Final Report *July 1970*

AGRICULTURAL VULNERABILITY IN THE NATIONAL ENTITY SURVIVAL CONTEXT

Prepared for:

OFFICE OF CIVIL DEFENSE
OFFICE OF THE SECRETARY OF THE ARMY
WASHINGTON, D.C. 20310

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OCD Work Unit 3535A

STANFORD RESEARCH INSTITUTE
Menlo Park, California 94025 · U.S.A.

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Detachable Summary

AGRICULTURAL VULNERABILITY IN THE NATIONAL ENTITY SURVIVAL CONTEXT

By: STEPHEN L. BROWN and PAMELA G. KRUZIC

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DETACHABLE SUMMARY

1. Title. AGRICULTURAL VULNERABILITY IN THE NATIONAL ENTITY SURVIVAL CONTEXT

   Authors: Stephen L. Brown and Pamela G. Kruzic

   Contractor: Stanford Research Institute

   Contract Number: DAHC 20-69-C-0186

   SRI Project Number: EGU 7979-001

   Date: July 1970

2. Type of Study. This study is an analysis of the sensitivity of agricultural damage assessment results to variations in assumptions.

3. Key Descriptors. The key descriptors are nuclear attack, agricultural vulnerability, damage assessment, sensitivity analysis, fallout, fertilizer, livestock, crops.

4. Objectives. Determine the range of validity of previous assessments of agricultural vulnerability to nuclear attack. Test the assessments for their sensitivity to variations in uncertain parameters and assumptions.

5. Assumptions, Analytical Techniques, and Models. Standard case assumptions regarding attack types, attack efficiencies, and attack weights, as well as vulnerability criteria, were taken from previous reports in this series. Worst case assumptions were postulated on the basis of an intuitive assignment that only ten percent probability of an even worse case existed. The models for agricultural damage assessment were simplifications of previously proposed agricultural

10. Recommendations. In future damage assessments assume that the duration of vulnerability is the entire growing season. Assume a high fraction of ground bursts for any type of attack. Research priorities should be higher for total/gamma dose multiplier than other vulnerability criteria. Look for break points in the 1,000-10,000 MT range. Reexamine the fertilizer outlook on a recurring basis because of the significant changes occurring.

11. Contribution. This study has shown that presently available damage assessment methods for agriculture are suitable unless parameters are found to exceed certain limiting values. Relative sensitivities have indicated which parameters are most deserving of further research. The increasing vulnerability of agriculture because of dependence on fertilizer suggests careful consideration of post-attack management of this resource.

12. Key References. The key references are:

- Stephen L. Brown, Hong Lee, and Oliver S. Yu, Postattack Food Production and Food and Water Contamination, SRI Project MU 6250-050, Stanford Research Institute, June 1968

- Stephen L. Brown, and Ulrich F. Pilz, U.S. Agriculture: Potential Vulnerabilities, SRI Project MU 6250-052, Stanford Research Institute, January 1969

- Chemical Economics Handbook, Stanford Research Institute, 1968 and 1969

- L. B. Nelson, ed., Changing Patterns in Fertilizer Use, Soil Science Society of America, 1968

13. Costs Associated with Recommendations. None

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ABSTRACT

Two separate studies of agricultural vulnerability are reported. One is a sensitivity analysis of agricultural damage assessment. Several important input assumptions are tested for their effect on the results of the damage assessment. The other study identifies trends in the production and utilization of fertilizers and relates them to changes in the vulnerability of agricultural production through potential loss of the fertilizer input.

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ACKNOWLEDGMENTS

The authors are indebted to George Walter and E. L. Sharman of the U.S. Department of Agriculture, both for their comments in the early phases of the work and for their assistance in evaluating some sources of data.

We also gratefully acknowledge the assistance of Lyle M. Schump, Lung-Hsin Wu, and Christopher Kendall for reducing much of the data.

INTRODUCTION

This is the third in a series of reports on agriculture vulnerability in the context of national entity survival. The first was Postattack Food Production and Food and Water Contamination, which presented detailed damage assessments for agriculture based on two specific hypothetical nuclear attacks.[1*] The second was U.S. Agriculture: Potential Vulnerabilities, which presented sensitivity analyses of the original results to date of attack, foliar fallout contamination parameters, and radiation vulnerability criteria, as well as a semi-quantitative discussion of the importance of several agricultural practices and a preliminary methodology for the study of geographical imbalances.[2] Much of the work in the present study depends heavily on the results presented in those reports, and their analyses will not be repeated here. Additional background information is contained in Analysis of National Entity Survival[3] and Critical Factors Affecting National Survival,[4] both produced also as part of continuing NES (National Entity Survival) studies.

The essential conclusions from the previous two agriculture studies were as follows. First, for the specific attacks assigned, basic agricultural resources (food and feed crop production and livestock herds) survived about as well as, or somewhat better than, the national population. Secondly, this conclusion was not particularly sensitive to the date of attack, the model of foliar contamination proposed, or the radiation dose criteria used. The simple analysis of geographical imbalances also did not seem to place unusual demands on the transportation system.

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* References are listed at the end of this report.

Although fertilizers, pesticides, electricity, and especially petroleum, were all acknowledged to be essential for high yields of crops and livestock, the analysis was not able to demonstrate that the production and distribution of these resources would necessarily be so reduced as to threaten food production seriously. The management of somewhat scarce resources seemed to be the most likely element of the system to fail, and the one most responsive to preattack planning and countermeasures.

These conclusions have been reviewed by a variety of knowledgeable critics, with reactions ranging from the opinion that the conclusions should have been obvious from the outset to the concern that serious underestimates of the effects of nuclear attack on agriculture had been made. Confronted with such a diversity of opinion, we decided that it would be worth while to test the sensitivity of our conclusions to variations in our assumptions, which admittedly are for the most part based on sparse and often contradictory information. The results of these tests are presented in this report. Two principal lines of attack were chosen. First, a direct assault on the question of the damage to crops and livestock from fallout was made by varying disputed parameter values from the standard case used in the previous studies to a "worst case." The worst case values were chosen to correspond roughly to an intuitive assignment that the probability for the parameter to be worse than the worst case value is less than 10 percent.

A second approach was to single out one particular agricultural input for a more detailed analysis than was possible in Ref. 2. If the detailed analysis should give a grossly different interpretation of the magnitude of the problem than did the earlier analysis, then concern about our assumptions would be clearly justified. If, on the other hand, the conclusions were relatively consistent with one another, somewhat ›re confidence could be placed in our simplified methodology, even though its validity for practices other than the one chosen would not have been demonstrated conclusively. We chose fertilizers for study for two reasons. First, our initial analysis had indicated that fertilizer losses might cut agricultural production by half in the worst case, placing it in the group with the more important resources; also the question of allocating production among alternative demands would be less complicated than for petroleum and electric power.

The two investigations were carried out independently of one another and are reported in Parts I and II, respectively.

SUMMARY

The principle objective of the current study was to test the range of validity of the findings of previous studies in this series on the vulnerability of agriculture to nuclear attack. Two independent research tasks were conducted toward this objective. The first consisted of sensitivity analyses of the most uncertain parameters of the damage assessment system for livestock, food crops and feed crops. The second made a more complete investigation of the importance of fertilizer to crop production and the vulnerability of fertilizer production to nuclear attack than was possible in the previous study.

The parameters varied in the sensitivity analysis were weight of attack (100 MT to 100,000 MT), duration of assumed vulnerability (vulnerable period, growing period, or one year), type of attack (counterforce or mixed counterforce-countervalue), efficiency of attack (unity or maximum), lethal dose (standard or worst case), dose rate multiplier (standard or worst case), total/gamma dose multiplier (standard or worst case), and lethal/threshold dose multiplier (standard or worst case). The dependent sensitive variable was the fraction of a given agricultural resource lost as a result of fallout damage. Twenty-two food and feed crops and five livestock resources were included in the analysis.

The most sensitive assumption was clearly whether the attack would be aimed so as to do maximum damage to agriculture or would instead be more or less random in design with respect to agriculture. The fact that the same can be said with even more truth of other key resources leads us to believe that agriculturally efficient attacks are very unlikely. On an individual crop basis, the second most important assumption is probably

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the date of attack and the season over which the crop is vulnerable to fallout. Since crops vary markedly as to the most critical date of attack, the sensitivity is somewhat reduced when aggregate measures are used. Therefore a reasonably conservative approach would be to assume that the entire growing season is vulnerable.

The type and weight of attack are parameters of intermediate sensitivity. The difference in the effectiveness between counterforce and mixed attack depends principally on the higher fraction of surface bursts for counterforce attacks. The increase in resource loss with attack weight is gradual, becoming steepest in the range 1,000 MT to 10,000 MT, where it is possible that a break point has been identified.

Lethal dose, dose rate multiplier, and total/gamma dose multiplier have equal sensitivities, all fairly low. Of those three (on the basis of relative uncertainties) the total/gamma dose multiplier would seem to be most deserving of further research, and the dose rate multiplier least deserving. The ratio of lethal to threshold doses has the least effect on the fraction of resource lost.

The principal method of approach of the fertilizer study was to discover trends in the manufacture and use of fertilizers that would alter the vulnerability imputed to this facet of agriculture by the earlier study, which was based on older data sources. Most of the trends were in directions that would increase the vulnerability of agriculture.

An almost universally recognized trend in agriculture is the production of more food from less land with less direct labor. The drive for ever higher yields has resulted not only in higher demands for the standard types of fertilizers, but for new formulations designed for specific uses. Yields are increasing not so much because of increased use of fertilizer as because of the combined use of fertilizer with special soil cultivation techniques, irrigation, trace nutrients, and new plant varieties. The net effect is the increasing dependence of agriculture on fertilizers, particularly specialized formulations.

The most significant soil nutrient from the point of agricultural vulnerability is nitrogen, which is highly depleted in a single season for many of the most important crops. (Legumes are an obvious exception because they fix nitrogen in the soil.) Potash and phosphate tend to be used in relatively small fractions of that available in the soil, so that residual fertilizing capacity would be sufficient for the immediate postattack period.

The demand for special purpose fertilizers has caused two trends that are somewhat contradictory in terms of agricultural vulnerability. The complexity of the processes necessary for the special formulations has tended to give economic advantages to the large plants located close to sources of raw materials, such as natural gas for ammonia plants. On the other hand, very specialized requirements--coupled with difficulties of storage because of the seasonality of the demand--have caused smaller plants to open near the crop areas they supply. The former trend represents concentration and increased vulnerability, while the latter can probably be termed dispersal.

Trends in distribution of fertilizers are somewhat harder to assess. Manufacturers no longer mix blends at the plant, but ship the basic components in bulk to mixing plants located closer to their markets. Therefore mixing facilities are probably not very vulnerable. On the other hand, there seems to be a trend toward liquid fertilizers, which may eventually be shipped by pipeline, making analogies with petroleum (finished product) pipelines attractive.

Another petroleum analogy is that, on balance, fertilizer production is becoming concentrated in larger plants and these plants are often found near supplies of natural gas such as in Louisiana and Texas, raising the possibility of collateral damage during a petroleum refinery directed attack.

If one considers only nitrogen plants, fertilizer is much more concentrated and vulnerable than population or MVA (Manufacturing Value Added). However, the plants are typically outside metropolitan areas, and would not likely suffer much collateral damage from the more usual countervalue attacks.

Most of the above trends would result in increasing agricultural vulnerability. One factor argues for less concern, however. Even now nitrogen production capacity exceeds output by 3 to 2, and much fertilizer is exported. Manufacturers appear to be trying to develop further foreign markets, which will tend to encourage even more capacity to be built. In case of nuclear attack, then, a relatively small fraction of capacity surviving may be able to supply all domestic needs, assuming that distribution and management function properly.

Part One

SENSITIVITY STUDIES

by

Stephen L. Brown

I THE CONCEPT

The Office of Civil Defense is continually faced with decisions about how to allocate its scarce resources to best serve its mission, which is (in highly simplified terms) to make preparations that would lessen the impact of nuclear war on the nation if an attack should in fact occur. The allocations must be made in such a way that the net estimated improvement in the nationwide postattack situation is maximized, no matter what budget may be available for civil defense purposes. Both allocations for plans and operations and for research are affected by such considerations. A major purpose of the NES (National Entity Survival) studies is, therefore, the identification of those elements of the national entity that are most vulnerable, so that additional research or operational preparations in those areas will be of most benefit to the nation. The emphasis, to repeat, is on the perceived long term national benefit, whether or not specific preparations may seem to benefit preferentially some particular group. In this context, the NES approach is in effect a large scale sensitivity analysis, in which is embedded many smaller scale analyses.

The agricultural part of the NES is, therefore, undertaken with the intention of assessing the vulnerability of agriculture relative to other elements of the national entity and, within the sphere of agriculture, to identify the most vulnerable factors and the most sensitive uncertainties. A clearly identified vulnerability would be a subject for operational preparations, whereas a highly sensitive uncertainty would be a subject for additional research.

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The present research task, as noted in the Introduction, is directed at appraising the sensitivity of agricultural damage assessment to uncertainties in the parameters of the models. In the sense that many of the assumptions amount to little more than assignments of values to certain parameters, these tasks can also be called parametric analyses. The range of uncertainty that was considered here was from "standard" values, as used in the previous damage assessments, to "worst case" values, thought to be the limiting credible values. The standard values, needless to say, were thought by us, at least at the time they were set, to be the most probable values, albeit in many cases there was already a somewhat conservative bias. (For example, in the instance of beta dose calculations, no correction for self-shielding by densely planted crops has ever been applied.) The worst case values are much more difficult to set, and undoubtedly an "even worse" value for some of them will eventually be found. However, an attempt was made to choose values that would very probably be the worst (with perhaps 90 percent confidence), although such probability assignments are clearly no more than intuitive.

One parameter that has an important effect on the results is the total weight of the attack. The parametric analysis on attack weight was hoped to yield, in addition, information with respect to a possible break point, at which the results are changing very rapidly with attack weight, and above which attacks could well be characterized as having "broken" the agricultural system. Classic break points occur in systems with thresholds, as for instance an antiballistic missile defense, which may keep damage nearly to zero for any number of weapons up to some saturation level, then fails rapidly with damage increasing sharply with additional numbers of weapons. Widely dispersed resources such as agriculture, on the other hand, are not likely to have well defined break points; even so, certain insights can be gained through the break point concept, as will be discussed later.

