	.55	9.4
	D_{60}	7.2	2.5	.53	9.0
	D_{80}	8.3	2.4	.57	10.0
	D_{100}	9.1	2.6	.56	9.7
	D_{200}	15.7	15.8	.58	10.1
	median	-.03	16.1	.0	.01

Table 3d. Results of regression analyses for nth ranked stone diameter predictor types.

EARLY CORN -- SAMPLE SIZE = 61

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
	No. of stones:				
DIRECT DAMAGE	D_{max}	.40	-.51	.43	3.6
	D_{20}	.54	-.22	.41	3.5
	D_{40}	.61	-.17	.40	3.3
	D_{60}	.77	-.19	.42	3.6
	D_{80}	.83	-.17	.43	3.6
	D_{100}	1.2	-.22	.49	4.3
	D_{200}	2.7	-.31	.57	5.3
	median	-.27	+.23	-.03	-.22
DEFOLIATION	D_{max}	3.3	8.5	.21	1.6
	D_{20}	7.2	8.8	.33	2.7
	D_{40}	7.6	9.8	.29	2.3
	D_{60}	6.3	11.2	.20	1.6
	D_{80}	6.9	11.3	.21	1.7
	D_{100}	8.7	11.3	.21	1.7
	D_{200}	-12.7	16.7	-.15	-1.2
	median	-19.5	17.1	-.13	-1.0
TOTAL LOSS OF YIELD	D_{max}	.74	.62	.32	2.6
	D_{20}	1.2	1.0	.37	3.0
	D_{40}	1.4	1.1	.37	3.0
	D_{60}	1.6	1.2	.34	2.8
	D_{80}	1.5	1.3	.32	2.6
	D_{100}	2.4	1.1	.40	3.3
	D_{200}	1.1	1.7	.09	.71
	median	-2.6	2.3	-.12	-.91

Table 3e. Results of regression analyses for nth ranked stone diameter predictor types.

LATE CORN ---- SAMPLE SIZE = 142

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
	No. of stones:				
DEFOLIATION	D_{max}	11.1	-2.5	.45	6.1
	D_{20}	12.8	+5.9	.51	7.1
	D_{40}	14.0	+7.4	.50	6.8
	D_{60}	15.6	8.0	.50	6.9
	D_{80}	17.6	8.1	.55	7.7
	D_{100}	21.0	8.0	.58	8.5
	D_{200}	33.5	7.7	.64	10.0
	median	38.7	8.8	.47	6.3
TOTAL LOSS OF YIELD	D_{max}	3.9	2.4	.40	5.2
	D_{20}	5.0	1.0	.50	6.9
	D_{40}	5.9	.42	.53	7.4
	D_{60}	6.8	.59	.55	7.8
	D_{80}	7.7	.63	.60	8.9
	D_{100}	8.3	.89	.58	8.5
	D_{200}	14.9	.38	.72	12.2
	median	19.6	.48	.60	8.8

Table 3f. Results of regression analyses for nth ranked stone diameter predictor types.

ALL-TYPES CORN -- SAMPLE SIZE = 203

	PREDICTOR	SLOPE	INTERCEPT	CORRELATION COEFFICIENT	t-RATIO
	No. of stones:				
DIRECT DAMAGE	D_{max}	.23	-.32	.33	5.0
	D_{20}	.22	-.10	.17	3.9
	D_{40}	.23	-.08	.25	3.6
	D_{60}	.26	-.06	.25	3.6
	D_{80}	.28	-.06	.25	3.7
	D_{100}	.33	-.05	.26	3.8
	D_{200}	.43	-.03	.21	3.1
	median	-.08	+ .07	-.02	-0.35
DEFOLIATION	D_{max}	6.7	3.9	.33	5.0
	D_{20}	10.6	7.1	.44	7.0
	D_{40}	11.6	8.3	.42	6.6
	D_{60}	12.6	9.1	.40	6.3
	D_{80}	14.0	9.1	.43	6.8
	D_{100}	17.5	8.9	.47	7.5
	D_{200}	25.8	9.4	.45	7.1
	median	31.4	1.0.0	.33	5.0
TOTAL LOSS OF YIELD	D_{max}	2.0	-.09	.29	4.3
	D_{20}	3.4	+ .64	.42	6.6
	D_{40}	4.2	.80	.45	7.1
	D_{60}	5.0	.83	.47	7.6
	D_{80}	5.6	.87	.51	8.3
	D_{100}	6.6	.90	.52	8.6
	D_{200}	25.8	-.03	.65	12.0
	median	31.4	+ .07	.53	9.0

the defoliation. The slightly higher correlation coefficients for total loss of yield, which is a function of the defoliation, can only be a sampling quirk.