The other major uncertain parameters appear to be:

- The dose criteria at which the losses of the agricultural resources become total (the lethal doses)

- The dose criteria below which no losses occur (the threshold doses)

- The degree to which beta radiation increases the effective total dose to critical tissues (thus changing the "total/ gamma dose multiplier")

- The factor that relates standard intensities--gamma dose rates at one hour--to accumulated gamma dose (the dose rate multiplier)

- The duration of the period over which the resources are assumed to be vulnerable

Two additional uncertainties relate to attack design. In general, nuclear attacks are usually classified as counterforce (directed at strategic military targets) or countervalue (directed at a nation's resources, such as population, industry, or institutions). If the target is not agriculture, the resulting fallout patterns will often be distributed in a way that could be called "neutral" with respect to agricultural resources. Population attacks, and most other countervalue and mixed counterforce-countervalue attacks, would likely fall in this category. Counterforce attacks might be either more or less effective against agriculture than neutral attacks. Less so when the concentration of weapons covers less of the United States with fallout for a given weight of attack than does the countervalue attack, but more so when that concentration itself happens to fall in an agriculturally rich region. If agriculture itself is attacked, then the maximum damage can be inflicted if the fallout is concentrated in agricultural regions to the exclusion of other areas.

Sensitivity analyses can generally be carried out in either of two ways. The brute force method simply repeats all of the computations for each of the permissible values of each parameter. This method is attractive because of its simplicity and unambiguity. However, when the computational scheme is complex (as in the agricultural vulnerability models of Ref. 1) and the number of parameters large (about seven have been mentioned), the brute force method becomes rather unwieldy and expensive. For instance, the sensitivity analysis on date of attack, although limited to one parameter and one region of the nation, was a major undertaking.

A sophisticated method, on the other hand, operates on the partial derivatives of the computational output with respect to each input parameter, evaluated at the standard values of each parameter and at selected other parameter sets. This method has the virtues of elegance and the ability to dispense with much of the computational details necessary in the brute force method. However, this approach depends on expressing the input data and mathematical relationships in reasonably analytic form, and it becomes increasingly cumbersome as the number of discontinuities and ranges of validity* become large. The agricultural problem is characterized both by tabular data not analytically determined and by multiple ranges of validity.

A compromise approach was taken to meet the challenge of these difficulties. Basically, the brute force method was selected, but it operated on a much simplified set of data and computational procedures. The parameters were varied in only two or three steps, e.g., standard

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* Branches in the computation.

and worst case values, except in the particularly significant instance of weight of attack. The results are therefore multiple values for the fraction destroyed of the various crop and livestock resources under the standard and worst case assumptions. Intermediate results can be roughly inferred by interpolation, and relative sensitivities are only qualitatively ranked.

II ANALYSIS AND DATA BASE

The most serious shortcoming of the standard agricultural damage assessment system with respect to sensitivity analyses is that it operates on a detailed data base that gives the acreage harvested for crops and the size of herds for livestock in each of over 3,000 counties in the United States. Although for any given agricultural resource many counties can be eliminated from the data base through a cutoff criterion (such as 100 acres), the damage calculations must still be accomplished for each remaining county, then aggregated and summarized. For some resources over 2,000 counties must be considered, which makes the brute force sensitivity analysis very expensive. Thus it was necessary to find some way of characterizing the extent of dispersion of agricultural resources on a nationwide basis without resorting to a 2,000-entry table.

The most promising approach seemed to be to sort the data into a rank order on the basis of resource concentration. Since agriculture is geographically dispersed and is vulnerable to a diffuse threat like fallout, it is not appropriate to rank order the counties simply on the basis of total production, but rather on production density, defined as the total production (in acres or number of animals) divided by the area of the county (in square miles).* To this end, the areas of the counties were obtained from the County and City Data Book[6] and added to the data base.

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* The rank order sorting was carried out by an efficient sorting routine, SORTAG, developed by Richard C. Singleton of SRI.

The data now in convenient form on tape are summarized in Table 1. The data base is still founded on the 1959 Census of Agriculture[6] even though more recent data are available. It is believed that production patterns are not changing too rapidly, particularly in the aggregated form used here,* and comparability with earlier studies is more evident if no change in data base occurs. There have also been some changes in county alignments since 1959, but the compilation reflects only those in existence in 1959. The data base was first compiled in 1963,[7] but only the most important resources were studied in 1967.[1] In this study, the garden vegetables have again been included, but fruits and pasturage have not been. Current methods for field crops cannot deal adequately with tree fruits, and pasturage cannot be assigned the planting and harvesting dates necessary for the analysis.

The rank-ordered county production and the corresponding county areas were normalized by dividing by the total annual resource production and total U.S. area, respectively, to place them in fractional form. The values for the fraction of total annual production and for the fraction of total U.S. area were then cumulated to form cumulative

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* Some additional data concerning production patterns were made available by Rex F. Daly of the Department of Agriculture during the time this report was under review. The acreage from which crops are harvested has declined about eight percent since 1959. The decrease has been in large part due to reduced wheat and corn plantings. The resulting increases in crop concentration would make agriculture slightly more vulnerable to direct attack. Similarly, there are increases in the scale of livestock operations that represent increased concentration and increased vulnerability. Some mention of the latter trend was made in Ref. 2. However, both the major grains and the livestock resources are among the most widely distributed and consequently can most afford some concentration. Shifts in agricultural production by region are also being observed, but the methods used in the current study do not recognize geographical shifts except to the extent that they affect concentration.

Table 1

AGRICULTURAL DATA BASE

A. Livestock

Each record contains a region-state-county code, the national location code, the latitude and longitude of the "center" of the county, the area of the county, and the number of animals in the county for the following animals:

Chickens	Hogs & Pigs	Milk Cows	Bulls, Steers & Calves	Sheep & Lambs
11*	12	13	14	15

B. Crops

Each record contains a region-state-county code, the national location code, the latitude and longitude of the "center" of the county, the crop number code, the number of acres harvested, the yield per acre (in tons), the normal planting and harvest dates, and the area of the county. Crops included at present are:

Corn 21	Sorghum 22	Winter Wheat 23	Spring Wheat 24	Winter Oats 25
Spring Oats 26	Winter Barley 27	Spring Barley 28	Rice 29	Dry Beans 31
Soy Beans 32	Alfalfa 42	Potatoes 50	Green Peas 51	Sugarbeets 56
Tomatoes 57	Sweet Corn 61	Snap Beans 64	Cabbage 68	Dry Onions 72
Carrots 73	Lettuce 76			

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* The number below each resource is a two-digit code for that resource.

distribution functions such as shown in Figure 1.* (The illustration is exemplary and no significance should be attached to the resource chosen.)

In Figure 1, the cumulative fraction vulnerable reaches unity when sufficient area is considered. This behavior is observed whenever it is assumed that all of the resource would be vulnerable to an attack occurring at any time during the year, as would be more or less true of livestock. However, crops are much more likely to be vulnerable for only a short time, because the fallout radiation will decay to harmless levels unless the attack occurs shortly before or during the growing season. In fact, the standard assumption for the earlier crop vulnerability models was that the crop was vulnerable only during a certain fraction of its growing period. The stage of crop growth can be represented by the fractional age, f, where

$$f = \frac{AD - PD}{HD - PD} \quad . \tag{1}$$

AD is the attack date, PD the planting date, and HD the harvesting date, all in days from January 1. Unless f is between two criteria f_1 and f_5,† no loss is assumed to occur.

The rank order sorting was therefore repeated using only counties with crop planting and harvesting dates satisfying this condition when the postulated date of attack was June 15. (June 15 was the date used

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* Many of the illustrations for this report were generated directly from computer output by a cathode-ray-tube/film/xerography method called GRAPH4 developed by Bruce M. Sifford of SRI.

† f_1 occurs when the sensitive plant parts emerge from the ground and become exposed to fallout radiation. f_5 occurs when the edible portions have been fully formed and require only final ripening before harvest. Subscripts 2, 3, and 4 were assigned in Ref. 1 to other intermediate stages of crop growth.

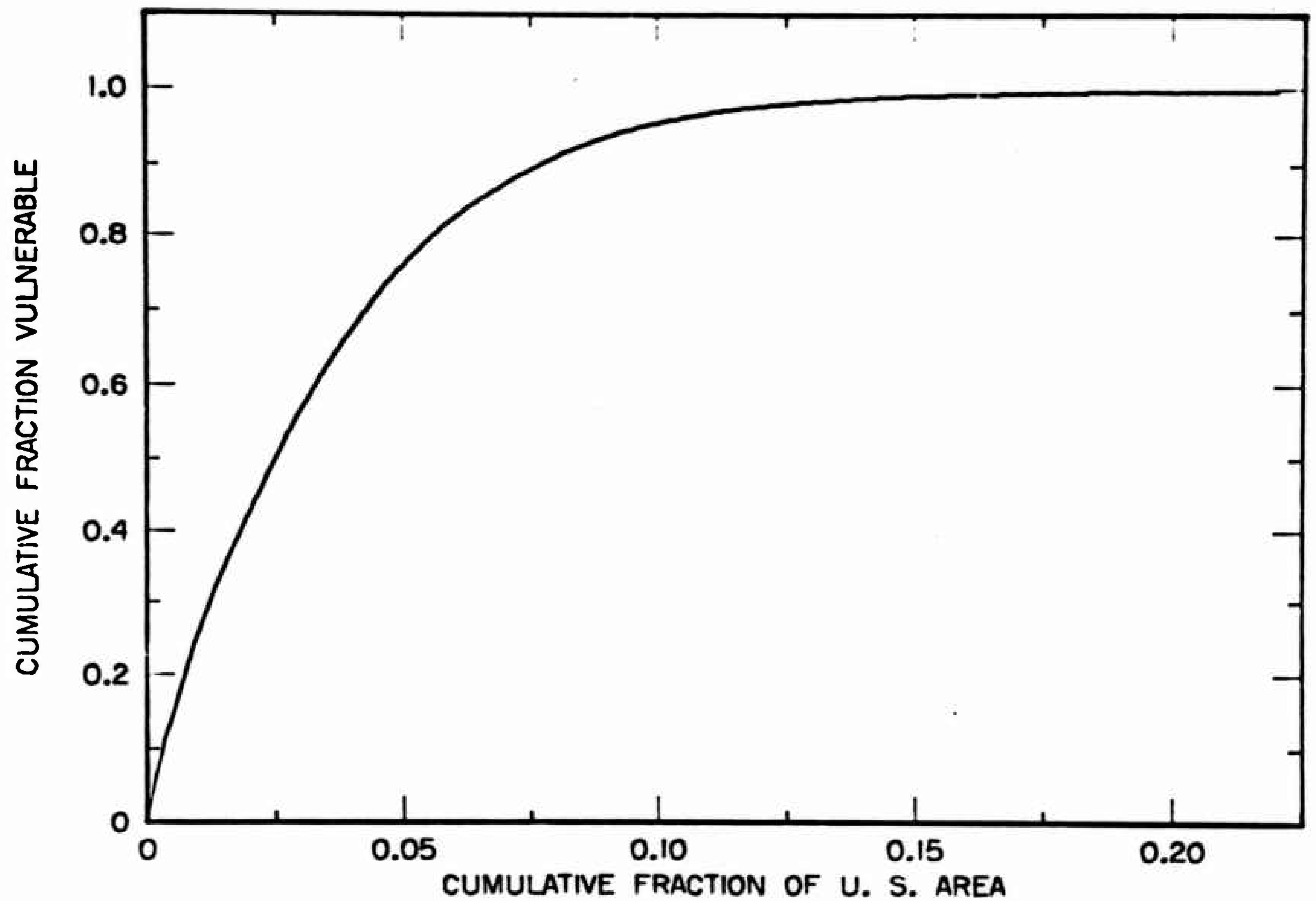


FIGURE 1 CUMULATIVE VULNERABILITY OF SOYBEANS

in the standard damage assessment of Ref. 1 and was shown in Ref. 2 to be near to the worst date of attack if all crops are considered.) The cumulative distribution functions in general do not reach unity because, under this assumption, the crops in some counties are not vulnerable on that date. Table 2 shows the values for f_1 and f_5 as taken from Ref. 1. In the case of the garden vegetables, the values were assigned conservatively, based on similarities to other crops.

An intermediate case was postulated in which the assumed duration of vulnerability was the entire growing period (from PD to HD), and the date of attack was again June 15. In this case, the values $f_1 = 0$ and $f_5 = 1$ were used for all crops rather than the values shown in Table 2, but the procedure was otherwise identical to the preceding one. This assumption also produces cumulative distribution functions that often fail to reach unity, but are everywhere greater than or equal to the functions produced by the more restricted assumption above.

The above three assumptions were each used in the construction of cumulative distribution functions for every crop, although only the first was used for livestock resources. They affect the cumulative distribution functions by limiting the set of counties in which crops are vulnerable, as illustrated by Figure 2. In this figure and in the following development, the three assumptions will be abbreviated by the statements that the duration of assumed vulnerability is the whole year (Y), the growing period (G), or the vulnerable period (V). The first (Y) case is the worst case, producing the largest number of counties that would experience crop loss if sufficient fallout was deposited upon them. The total area in such counties and the total crop production from them are accordingly also largest. The V case is the standard case and produces the smallest number of counties with vulnerable crops. Table 2 shows the number of counties with vulnerable crops under each of the three assumptions, and the corresponding fraction

Table 2

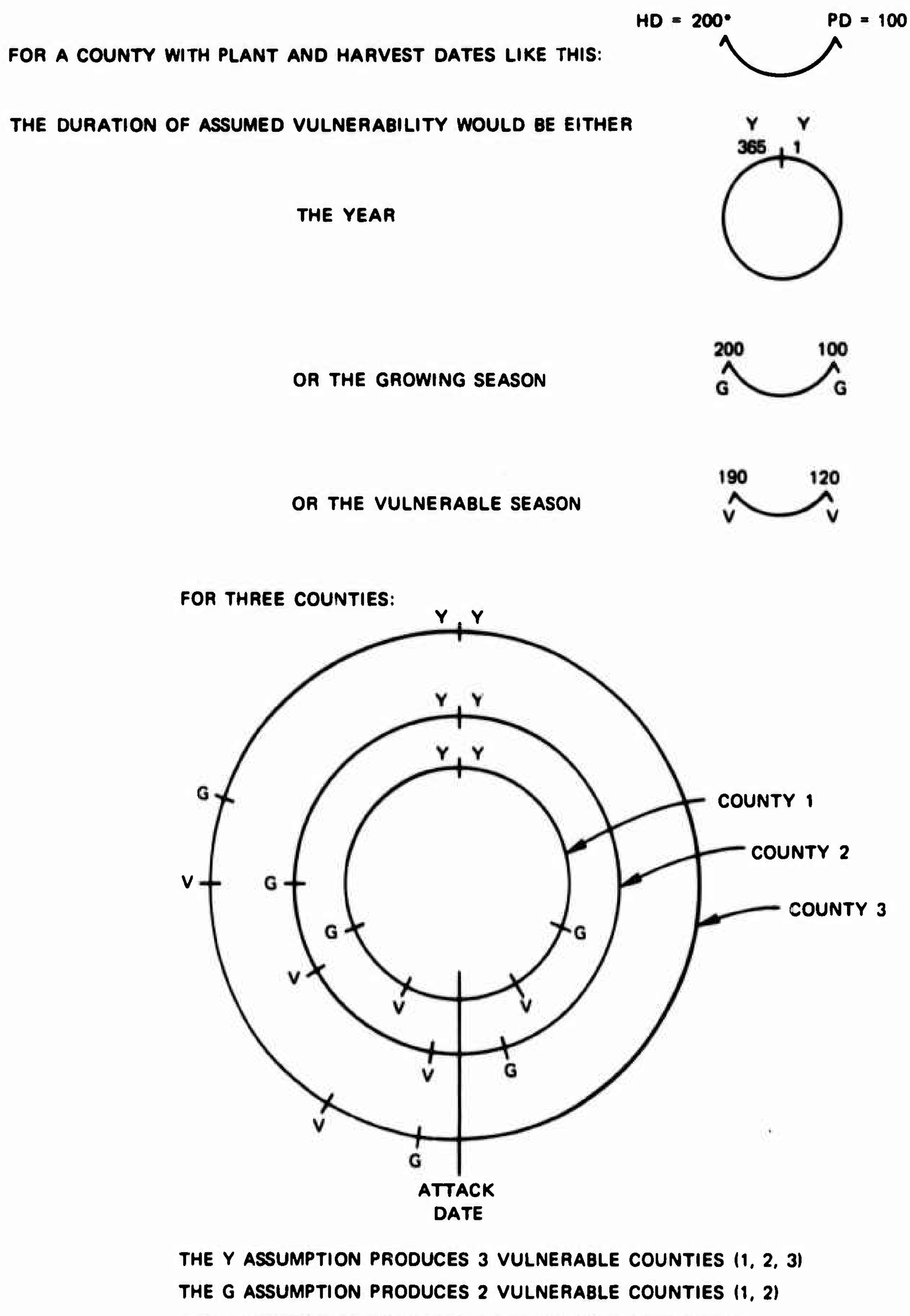
THE EFFECT OF THE DURATION OF ASSUMED VULNERABILITY ON THE NUMBER OF COUNTIES VULNERABLE

Crop	Code	f_1	f_5	Number of Counties Vulnerable			Fraction of U.S. Area		
				Y*	G	V	Y	G	V
Corn	21	.20	.74	2,818	2,818	1,320	.702	.702	.310
Sorghum	22	.20	.90	1,790	1,742	253	.444	.389	.073
Winter Wheat	23	.07	.95	2,190	1,926	1,405	.585	.545	.427
Spring Wheat	24	.17	.88	462	462	462	.237	.237	.237
Winter Oats	25	.06	.95	782	307	105	.193	.109	.076
Spring Oats	26	.15	.89	2,127	1,977	1,582	.616	.574	.514
Winter Barley	27	.06	.95	1,156	716	277	.316	.232	.163
Spring Barley	28	.14	.89	1,058	966	966	.379	.351	.351
Rice	29	.14	.91	126	126	126	.036	.036	.036
Dry Beans	31	.20	.90	89	54	0	.037	.031	.000
Soybeans	32	.20	.90	1,337	1,336	150	.221	.221	.024
Alfalfa	42	.25	.84	2,425	2,425	187	.715	.715	.027
Potatoes	50	.20	.75	609	571	211	.224	.213	.063
Green Peas	51	.20	.90	547	527	329	.091	.088	.066
Sugarbeets	56	.20	.75	221	221	199	.104	.104	.098
Tomatoes	57	.10	.99	286	247	230	.076	.059	.053
Sweet Corn	61	.29	.93	481	464	177	.122	.108	.049
Snap Beans	64	.20	.90	220	153	82	.059	.033	.014
Cabbage	68	.10	.99	110	44	23	.035	.007	.004
Dry Onions	72	.10	.99	89	73	73	.044	.039	.039
Carrots	73	.10	.99	41	21	21	.028	.018	.018
Lettuce	76	.10	.99	78	30	23	.047	.012	.011

* Y = Year

G = Growing Period--Attack Date is June 15.

V = Vulnerable Period--Attack Date is June 15.



*Days since January 1.

FIGURE 2 THE DURATION OF ASSUMED VULNERABILITY of the U.S. area represented by those counties. The numbers shown in the columns labeled Y indicate all counties that produce significant quantities of the resource. Note that for some resources, notably spring wheat, the duration of vulnerability assumption makes no difference, while for others (dry beans) it is critical. Which resources are most affected by these assumptions depends on the date of attack assumed, and the columns labeled G and V would change appreciably if an attack date other than June 15 were used.

Curves generated by the cumulative rank order technique must always have the general features shown in Figure 1--monotonic increasing value, monotonic decreasing slope--but the similarity of the shapes of all the curves generated suggested that a relatively simple analytic function might fit them. The function suggested is

$$f_v = \alpha (1 - e^{-\lambda f_a}) \quad (2)$$

where f_v is the fraction of the agricultural resource vulnerable, f_a is the associated fraction of the area of the United States, and α and λ are constants depending on the resource type and the duration of assumed vulnerability. The value assigned to α is the maximum fraction of the crop vulnerable under the assumed conditions and depends only on the assumed date of attack and the assumed duration of vulnerability, whereas λ is a measure of the concentration of the resource and, as will be discussed later, is related to the maximum efficiency that could be obtained by an attack directed against that resource.

In the attempt to fit the data with Eq. (2) the value of α was fixed by the maximum observed vulnerable fraction, and λ was then computed by assigning equal weights to points spaced evenly in f_v and minimizing the sum of squared percentage errors. The resulting fits ranged from very good to barely adequate. Barely adequate, in this case, means that the error, expressed now as a percentage of the maximum value α, never exceeded about 30 percent, which is acceptable when compared with other sources of error. The equation tends to overestimate f_v most in the range $f_v = 0.6\alpha$ to 0.8α, and underestimate f_v most in the range $f_v = 0$ to 0.2α. An example of a barely adequate fit is shown in Figure 3. A very good fit cannot be distinguished graphically from the original data, as is the case, for instance, for soybeans vulnerable over the entire year (Figure 1). As one might expect, many of the poorer fits occurred when there were few counties in the compilation, although the copious livestock data also produced curves that were flatter than the exponential fits.

In any case, the above procedure supplied an easily manipulable analytic function characterizing the agricultural data base with only two parameters per assumption, each of which is clearly interpretable. A summary of these fitted parameters is presented in Table 3. Although the analytic functions constitute exceedingly useful tools, one must recognize that there is a corresponding loss of information as to where the concentrations of resources are. In that the nationwide picture is the important one for the NES context, and because the next input will also be location-free, this sacrifice appears to be small compared with the gains secured.

The next input is an estimate of what fraction of the total U.S. area can be covered by a given radiation intensity as a function of the size of the nuclear attack. Obviously, the design of an attack coupled with the local and long range wind patterns over the United States on the day of attack and the days following can make large differences in the answer to this question. However, Carl Miller has compiled data[8] on a variety of postulated attacks and has found that the randomness

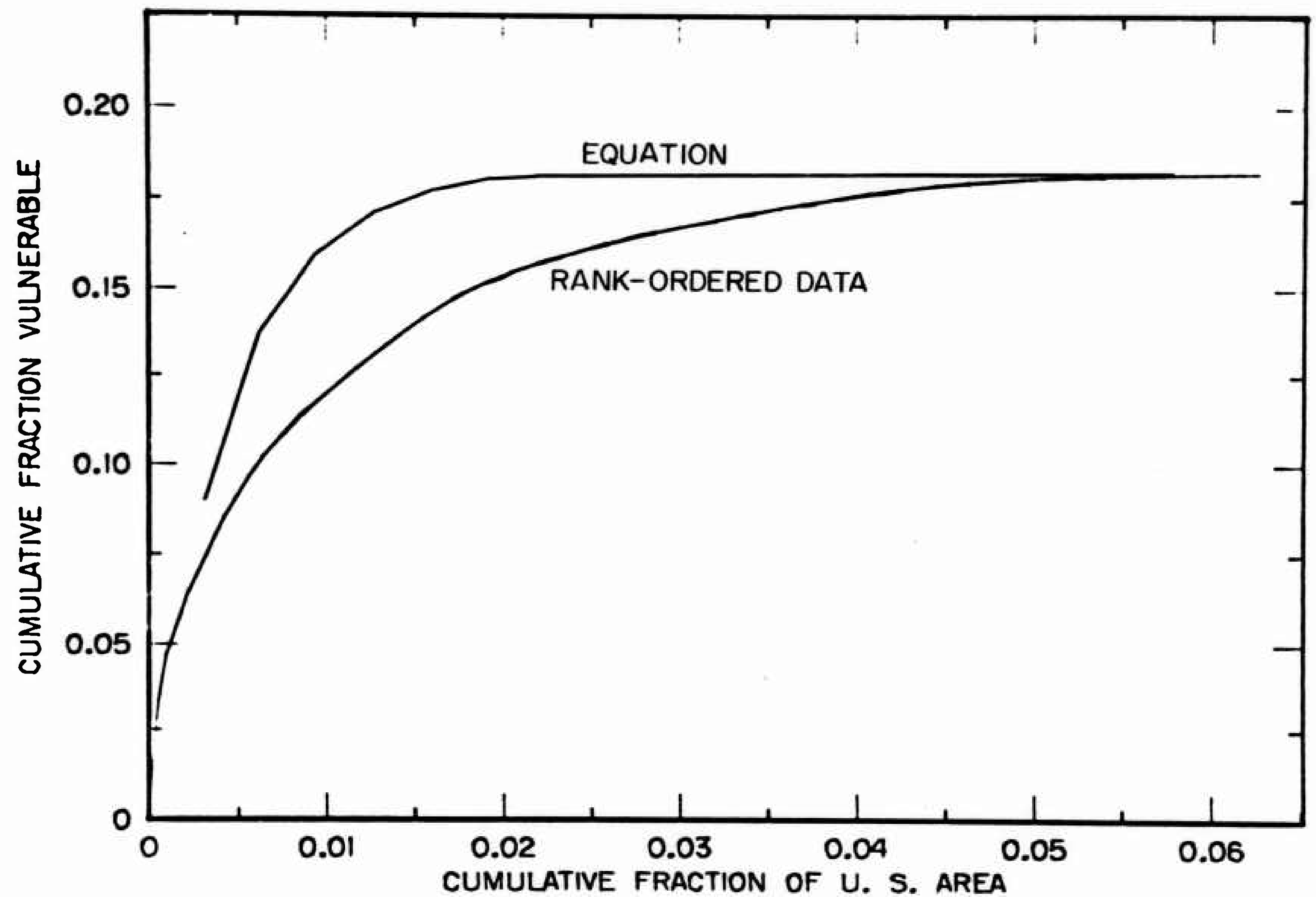


FIGURE 3 CUMULATIVE VULNERABILITY OF POTATOES

Table 3

PARAMETERS FOR THE AGRICULTURAL DATA BASE

Agricultural Resource	Code	Fraction Vulnerable*			Potential Efficiency†		
		Y	G	V	Y	G	V
Chickens	11	1.000	n.a.‡	n.a.	8.77	n.a.	n.a.
Hogs and Pigs	12	1.000	n.a.	n.a.	16.18	n.a.	n.a.
Milk Cows	13	1.000	n.a.	n.a.	10.17	n.a.	n.a.
Bulls, Steers & Calves	14	1.000	n.a.	n.a.	7.17	n.a.	n.a.
Sheep and Lambs	15	1.000	n.a.	n.a.	9.71	n.a.	n.a.
Corn	21	1.000	1,000	.229	12.73	12.70	21.90
Sorghum	22	1.000	.979	.424	32.94	34.46	116.53
Winter Wheat	23	1.000	.956	.844	17.23	18.53	21.69
Spring Wheat	24	1.000	1.000	1.000	39.71	40.03	40.05
Winter Oats	25	1.000	.252	.120	53.32	74.29	113.96
Spring Oats	26	1.000	.970	.927	15.52	15.52	17.71
Winter Barley	27	1.000	.810	.626	35.47	48.45	75.56
Spring Barley	28	1.000	.954	.954	37.92	40.90	39.88
Rice	29	1.000	1.000	1.000	313.11	225.69	225.48
Dry Beans	31	1.000	.327	.000	481.45	289.68	--
Soybeans	32	1.000	.997	.056	29.79	29.80	504.06
Alfalfa	42	1.000	1.000	.113	8.92	8.92	88.47
Potatoes	50	1.000	.951	.182	74.21	79.52	218.54
Green Peas	51	1.000	.964	.708	64.47	67.38	104.93
Sugarbeets	56	1.000	1.000	.949	83.81	83.81	91.95
Tomatoes	57	1.000	.790	.508	171.83	241.68	194.22
Sweet Corn	61	1.000	.930	.331	68.49	74.69	157.69
Snap Beans	64	1.000	.672	.270	129.01	207.08	371.67
Cabbage	65	1.000	.292	.127	251.40	630.77	1,511.29
Dry Onions	72	1.000	.653	.653	207.57	229.39	229.39
Carrots	73	1.000	.259	.259	569.03	300.76	300.76
Lettuce	76	1.000	.214	.195	133.91	515.92	572.61