The D_n regressions of Table 3 show very slightly higher correlations for early soybeans (Table 3a) than those of Table 2a, and slightly lower ones for late soybeans (Table 2b, vs Table 1b). The results at least suggest that there is enough value in the D concept to warrant further examination.

Comparison with previous results is only possible for the cases of total loss of yield. From Table 4 we see that the agreement between Garcia, <u>et al.</u> (1976) and Changnon (1971) for the dependence of corn loss on kinetic energy is fair, and the present results agree poorly with both of them. The same is true for the dependence of corn loss on numbers of stones greater than 1/4 inch (or 0.5 cm), although the present results for late stages approach the other two. For stones greater than 1/2 inch (or 1.0 cm) the agreement between present results and Garcia's is poor. Poor agreement is noted between previous and present results for soybean loss as a function of kinetic energy, while the results for the number of stones greater than 1/4 inch (or 0.5 cm) approach agreement for the early stages.

F. <u>The Significance of Intercorrelation of the Spectrum</u>

The correlation matrix which is generated by the statistical program enables us to make some observations about the significance of kinetic energy, momentum and mass, the spectrum integrals which are often used as damage predictors. Table 5 shows the simple intercorrelation

Table 4. Comparison of regression equations for total loss of yield (L percent) for several parameters.

	Changnon, 1971	Garcia *et al.*, 1976	Present Study
CORN			
S = no. of stones/m^2 of dia > 1/4" or 0.5 cm	May: $L^* = .0145\ S - 16.7$ June-August: $L = .0123\ S - 0.57$	All stages: $L = .011\ S + 4.87$	Early stages: $L = .001\ S + 1.21$ Late stages: $L = .0079\ S + 8.3$ All stages: $L = .003\ S + 0.7$
S = no. of stones > 1/2" or 1.0 cm		All stages: $L = .07\ S + 7.84$	All stages: $L = .007\ S + 3.5$
Kinetic energy (J/m^2)	July-August: $L - .87\ E - 2.3$	All stages: $L = .16\ E + 4.99$	Early stages: $L = .0017\ E + 1.72$ Late stages: $L = .034\ E + 1.38$ All stages: $L = .01\ E + 2.20$
SOYBEANS			
S = no. of stones/m^2 of dia > 1/4" or 0.5 cm	May-June: $L - .045\ S - 9.7$ July-August: $L - .012\ S - .96$		Early stages: $L = .042\ S + 2.4$ Late stages: $L = .004\ S + 2.8$ All stages: $L = .004\ S + 2.8$
Kinetic energy (J/m^2)	May: $L - 3.77\ E - 42.3$ June: $L - 4.3\ E - 1.89$ July-August: $L - 1.08\ E - .78$		Early stages: $L = .011\ E + 4.3$ Late stages: $L = .029\ E + 3.9$ All stages: $L = 0.15\ E + 4.5$

Table 5. The hail spectral simple correlation matrix for all cases of corn damage.

	Number of Stones								
	all sizes	≥0.25 cm	≥0.50 cm	≥0.75 cm	≥1.00 cm	≥1.50 cm	mass	momentum	kinetic energy
all stones	1.00								
≥0.25 cm	.54	1.00							
≥0.50 cm	.54	.99	1.00						
≥0.75 cm	.52	.99	.99	1.00					
≥1.00 cm	.43	.95	.96	.97	1.00				
≥1.50 cm	.22	.65	.65	.67	.79	1.00			
mass	.38	.85	.85	.87	.93	.94	1.00		
momentum	.32	.77	.77	.79	.88	.97	.99	1.00	
kinetic energy	.27	.68	.68	.70	.81	.97	.96	.99	1.00

matrix for the 205 cases of corn damage encountered (there is some repetition in this sample because the same hail spectrum can be paired with more than one damage case). The first six parameters are concerned with numbers of stones exceeding specified sizes. The last three are the mass, momentum and energy integrated over the spectrum. These integral quantities are all integrals of high powers of the stone diameter (D^3, $D^{3,5}$, and D^4, respectively), and hence their values are dominated by the large diameter parts of the spectrum. These quantities are poorly (.27 to .38) correlated with the total number of stones but as the size threshold increases the correlations increase to very high values. The three integral quantities are also very highly correlated with each other, one will note. Thus, seeking to find which of the three is a better determinant of crop damage is probably not a fruitful activity.