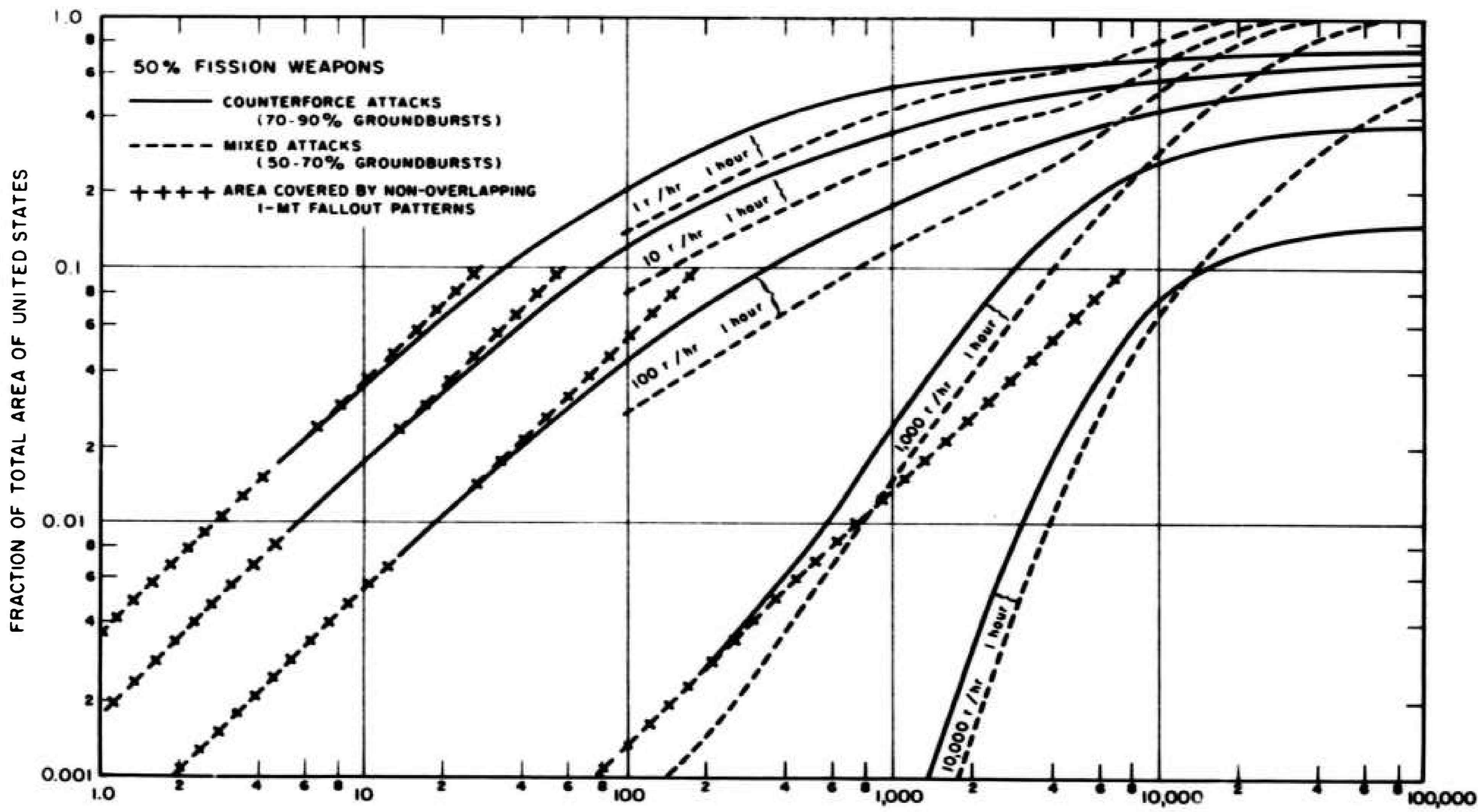
* α in Equation 2.

† λ in Equation 2.

‡ not applicable.

of wind variation tends to average out over the nation, and that the attack designs tend to fall into the two categories of counterforce (CF) and mixed counterforce-countervalue (M). From these data he has constructed Figure 4, which shows the variation of areal coverage with total attack yield for standard intensities of 1, 10, 100, 1,000, and 10,000 r/hr at one hour. For low total yields, both CF and M attacks tend to produce a roughly linear behavior because of the widely separated aimpoints. M attacks have fewer ground bursts, and thus fall below the CF values in this yield range. For higher yield attacks, there are certain areas of the country with very few valuable military targets upwind, and so the fallout patterns begin to overlap and the fractional area covered increases less than linearly with yield for low intensities but more than linearly for high intensities, approaching asymptotically values somewhat less than unity. Population and industry targets are likely to be spread more evenly throughout the nation, and so the M curves continue to rise and approach unity for large attacks.

How do these curves relate to the agricultural data base? Since they show how much of the area of the country is covered by a given intensity at a given level of attack, that fraction, f_a, may be inserted in Eq. (2) to determine what fraction of the annual crop production is vulnerable to fallout on the date of attack and can also be covered by the given intensity level. Recognize, however, that it is extremely unlikely for fallout to be so efficient. First, a particular agricultural resource would have to be specifically targeted. Second, the fallout patterns would have to fall in just such a way as to cover the counties with the highest production densities, and no others. Third, the variation of f_a with W, the total weight of the attack, must remain as high as postulated, which is unlikely when attacking a concentrated resource. Therefore, the maximum fraction of annual production that



SOURCE: Reference 8

FIGURE 4 FRACTION OF AREA ENCLOSED WITHIN SELECTED I_S CONTOURS could be exposed to intensity I by an attack directed at that specific resource is given by

$$f_v^m = \alpha \left|1 - e^{-\lambda f_a(W,I)}\right| \quad . \tag{3}$$

On the other hand, the attack may be aimed at another set of resources. If this set is not highly correlated with agriculture (either positively or negatively), the random variability of the wind structure will cause the fallout to be distributed nearly randomly with respect to agricultural resources. In this case, the probability that any point in the country will be covered by intensity I is just $f_a(W,I)$. Because the total vulnerable production is α, the fraction of annual production that could be exposed to intensity I is given by

$$f_v^n = \alpha \, f_a(W, I) \tag{4}$$

where the subscript n refers to the assumption that the attack is neutral with respect to agriculture.

When an attack is directed at a specific resource, it becomes much more efficient at damaging that resource than such a neutral attack, in that much less yield is required to do the same amount of damage. For a given weight of attack, the efficiency may be defined as

$$E = f_v / f_v^n \tag{5}$$

where f_v is the damage created by a given attack (however aimed) and f_v^n is the probable damage created by a neutral attack of the same weight. The neutral attack assumption thus produces unit efficiency, and an attack that deliberately avoided the given resource would have an efficiency less than one. For a specific weight of attack, the maximum efficiency against agriculture is obtained when $f_v = f_v^m$, as defined in Eq. (3). Because a smaller attack can be directed against the highest concentrations of agriculture only, this maximum efficiency in general increases as the weight of attack decreases. In the limit of the smallest attacks, where $f_a(W, I)$ approaches zero,

$$f_v^m \approx \alpha \lambda f_a (W, I) \tag{6}$$

by expansion of the exponential in Eq. (3). The maximum possible efficiency for small directed attacks is therefore $f_v^m/f_v^n = \lambda$. This, then, is why the parameter λ was called the potential efficiency for a given agricultural resource in Table 3.

All the curves of Figure 3 are not easily fit with analytic functions of the same general form. Instead, a tabular array $f_a(W_j, I_i) = f_{kj}$ was constructed, using values for W_j of 100, 200, 400, 700, 1,000, 2,000, 4,000, 7,000, 10,000, 20,000, 40,000, 70,000, and 100,000 MT, and values for I of 10, 100, 1,000, and 10,000 r/hr. The curves for I = 1 r/hr were excluded because very few effects on agricultural systems would be expected at this level even in the worst of worst cases. The values of f_v^n and f_v^m were then calculated for every i, j and for every resource category under all three duration of vulnerability assumptions. For a given attack weight the variation in f_v^n and f_v^m with intensity is typified by the curves in Figure 5. These curves show the cumulative fraction that could be exposed to an intensity level of I or greater.* The fraction exposed between I and I + dI is

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* For example, if a vulnerability criterion were set such that all of the resource were lost for intensities greater than I and none for intensities less than I, then the fraction lost would be just the value of the curve at I.

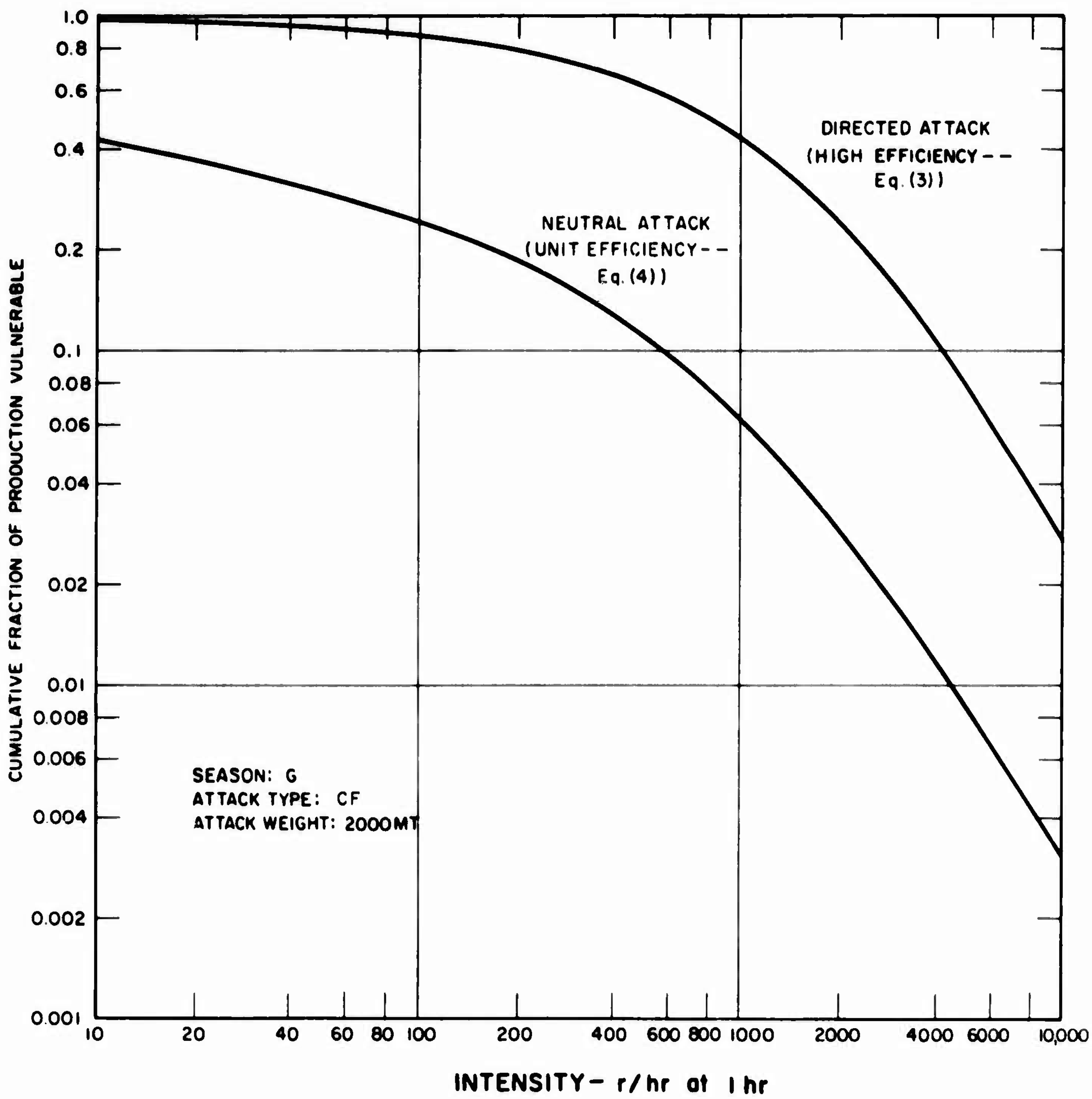

FIGURE 5 FRACTION OF ALFALFA PRODUCTION VULNERABLE

$$df = \frac{-df_v}{dI} \, dI \quad . \tag{7}$$

Curves like those shown in Figure 4 are also difficult to fit analytically, and interpolation can be done only approximately. An approximation that leads to a slight underestimate is

$$f_v(I) = A_i I^{-B_i}, \quad I_i < I < I_{i+1} \quad . \tag{8}$$

The index i ranges from 0 through 4 and $I_0 = 0$, $I_1 = 10$, $I_2 = 100$, $I_3 = 1{,}000$, and $I_4 = 10{,}000$ r/hr; I_5 is arbitrarily large. The parameters are given by

$$B_i = \log_{10} \left\{ f_v (I_i) \,/\, f_v (I_{i+1}) \right\} \tag{9}$$

and

$$A_i = f_v (I_i) \, I_i^{B_i} \quad . \tag{10}$$

For the lowest intensities, f_v is assumed to take the limiting value α at unit intensity, and for the highest intensities, f_v is assumed to fall off linearly with I, $B_4 = 1$. Both assumptions lead to slight overestimates in most cases. With these interpolation rules, Eq. (7) becomes

$$df \approx A_i \, B_i \, I^{-(B_i + 1)} \, dI \quad . \tag{11}$$

The background for including vulnerability criteria in the computation has now been laid. Each agricultural resource responds in a different way to radiation doses, but in general some rather regular features of the dose-response relationship can be observed. Two end points can usually be identified--a lethal dose, D_ℓ, above which very little of the resource survives, and a threshold dose, D_t, below which no notable loss of production is observed. Even though it is known that zero yield occurs at doses considerably below those for death of the plant, values for the latter must often be used for the former when better information is lacking. This is the origin of the use of "lethal dose" for the zero yield end point. Between the limits D_ℓ and D_t the surviving fraction gradually decreases as the dose is raised. Although data for determining the variation between the limits are sparse, many of the observed relationships are not inconsistent with an analytic function of the form

$$P_k = k\ell n(D/D_t), \quad D_t < D < D_\ell \tag{12}$$

where

$$k = 1/\ell n(D_\ell/D_t) \tag{13}$$

and P_k is the fraction lost of that portion of the resource receiving dose D.

The few data available at the time of Ref. 1 indicated, moreover, that the lethal/threshold dose ratio, $R = D_\ell/D_t$, might well equal about eight for a number of plant species of widely differing D_ℓ. Presumably the factors contributing to wide variations in D_ℓ (such as interphase chromosome volume)[9] contributed to approximately equal variations in threshold doses. New data for soybeans and rice* seem to be again consistent with a ratio of about eight, even though Constantin also shows th t the gross radiosensitivity, as indicated, say, by D_ℓ can vary

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* Milton J. Constantin, UT-AEC Agricultural Research Laboratory, private communication.

markedly with age of irradiation for crops such as corn, wheat, barley and soybeans. There is also a dose rate effect: greater effects are noted if the dose is delivered in a shorter time. The ratio of lethal to threshold dose for animals appears to be considerably smaller, and in fact Ref. 1 essentially assumed it to be unity and used the dose that kills half of the animals exposed to it within thirty days as D_ℓ. The standard case assumptions for D_ℓ and D_t are shown in Table 4, and are taken from Ref. 1 except for the garden vegetables, which are estimated from the same original sources.*

The next step in the logic is the relationship of dose levels to standard intensity levels. Doses can be obtained from standard intensities by the application of two multipliers:

$$D = M_{\beta\gamma} M_t I . \qquad (14)$$

The multiplier M_t, also known as the dose rate multiplier, is a function of the time of arrival of fallout and the times between which the cumulated dose is received, and converts standard intensities into gamma doses. Assuming doses to be calculated between time of arrival and about two weeks afterward, M_t varies from about 1 to nearly 4, depending on time of arrival.[10] An inspection of typical attack outputs shows that M_t averages about two, and rarely exceeds 3.5.

The multiplier $M_{\beta\gamma}$, which is called the total/gamma dose multiplier, converts gamma doses to gamma-plus-beta total doses; it is principally determined by plant type and age. In Ref. 1 it was shown to depend on the height of a plant's sensitive tissues, the amount of tissue surrounding the most sensitive ones, the amount of fallout retained on foliage

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* Several published and unpublished results of Arnold H. Sparrow and associates of Brookhaven National Laboratory.

Table 4

STANDARD CASE DOSE CRITERIA

Crop	Code	Lethal Dose (rad)	Threshold Dose (rad)	Total/Gamma Dose Multiplier
Chickens	11	900	900	2*
Hogs & Pigs	12	510	510	2*
Milk Cows	13	540	540	2*
Bulls, Steers & Calves	14	540	540	2*
Sheep & Lambs	15	520	520	2*
Corn	21	4,000	500	8
Sorghum	22	7,500	938	8
Winter Wheat	23	4,000	500	19
Spring Wheat	24	4,000	500	19
Winter Oats	25	4,000	500	19
Spring Oats	26	4,000	500	19
Winter Barley	27	4,000	500	12
Spring Barley	28	4,000	500	12
Rice	29	20,000	2,500	8
Dry Beans	31	12,000	1,500	23
Soybeans	32	14,000	1,750	23
Alfalfa	42	9,000	1,125	19
Potatoes	50	12,500	1,563	23
Green Peas	51	4,000	500	23
Sugarbeets	56	13,500	1,688	12
Tomatoes	57	3,000	375	23
Sweet Corn	61	4,000	500	8
Snap Beans	64	5,000	625	23
Cabbage	68	12,000	1,500	12
Dry Onions	72	2,000	250	17
Carrots	73	5,000	625	28
Lettuce	76	7,000	875	12

* This is a change from Ref. 1, which assumed a value of 1.

as opposed to that reaching the ground surface, the attenuation caused by ground roughness, and the time of arrival of the fallout. Other factors that can influence the value of $M_{\beta\gamma}$ are the self-shielding due to crop densities, the age of the plant (particularly through its affect on the other variables), and any difference between the RBE (relative biological effectiveness) of beta and gamma radiation. Reference 2 showed that, given the values of height and diameter of tissue, $M_{\beta\gamma}$ could be specified within a factor of about 2 over rather wide ranges of time of arrival, foliar retention, and surface roughness, as well as for several slightly different models of the source distribution. In the author's opinion, uncertainties in the remaining variables, such as the possibility of higher surface roughness attenuation or self-shielding, are in directions that would reduce $M_{\beta\gamma}$, thereby producing a conservative estimate of damage in the standard case.

Since $M_{\beta\gamma}$ depends on so many variables, all dependent on the age of the crop during the attack, and because a single crop is in several different growth stages in various parts of the country at the same time, it is difficult to choose one representative number for each crop. However, the set of $M_{\beta\gamma}$ shown in Table 4 was chosen for the standard case on the basis of intermediate values for the age of the crop and corresponding values for other variables. The sensitivity analysis assumed, then, that in the worst case $M_{\beta\gamma}$ would go up by a factor of two. For example, the total/gamma dose multiplier shown for wheat is 19. This might be appropriate for wheat 30 days old. When it is doubled ($M_{\beta\gamma} = 38$) it is probably conservative even for very young wheat.

For livestock, $M_{\beta\gamma}$ has generally been assumed to be unity, because the size of economically important animals prevents any very critical tissues to be exposed to beta radiation from external sources. However, recent work by Carl Bell on the feeding of cattle and sheep with feed contaminated with a beta-emitting fallout simulant (see for instance Ref. 11) showed that gastrointestinal beta insult, when coupled with external gamma radiation, could reduce the lethal dosage of the latter by about half. Although some question still remains whether ingestion of fallout would be so heavy in a real postattack situation, a conservative approach assigns a standard value of $M_{\beta\gamma}$ of two* for livestock (see Table 4) and again doubles it for the worst case.

These relationships now allow us to express the damage equation (Equation 12) as

$$P_k = k\, \ell n\, (I/I_t), \quad I_t < I < I_\ell \tag{15}$$

where

$$I_t = D_t/(M_t\, M_{\beta\gamma}) \tag{16}$$

and

$$I_\ell = D_\ell/(M_t\, M_{\beta\gamma}) \quad . \tag{17}$$

If df_v is the fraction of an agricultural resource vulnerable between I and I + dI, then the incremental fraction killed is $P_k df_v$, and the total fraction lost is

$$f_k = \int_0^\infty P_k\, df_v \quad . \tag{18}$$

When Eqs. (11) and (15) are used, assuming for the moment that $I_i < I_t < I_\ell < I_{i+1}$,

* This is a departure from the standard of Ref. 1, where $M_{\beta\gamma} = 1$.

$$f_k = f_v (I_\ell) + \int_{I_t}^{I_\ell} k \, \ell n \, (I/I_t) \, A_i \, B_i \, I^{-(B_i+1)} \, dI \qquad (19)$$

$$= f_v (I_\ell) + kA_i \left[I_t^{-B_i} / B_i - I_\ell^{-B_i} (1/k + 1/B_i) \right] \quad . \qquad (20)$$

Extra terms are added when the range $I_t - I_\ell$ spans more than one range of constant A_i and B_i, from integrals between limits I_t and I_i, I_i and I_{i+1}, ..., I_j and I_ℓ.

These integrals are carried out over the ranges assigned to each parameter whose sensitivity is being tested. A summary of these parameters and their values is given in Table 5. Since the sensitivity to changes in D_ℓ is essentially equivalent to changes in $M_{\beta\gamma}$ or M_t of the same magnitude, and since the effect of lethal dose reduction by a factor of two has already been tested in Ref. 2, the worst case value of D_ℓ is chosen as one fourth the standard. Notice that many* combinations of parameters for each attack weight and each resource are possible, although in some cases the results will be identical. For example, the duration of assumed vulnerability makes no difference for spring wheat, because the same number of counties are vulnerable under each assumption.

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* From Table 5, 2 × 3 × 2 × 2 × 2 × 2 × 2 = 192 combinations. Since there were 13 attack weights and 27 resources, over 65,000 "answers" were possible.

Table 5

PARAMETERS OF THE SENSITIVITY ANALYSIS

Parameter	Symbol	Units	Range
Type of attack	IAT	--	Counterforce, Mixed
Weight of attack	W	MT	100; 200; 400; 700; 1,000; 2,000; 4,000; 7,000; 10,000; 20,000; 40,000; 70,000; 100,000
Duration of vulnerability	ISV	--	Vulnerable period (standard), Growing period, Year (worst case)
Efficiency of attack	E	--	Unity (standard), Maximum (worst case)
Lethal dose	D_ℓ	rad	D_ℓ (standard, Table 4), $D_\ell/4$ (worst case)
Dose rate multiplier	M_t	hr	2.0 (standard), 3.33 (worst case)
Total/gamma dose multiplier	$M_{\beta\gamma}$	--	$M_{\beta\gamma}$ (standard, Table 4), $2\ M_{\beta\gamma}$ (worst case)
Lethal/threshold dose ratio	R	--	Crops: 8 (standard), 16 (worst case) Livestock: 1 (standard), 2 (worst case)

III RESULTS

The footnote at the end of the preceding section indicated that the tabular output of the sensitivity analysis consisted of the order of 65,000 numbers. In addition, numerous intermediate outputs were also generated. The interpretation of such a quantity of information is nearly impossible without a great deal of systematization, generalization, simplification, and excerpting. As for the intermediate output discussions in the previous section, no attempt will be made in this section to present the entire range of results.

Sampling of the tabular results immediately suggests ways of reducing the amount of data to comprehend. A first generalization is that counterforce (CF) attacks most often produce slightly more damage than mixed (M) attacks for the same delivered megatonnage and identical values of the other parameters. The exceptions occurred in the region of greater than about 10,000 MT, which are clearly due to the crossover of the CF and M curves in Figure 4. Also as expected from Figure 4, the variance between CF and M is rarely greater than a factor of about 1.5, which generally narrows for increasingly worse cases. Since CF damage is greater than M damage in the region of the standard attacks (1,300 MT, 2,500 MT), emphasis will be placed on the CF results.

Further generalizations can be obtained by plotting a few representative curves of f_k versus W for various combinations of all the other parameters. It was observed that for a given resource, a given attack type, a given efficiency of attack, and a given season of vulnerability, the curves virtually never cross over one another, and

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occur in much the same ascending order with respect to combinations of the remaining parameters. Obviously the situation wherein all parameters have the standard case values causes the least damage, and that with all worst case values the most damage. Table 6 shows the order of sensitivity for the various combinations, which are coded numerically in order of increasing sensitivity. The same pattern holds for directed attacks as for neutral attacks, and in general the lowest curve for a directed attack falls above almost all curves for a neutral attack, although crossovers are possible between the two sets. The code is simply an abbreviation for the combinations of assumptions, in order of increasing effect.

Most of the pattern is due to the fact that lethal dose, total/gamma dose ratio, and dose rate multiplier all have essentially the same sensitivity if assumed to vary by the same factor. Since the worst case factors were lowest for M_t and highest for D_ℓ, much of Table 6 follows immediately. A stronger result is that the ratio of lethal to threshold dose is the least sensitive parameter. This finding relates to the fact that the majority of the damage occurs in those areas affected by doses greater than the lethal dose, with little extra damage coming from the added area encompassed by lowering the threshold dose.

The next consideration is one of statistical probability. If the worst case--or worse--will occur only about 10 percent of the time (intuitively) for any one parameter, then the probability of two or more parameters simultaneously taking on their worst case values becomes very small indeed. Most interest should be placed, therefore, in the cases for which only one or two parameters take on their worst values. With respect to Table 6, the sets of assumptions labeled by codes 01, 02, 03, 04, and 08 deserve most consideration. Inspection of the tabular output revealed that the data for assumptions 03 were

Table 6

RELATIVE SENSITIVITIES OF VARIOUS COMBINATIONS OF PARAMETERS

Lethal Dose	Lethal/ Threshold Ratio	Total/Gamma Dose Ratio	Dose Rate Multiplier	Code	
Standard	Standard	Standard	Standard	01	↑
Standard	Worst	Standard	Standard	02	
Standard	Standard	Standard	Worst	03	
Standard	Standard	Worst	Standard	04	
Standard	Worst	Standard	Worst	05	
Standard	Worst	Worst	Standard	06	
Standard	Standard	Worst	Worst	07	Less Sensitive
Worst	Standard	Standard	Standard	08	
Standard	Worst	Worst	Worst	09	More Sensitive
Worst	Worst	Standard	Standard	10	
Worst	Standard	Standard	Worst	11	
Worst	Standard	Worst	Standard	12	
Worst	Worst	Standard	Worst	13	
Worst	Worst	Worst	Standard	14	
Worst	Standard	Worst	Worst	15	
Worst	Worst	Worst	Worst	16	↓

always closely bracketed by those for 02 and 04, so that they yield little additional information. The remaining four cases are of interest both under the neutral and directed attack assumptions, and the situation with all worst cases values, including maximum efficiency (call it the maximum of maxima), should be considered as a highly unlikely upper bound.

These nine sets of data can be examined as functions of the assumed weight of attack and of the duration of assumed vulnerability. Nine curves of f_k versus W were therefore plotted for each duration of vulnerability assumption and for each agricultural resource. For a given resource and attack weight, the values of f_k always increase in this order: vulnerable period (V), growing period (G), and year (Y); however, there is no particularly evident pattern that can eliminate one of these assumptions. Sometimes the V and G assumptions yield identical results, sometimes G and Y, and occasionally all three.

A selection of typical lost-production curves are shown in Figures 6 through 12. They span the types of behavior found in the entire range of output, and are chosen for their illustrative qualities rather than for their significance as resources. In examining these sets of curves, notice first that the groups of curves for neutral and directed attacks are quite distinct and characteristically different. All of the neutral curves appear much the same, even though the scales for f_k differ widely. This feature arises from the fact that these curves depend directly on the curves of Figure 4 through the maximum fraction vulnerable, α. Differences among crops and among vulnerable seasons depend principally on α, with a much smaller effect operating through the differences in the limits I_t and I_ℓ between which the intensity integration is carried out. The typical broad "S" shape is due in part to the choice of axes (the asymptotic approach to 0 for small attacks) and partly to the shape