It suggests, too, that the hail mass measurement employed in NHRE could have been as effective an index of damage potential as kinetic energy would have been. The worry of some that hail mass reductions due to seeding could be accompanied by kinetic energy increases appears unrealistic, at least for Illinois. The weaker, but nevertheless high, correlations between the integrals and the stone-number parameters can be taken as explaining the overall fair performance of these integrals in predicting damage. That is to say, the degree to which they predict well reflects the degree to which they are correlated with the more fundamental stone-number parameters.

G. Direction of Hailstone Arrival

For each hailpad, the analysts estimated from the orientation of the elongated dents the average direction from which the hailstones arrived. This is easily accomplished for most hailpads because, in general, the wind direction is fairly uni-directional for the brief duration of the hail. A primary direction was clear for 137 (68%) of the 201 hailpads, but was indeterminate or variable for 64 pads (32%).

The relative frequency of occurrence of the hailstone arrival direction has been determined and is shown as the solid curve of Figure 11. Also shown in Fig. 11 is the relative frequency of occurrence of direction of hailstreak motion (orientation of major axis of hailstreak) for 421 hailstreaks analyzed by Changnon and Towery (1972). The hailstreak directional distribution is narrower than that for hailstones and peaks at 270°. The hailstones tend to arrive from more northerly directions, supporting the observation of Morgan and Towery (1976) that hailstones most often are blown toward the right of the apparent direction of advance of the hail zones.

This finding suggests that the direction of arrival of the hailstones cannot be inferred, case by case, from the hailstreak orientation, so that attempts to relate crop row orientation and streak orientation to crop damage cannot succeed.

The hailstone arrival-direction distribution of Figure 11 is the first to be published, and can be of some use. The fact that it peaks (allowing for some noisiness in the data due to sampling) at 315° (NW) suggests that there would be no long range benefit, in Illinois, from preferentially planting crops either N-S or E-W. It will be very interesting to see an analogous distribution from NE Colorado and other High Plains locations.

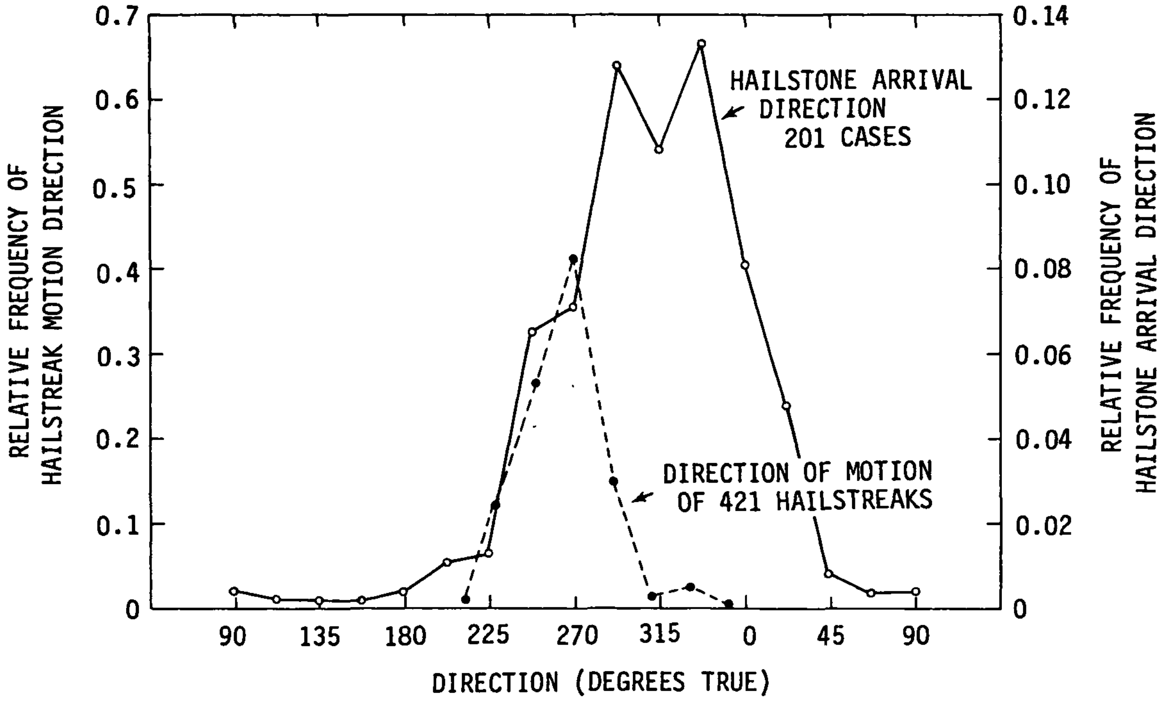

Figure 11. Frequency of hailstreak motion (left abscissa) and hailstone arrival (right abscissa) versus direction (true degrees).