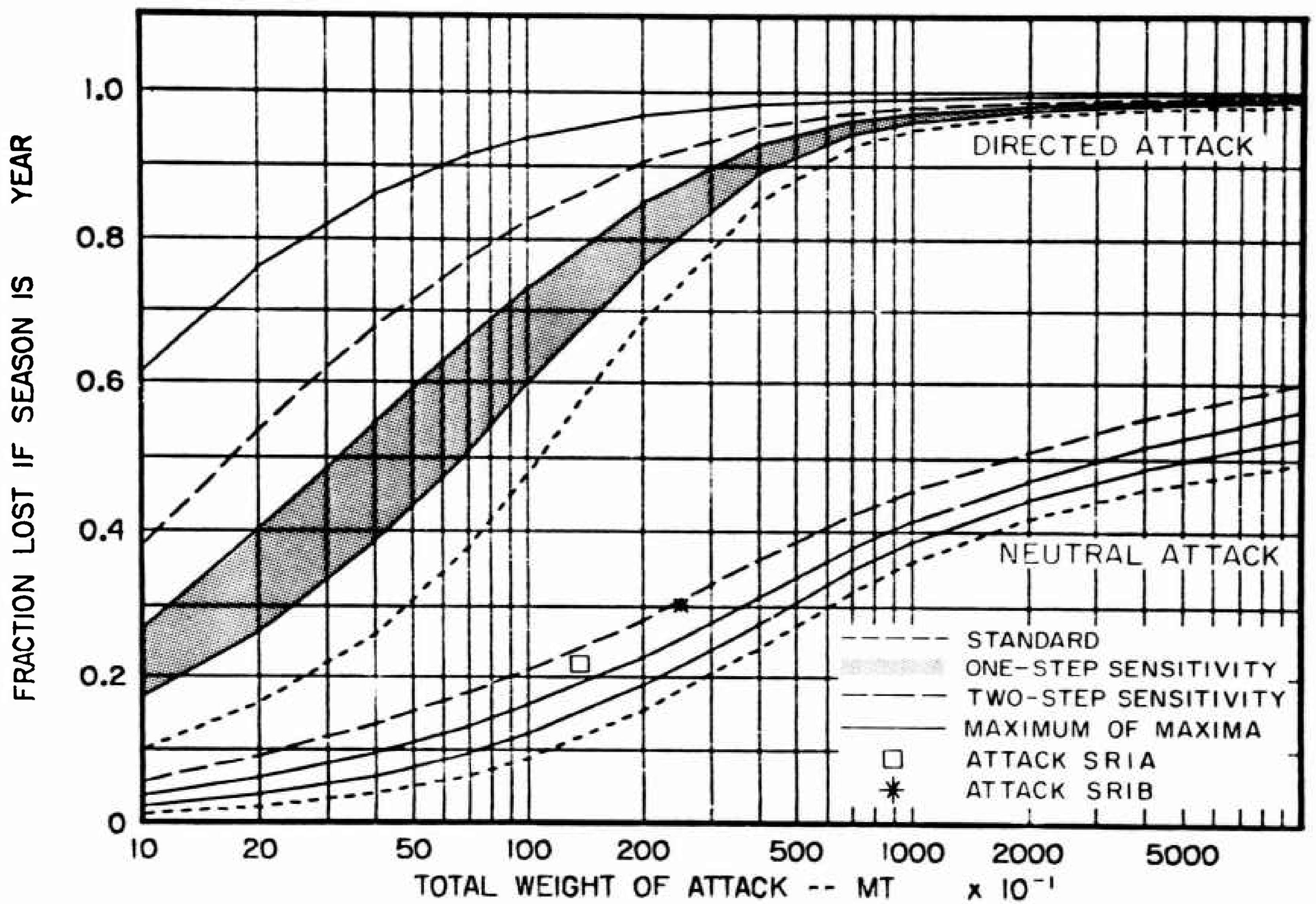

FIGURE 6 FRACTION OF ANNUAL PRODUCTION LOST FOR CHICKENS

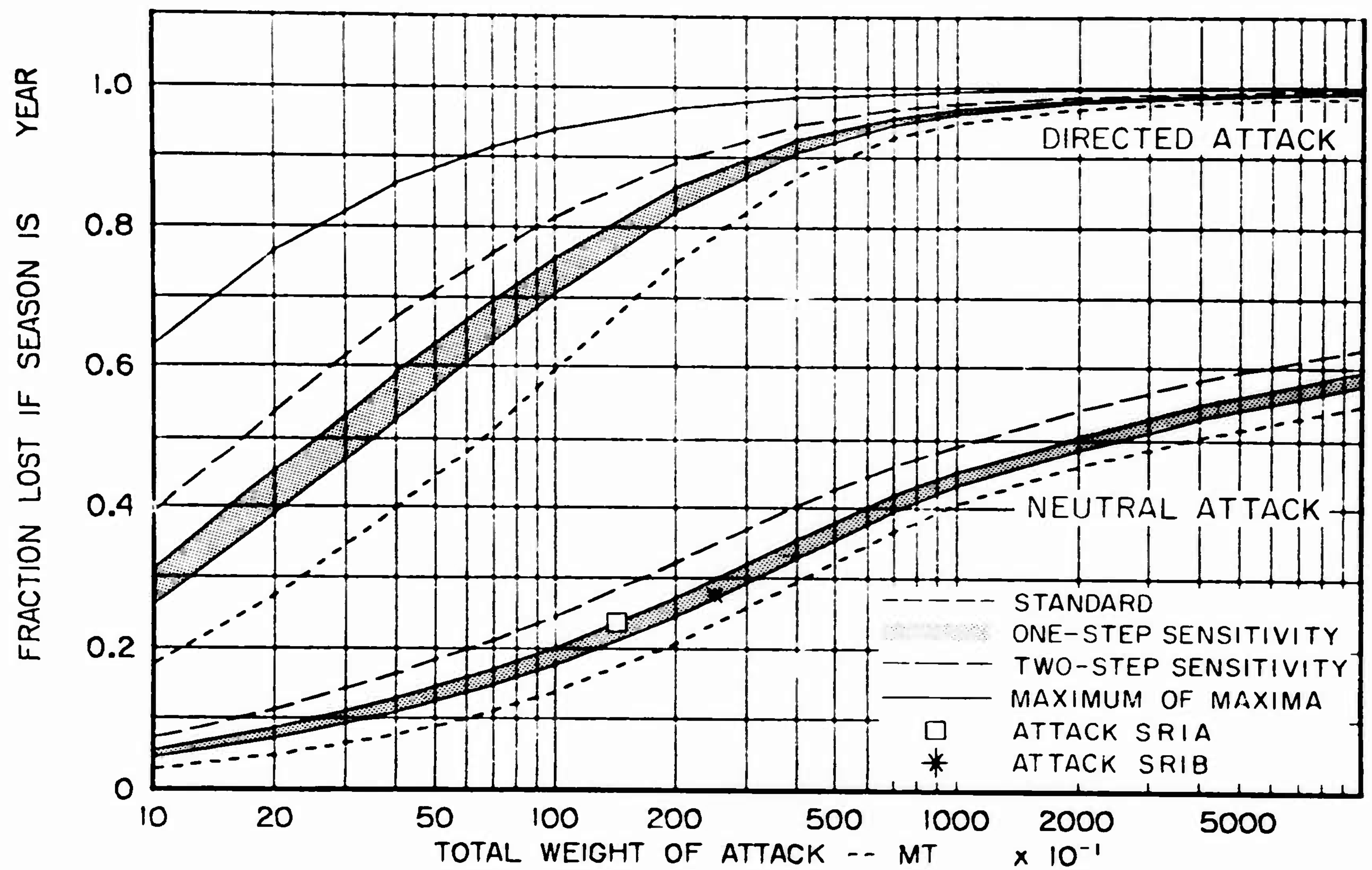

FIGURE 7 FRACTION OF ANNUAL PRODUCTION LOST FOR CATTLE

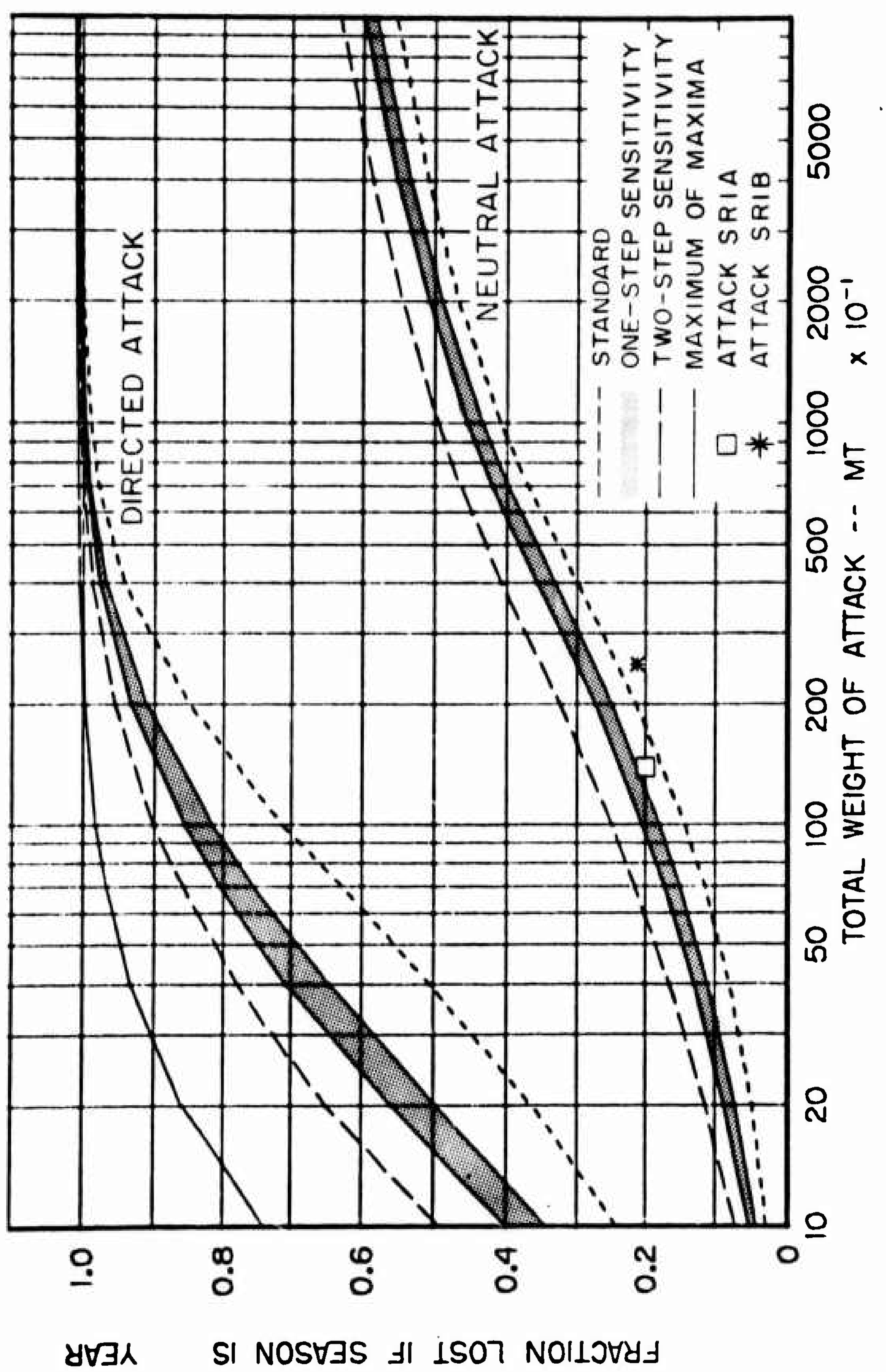

FIGURE 8 FRACTION OF ANNUAL PRODUCTION LOST FOR SHEEP AND LAMB

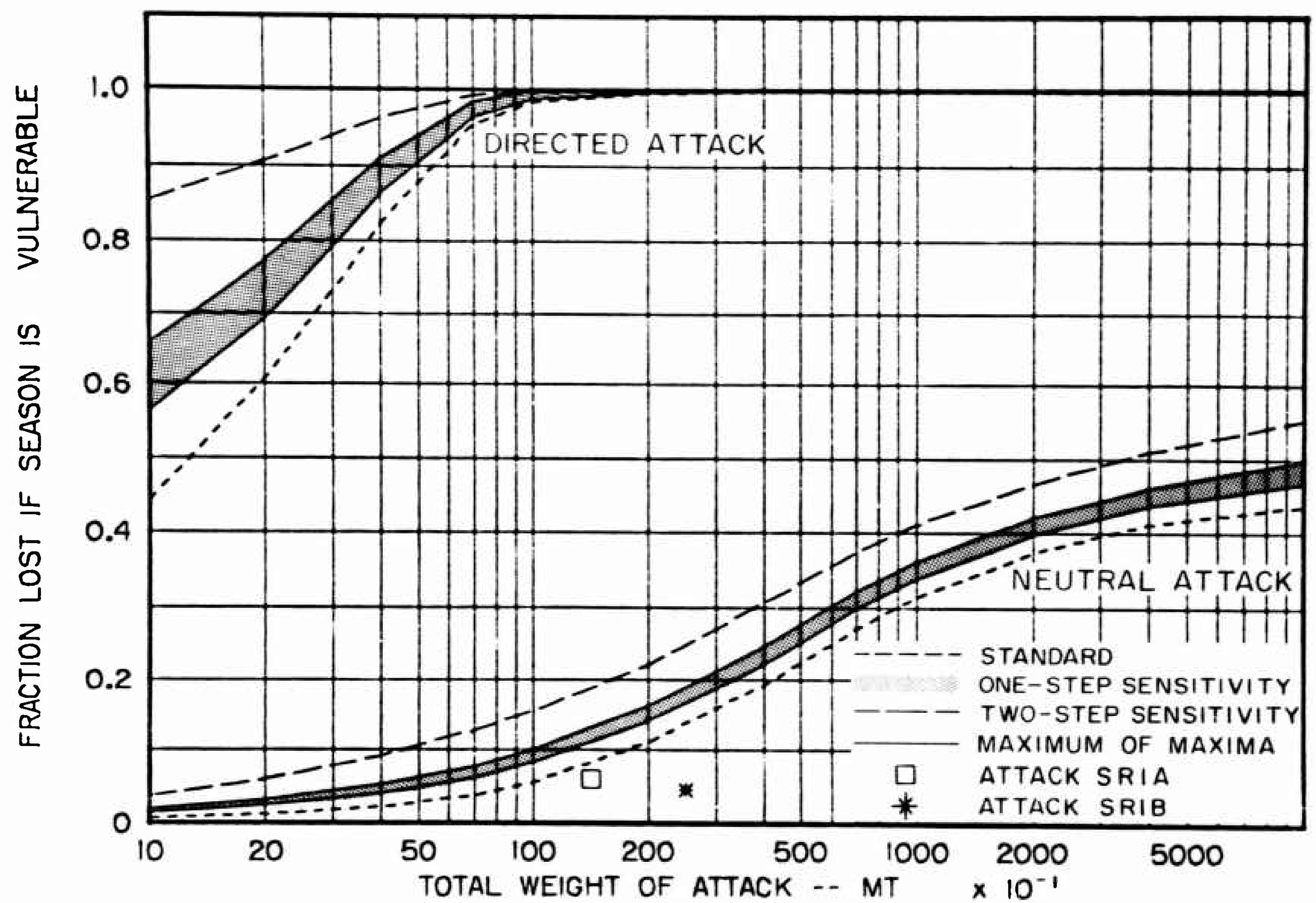

FIGURE 9 FRACTION OF ANNUAL PRODUCTION LOST FOR RICE

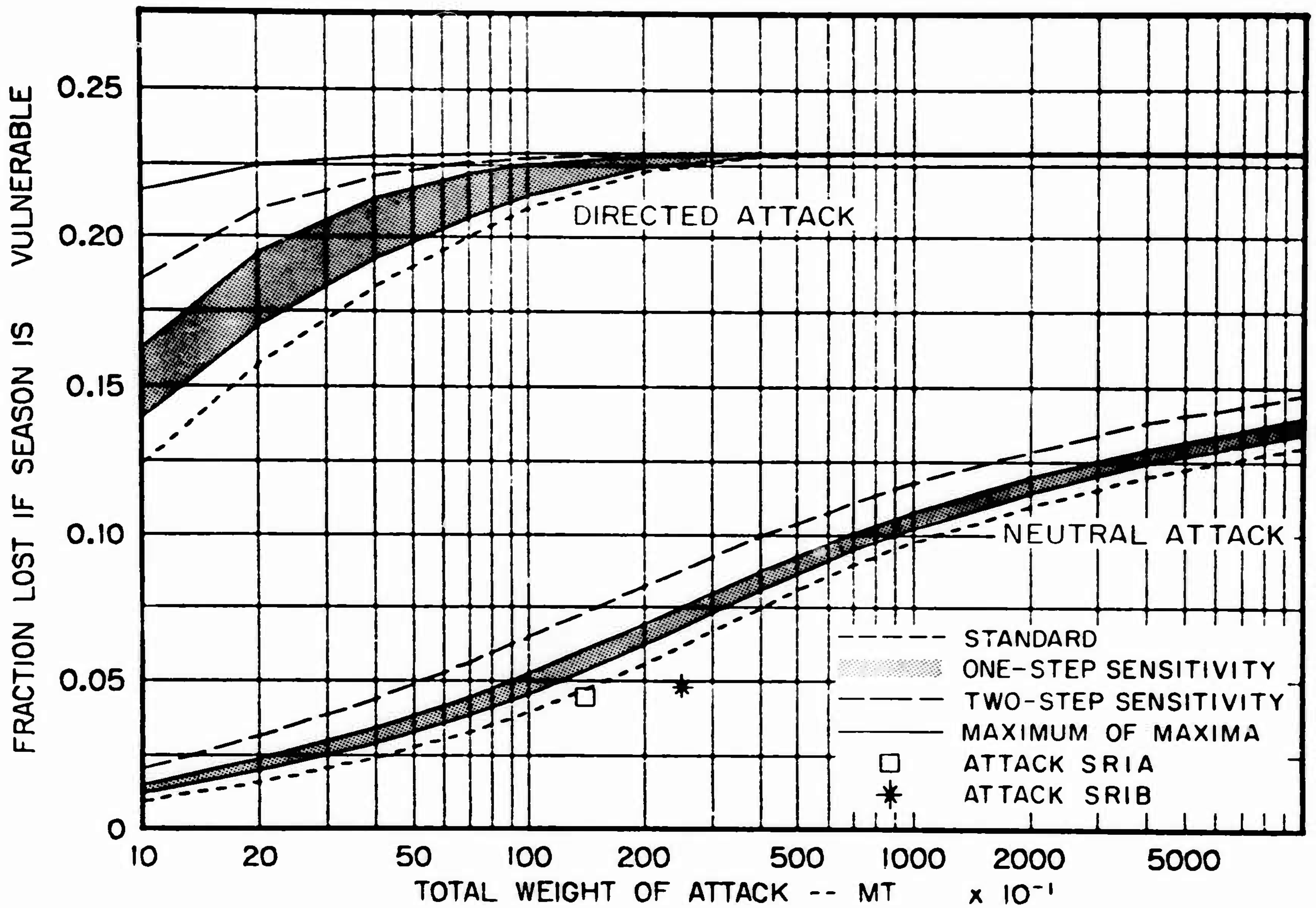

FIGURE 10 FRACTION OF ANNUAL PRODUCTION LOST FOR CORN

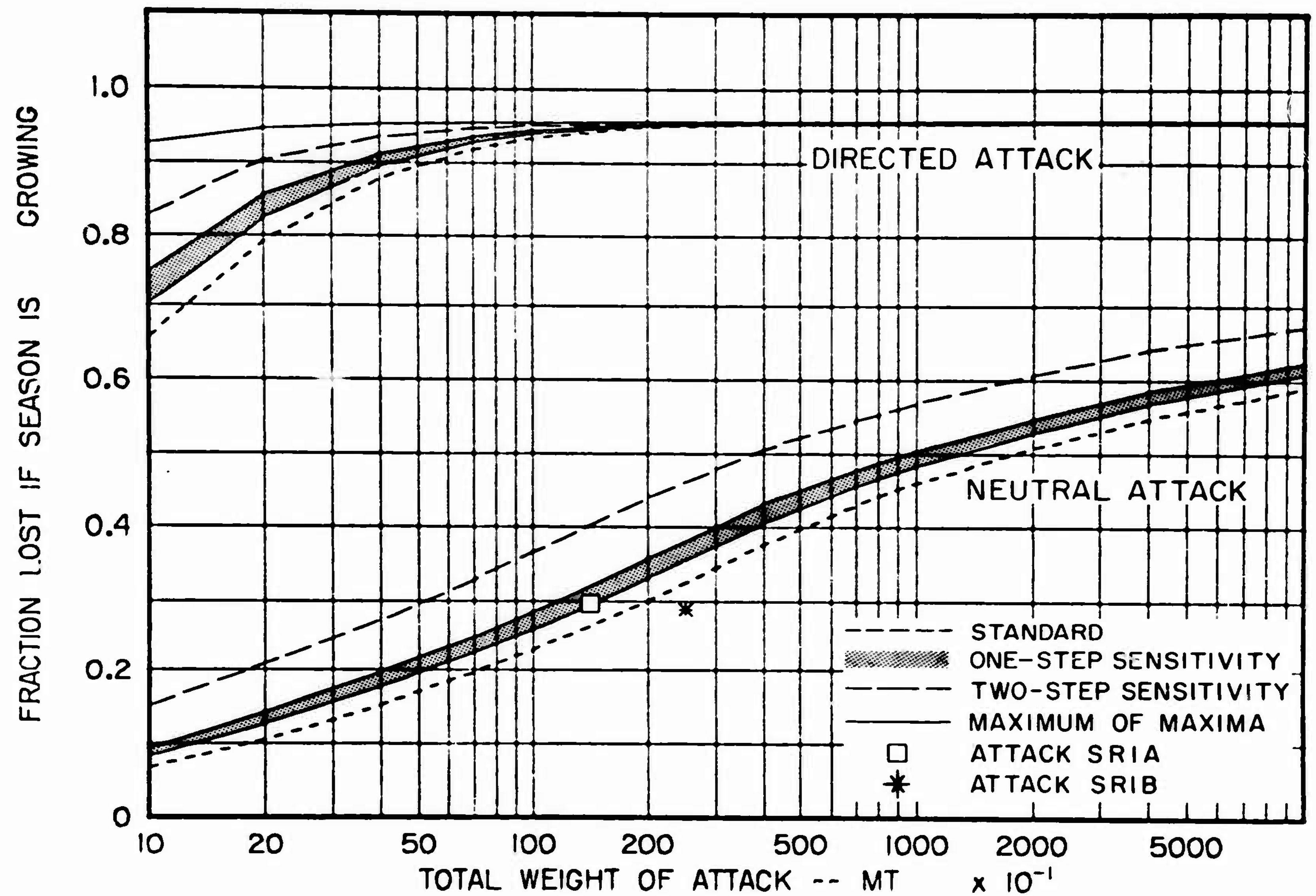

FIGURE 11 FRACTION OF ANNUAL PRODUCTION LOST FOR W. WHEAT

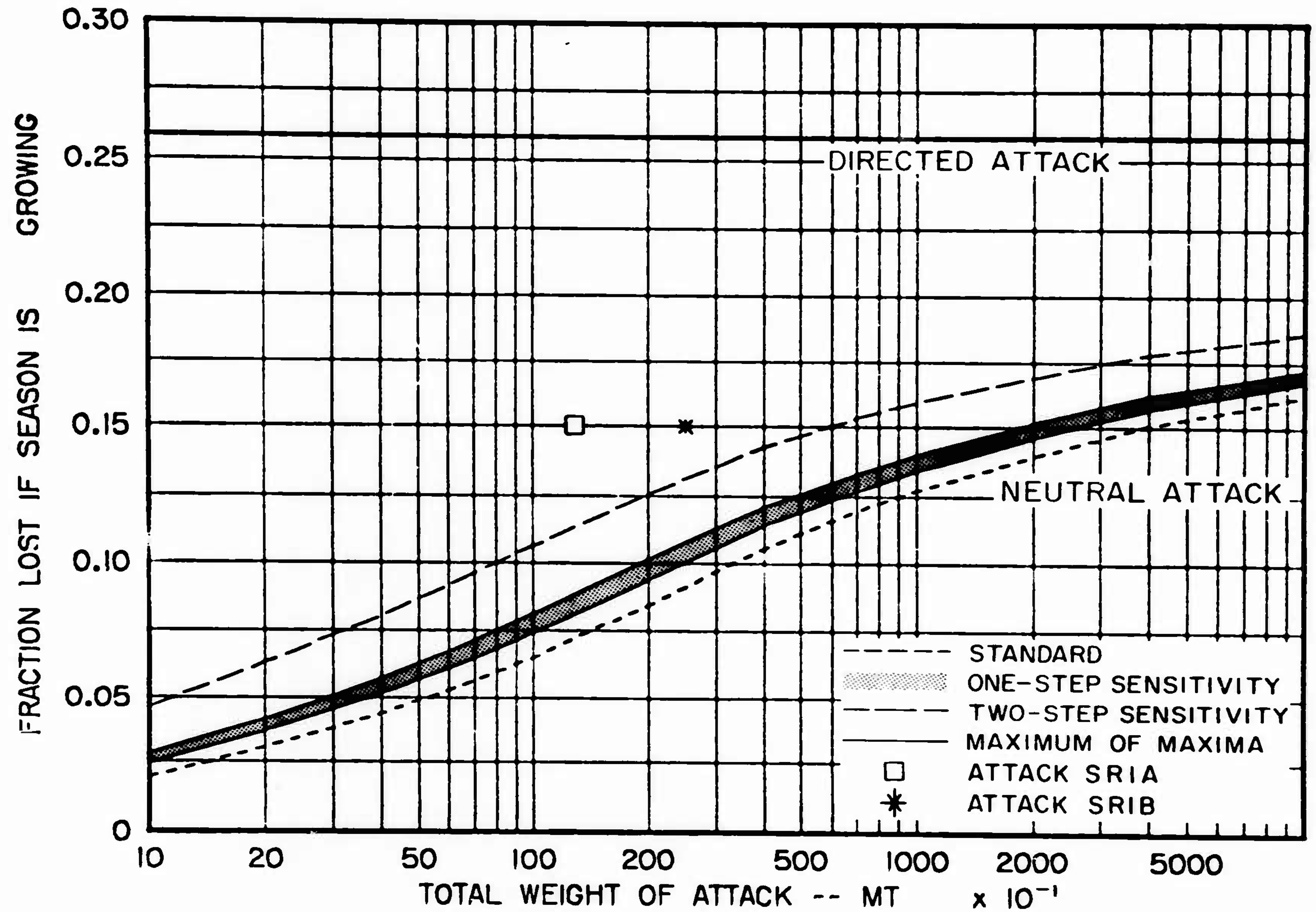

FIGURE 12 FRACTION OF ANNUAL PRODUCTION LOST FOR CARROTS

of the counterforce curves in Figure 4 (the asymptotic behavior for heavy attacks). The curves would continue to rise toward an asymptote of α in the case of mixed attacks.

The directed attack curves, on the other hand, show more differences, although they all approach the α asymptote for heavy yields. A broad spread in the curves such as for chickens (Figure 6) corresponds to a widely dispersed resource with a low potential efficiency, λ (review Table 3), especially if the lethal intensity criterion I_ℓ, is high (review Table 4). As I_ℓ decreases or λ increases it becomes increasingly easy to inflict maximum damage on the agricultural resource with smaller attacks; for example, a very small attack could destroy entirely that portion of the carrot crop that is vulnerable (Figure 12) if exactly tailored to do so.

In the figures, the shaded area lies between the curves generated from the assumptions coded 02 and 04 and represents the range of increase in f_k caused by varying D_ℓ, M_t, $M_{\beta\gamma}$, or D_ℓ/D_t by a factor of two or less. According to the intuitive probability assignments, the choices are perhaps nine in ten that the fraction lost will not exceed the upper bound of this region given the postulated values of the other parameters. The long-dashed curve is assumption code 08 and is the result of setting D_ℓ to one-fourth of its standard value, equivalent to varying both D_ℓ and $M_{\beta\gamma}$ or M_t by a factor of two. Thus in the sense that the first range is a one-step sensitivity, this curve is a two-step sensitivity, and may be rejected at about the 99 percent confidence level. The maximum of maxima curve would occur only under the conditions of a most incredible chain of misestimations.

Another generalization based on inspection of Figures 6 through 12, and on others like them, is that rate of change of f_k with respect to the logarithm of W (the slope of the curves in the form plotted) is greatest (for the neutral attacks) in the region of 1,000 MT to 10,000 MT, approximately. It is often also in this range that the directed attack curves begin to approach total destruction of all of the crop assumed vulnerable. In a very loose sense, this may be considered the region in which a break point has been identified. Care in interpreting this finding must be taken in view of the possibility that bias has been introduced by the fact that this region has been most extensively studied. It is also quite probable that population losses from counterforce attacks would follow much the same sort of curve, although differences in shelter assumptions and other parameters make it difficult to construct such a curve.

Once again on the question of sensitivity to the uncertainty in parameter values, the figures also clearly show that the increment in f_k is not only a relatively constant fraction of α over the entire range of attack weights, but also is reasonably uniform from crop to crop, for the neutral attack assumption. A summary of one-step sensitivity values is given in Table 7. These were computed by subtracting the f_k values for the assumption set coded 01 from those for code 04, where both of the fraction destroyed numbers corresponded to an attack weight of about 1,300 MT, the weight of the counterforce attack (SRIA) in Ref. 1. The spread in sensitivity values as so defined is from 0.048 (rice) to 0.081 (dry onions), and the average is only about six percent.