V. CONCLUSIONS AND RECOMMENDATIONS

The observations derived from this extensive hail and crop-damage data collection program in 1975 show very noisy relationships between crop damage and hailfall parameters. A limited range of values of loss of yield was experienced during the field program with most generally below 20%. This is a critical problem affecting the results herein and other work suggests that relationships improve in the higher loss values. The poor relationships found in the 1975 data are probably due to a combination of:

a) uncertainties in hail measurements due to the variability of the hail itself;

b) uncertainties due to separation between the hail measurement and the crop-loss assessment;

c) uncertainties in the assessments of crop loss;

d) failure to measure all relevant factors, specifically the lack of estimates of wind effects;

e) failure to define the proper functions of the hailfall spectrum for use as damage predictors.

The following recommendations are considered essential for further clarification of the relationship between crop damage and hailfall parameters:

1) Future studies of damage-hail relations should include instruments, such as hailcubes, designed to measure the effects of windblown hail.
2) The absence of cases with high values of crop loss is the most serious shortcoming in the data sample. This raises the question of how long a project of this type must run in order

to have a high probability of sampling severe crop damage. The occurrence of severe (>60% loss of yield) crop damage is a relatively rare event over a small area and we have only recently acquired data to estimate just how rare. A research project investigating the use of aerial photography to assess crop damage, funded by an insurance company in Illinois, has been in progress for 3 years (Towery *et al.*, 1976) and, with some simple assumptions, the records of that project can provide a rough estimate of required project length.

The objectives of the project required that storms with severe damage be investigated. During the three years only 11 such storms were found over the entire state of Illinois (56,400 sq mi). There were 3 in 1974, 6 in 1975, and 2 in 1976, for an average per year of 3.7. Considerable effort was made to seek out these storms and it is unlikely that any others went undetected.

The eleven storms ranged in size from 4 to 140 mi^2. The average was 30 mi^2 and the median 13 mi^2. Four storms of average size each year would produce damage over 120 mi^2 or 0.2 percent of the area of the state. This is the probability that a given square mile in Illinois will experience such a storm. The 625 mi^2 hailpad network occupies 1.1% of the state, in which there are annually 4 severe crop damage events, on the average. The average number of such events in the network would then be .044. In 25 years the average accumulated number would be one and such would be the length of program required to be certain ≥ of observing such an event. This means that the annual probability is 4 percent. It thus would not be reasonable to pursue this type of field study in Illinois. The improvement in this situation to be accrued by attempting this project in a higher hail frequency area like Colorado where the likelihood can be estimated from some insurance data furnished by Fosse (1976). He shows that, for corn in Illinois two percent of claims paid are for damages exceeding 70%, whereas for wheat in Colorado the same figure becomes 20%, a tenfold Increase, The greatest such increase for corn areas, according to Fosse, would be found in South Dakota where six percent of claims paid on corn are for losses exceeding 70%, a threefold increase. For soybeans, the Illinois figure is two percent and the greatest occurs in Minnesota where 11% of soybean losses are paid on damages in excess of 70%. That amounts to slightly more than a fivefold increase. Thus, there are areas much more suitable for the pursuit of small area field studies aimed at establishing hail-crop damage functions than Illinois.

3) There is some divergence between the various groups who collect field data with hailpads concerning the calibrations which are used and the manner in which these can best be determined. Some effort toward resolution of this divergence would be well invested.

4) Future studies should emphasize more the relationship between hail and the estimates of immediate physical damage, and less that between hail and the predicted loss of yield.

5) The simplifying assumptions used both in discussing the effects of wind on damage and in the analysis of hailpads and hail cubes are subject to investigation. Measurements of the horizontal and vertical velocity components of real hailstones should be made. This could be done by equipping a chase vehicle with high-speed cinematographic equipment and photographing hailfalls against a suitable background.

6) A careful evaluation should be made, again by high speed cinematography, of the effects of wind deformation around the hailpads and hail cubes on their estimates of hailfall parameters.

7) Further theoretical consideration of the damage process and the influence of the wind on it, with more serious attempts to realistically model the crops and the hail, is in order.

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Edna M. Anderson supervised the processing and inspection of all 4,500 pads exchanged on the network. She painstakingly supervised the large number of students employed to measure and count all the dents on the hail pads.

Clifford M. Hoag visited each site and made all of the loss assessments used for this study. The use of his 18 years of experience provided us with excellent damage data. This project would not have been possible without his help.

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VII. PROJECT PERSONNEL

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Margaret Evangelista	Hailpad Analyst
Sandy Miller	Hailpad Analyst
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