Another comparison of interest is how well the highly simplified model and data base developed for sensitivity analysis compares with the detailed model and data base used in Ref. 1. For this purpose, the values for f_k from the detailed analysis have been plotted at 1,300 MT for the counterforce attack (SRIA), and points at 2,600 MT for the mixed attack (SRIB) have also been added as a further comparison. See Figures 6 through 12 for examples. The interpolated values for f_k (again for the assumption set coded 01, all standard case assumptions)

Table 7

SENSITIVITY OF FRACTION LOST AT THE 90 PERCENT CONFIDENCE LEVEL

Agricultural Resource	Code	Sensitivity Y	G	V
Chickens	11	.073	n.a.	n.a.
Hogs and Pigs	12	.059	n.a.	n.a.
Milk Cows	13	.064	n.a.	n.a.
Bulls, Steers & Calves	14	.063	n.a.	n.a.
Sheep & Lambs	15	.061	n.a.	n.a.
Corn	21	.057	.057	.057
Sorghum	22	.057	.057	.057
Winter Wheat	23	.058	.059	.058
Spring Wheat	24	.058	.058	.058
Winter Oats	25	.058	.060	.058
Spring Oats	26	.058	.058	.058
Winter Barley	27	.054	.054	.054
Spring Barley	28	.054	.054	.054
Rice	29	.048	.048	.048
Dry Beans	31	.057	.058	--
Soybeans	32	.057	.057	.054
Alfalfa	42	.057	.057	.053
Potatoes	50	.057	.057	.055
Green Peas	51	.063	.064	.064
Sugarbeets	56	.057	.057	.057
Tomatoes	57	.074	.076	.075
Sweet Corn	61	.057	.057	.058
Snap Beans	64	.053	.058	.059
Cabbage	68	.056	.058	.055
Dry Onions	72	.081	.081	.081
Carrots	73	.063	.062	.062
Lettuce	76	.055	.056	.056

are presented in Table 8 for each of the duration-of-vulnerability assumptions. The values shown in the column labeled STD are the standard damage assessment results for attack SRIA* and should be compared with the sensitivity analysis results shown in the column labeled V. The column headed "Relative Difference" was computed by subtracting the values in the STD column from those in the V column and dividing by the latter. The preponderance of negative values indicates that the simplified method has underestimated the fraction lost by an average of about 35 percent. One major contribution to this difference is that attack SRIA assumed 100 percent groundbursts, whereas the simplified method assumes about 80 percent. The correction would be very nearly directly proportional. A second important systematic error probably comes from the underestimates built into the interpolation in the curves of $f_v(I)$ (see the discussion of Figure 5 on page 34). Most of the remaining scatter can probably be attributed to misestimation of the typical standard case values to assign to the parameters. The value of the total/gamma dose multiplier is particularly suspect because of the multitude of variables that might affect it. For instance, the overestimate for rice is undoubtedly due to the fact that no provision was made in the simplified model for shielding of the beta radiation by water in the rice fields. This oversight could be corrected by dropping $M_{\beta\gamma}$ to, say, 3. A final possibility is that, by coincidence, the efficiency of attack SRIA with respect to certain resources was substantially different from unity, i.e., that it was not neutral with respect to agriculture. This might contribute to the large error noted

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* Because the standard damage assessment did not consider the garden vegetables, the values shown in parentheses are guesses based on the fraction of the crop vulnerable at the time of the attack, and are included principally for consistency.

Table 8

COMPARISON OF SIMPLIFIED AND DETAILED MODEL RESULTS
(Values in parentheses are for plotting purposes only)

Agricultural Resource	Code	Fraction Lost @ 1300 MT Y	G	V	STD	Relative Difference
Chickens	11	.115	n.a.	n.a.	.222	-.931
Hogs and Pigs	12	.173	n.a.	n.a.	.235	-.361
Milk Cows	13	.169	n.a.	n.a.	.296	-.753
Bulls, Steers & Calves	14	.167	n.a.	n.a.	.247	-.480
Sheep and Lambs	15	.172	n.a.	n.a.	.194	-.127
Corn	21	.201	.201	.046	.045	.023
Sorghum	22	.149	.146	.063	.085	-.344
Winter Wheat	23	.270	.259	.229	.291	-.273
Spring Wheat	24	.270	.270	.270	.342	-.264
Winter Oats	25	.270	.068	.033	.031	.046
Spring Oats	26	.270	.262	.251	.276	-.101
Winter Barley	27	.235	.190	.147	.200	-.360
Spring Barley	28	.235	.224	.224	.347	-.547
Rice	29	.078	.078	.078	.053	.322
Dry Beans	31	.197	.064	.000	(.000)	--
Soybeans	22	.183	.183	.010	.021	-1.060
Alfalfa	42	.205	.205	.023	.026	-.120
Potatoes	50	.193	.184	.035	.071	-1.021
Green Peas	51	.281	.274	.202	(.300)	--
Sugarbeets	56	.135	.135	.128	.173	-.351
Tomatoes	57	.297	.243	.157	(.300)	--
Sweet Corn	61	.201	.187	.066	.106	-.595
Snap Beans	64	.244	.180	.072	(.150)	--
Cabbage	68	.143	.042	.018	(.060)	--
Dry Onions	72	.318	.208	.208	(.300)	--
Carrots	73	.283	.073	.073	(.150)	--
Lettuce	76	.181	.040	.037	(.100)	--

for chickens, for instance, for which no other ready explanation is available.

This last observation emphasizes the importance that changes in the efficiency of the attack can have. Table 9 exhibits maximum efficiencies achievable with a counterforce attack of the size of SRIA. The efficiencies were calculated by dividing the results for assumption code 01 under the directed attack assumption by that for the neutral attack assumption. They vary little--if at all--between the duration of vulnerability assumptions, but considerably more from crop to crop, ranging from a little over three to almost 13, a factor of four. This variation is clearly related to the concentration of the resource, but the range is not nearly as large as for the potential efficiencies (Table 3), because the condition of a very small attack is just as clearly not satisfied. The relative uniformity of the values is supported by two observations. First, in neutral attacks, the range in f_k (if normalized by the fraction vulnerable, α) is not too large at 1,300 MT. Second, for many of the resources, f_k is approaching α for the directed attacks at this weight of attack.

Even though the efficiencies as defined are not numerically large in this region of total yield, they are exceedingly important because they change the loss picture from a relatively modest 25 percent or so to near total losses, if the assumption of a fairly lengthy vulnerable season is accepted. However, a number of arguments indicate that attacks directed against agriculture are unlikely. First, the resources are not nearly so concentrated geographically as the rank orders might indicate, because the highest production counties are often widely scattered through the country. Secondly, efficient coverage of just those counties with concentrations of resources is impossible because one cannot tailor a fallout pattern to the shape of a county. Moreover, meteorological

Table 9

EFFICIENCIES ACHIEVABLE WITH 1,300 MT ATTACK

Agricultural Resource	Code	Efficiency @ 1300 MT		
		Y	G	V
Chickens	11	4.92	n.a.	n.a.
Hogs and Pigs	12	5.13	n.a.	n.a.
Milk Cows	13	4.60	n.a.	n.a.
Bulls, Steers & Calves	14	3.96	n.a.	n.a.
Sheep and Lambs	15	4.48	n.a.	n.a.
Corn	21	4.30	4.30	4.68
Sorghum	22	6.10	6.13	6.64
Winter Wheat	23	3.62	3.64	3.66
Spring Wheat	24	3.69	3.69	3.69
Winter Oats	25	3.70	3.70	3.70
Spring Oats	26	3.59	3.59	3.63
Winter Barley	27	4.21	4.23	4.25
Spring Barley	28	4.22	4.22	4.22
Rice	29	12.70	12.67	12.67
Dry Beans	31	5.09	5.09	--
Soybeans	32	5.14	5.14	5.46
Alfalfa	42	3.85	3.85	4.85
Potatoes	50	5.13	5.13	5.18
Green Peas	51	3.51	3.51	3.51
Sugarbeets	56	7.23	7.23	7.26
Tomatoes	57	3.25	3.25	3.25
Sweet Corn	61	4.92	4.93	4.97
Snap Beans	64	3.74	3.74	3.73
Cabbage	68	6.93	6.93	6.94
Dry Onions	72	3.14	3.14	3.14
Carrots	73	3.54	3.53	3.53
Lettuce	76	5.29	5.31	5.31

forecasting is not sufficiently trustworthy that even the direction a pattern will take can be confidently predicted. Finally, if attacks against particular sectors of the U.S. economy are contemplated, there are many better target resources in the manufacturing industries. In terms of the present definition, efficiencies of the order of 100,000 could be achieved against, say, the petroleum refining capacity; the resultant damage would probably do nearly as much harm to agriculture as a direct attack, and in addition cripple other sectors.

IV INTERPRETATION

Much of the technical interpretation of the results of the sensitivity studies has already been given in the preceding section. In this section an attempt will be made to extend the technical interpretations and synthesize them, as well as to make the transition to policy recommendations.

Certainly no monopoly on truth has been demonstrated with respect to the range of attitudes on agricultural vulnerability. Clearly a nuclear attack designed to damage agriculture could do so rather efficiently. Almost as clear is the fact that uncertainties about the appropriate growing season to assume can make substantial differences in the fraction vulnerable, α.

On the other hand, sensitivities to other assumptions of the calculations are much less severe, leading to uncertainties in the fraction lost of less than about thirty percent of the standard case values (six percent of the maximum fraction vulnerable). If the premise that counter-agriculture attacks should not appear particularly attractive to a potential enemy is accepted, the remaining uncertainties in damage assessment should generate only moderate concern.

Some additional insights are obtained by reviewing the importance of various foodstuffs in the U.S. diet. Figure 13 shows approximate contributions of energy from selected components of the diet. The portion labeled animal calories shows the relative contributions of energy in animal diets from the feed crops included in this study. It does not include contributions from pasturage and certain hays for the reasons stated in Section II, Analysis and Data Base. This procedure

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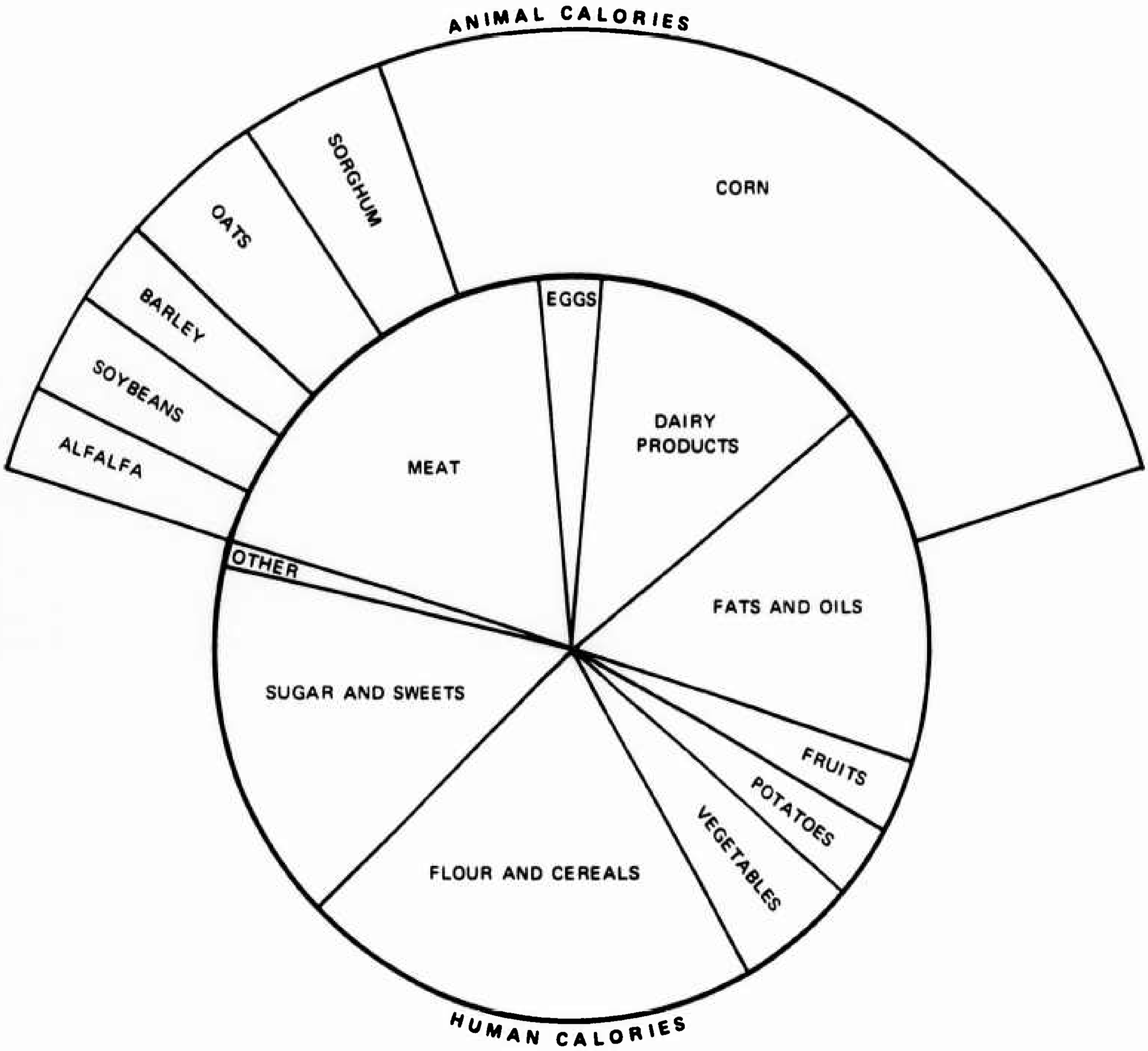

FIGURE 13 ENERGY SUPPLY FOR THE U.S. DIET

exaggerates the importance of feeds, because substantial energy is obtained from pasture, especially by beef cattle and sheep. However, corn is still clearly the most important single component of animal feeds from an energy viewpoint, and may be about as important as all pasturage combined when all five livestock categories are considered.

Although Figure 13 does not recognize the obvious changes in relative importance when other dietary requirements are considered, the energy contributions are probably the most important for national entity survival over the few months before normal agricultural operations can be resumed.* Notice that the omission of fruits and the de-emphasis on vegetables are justifiable on these grounds. Livestock accounts for about 40 percent of all human calories, and corn contributes over 60 percent to livestock calories (of the crops studied), so that corn is indirectly responsible for about 25 percent of human calories. Flour and cereals, principally from wheat, contribute another 20 percent. Sweets contribute about 15 percent, and fats and oils other than animal contribute about 10 percent.

No agreement has been reached on the extent to which the postattack diet must reflect the balance of the preattack diet. If the preattack balance is assumed desirable, however, the survival of the first four livestock categories (lamb does not contribute a significant share of meat calories) and the survival of corn, wheat, soybeans, and sugarbeets would be most important. Excerpts from previous tables are shown for these eight commodities in Table 10. The growing period assumption (G) is used for the duration of vulnerability. All entries except the column labeled "Lethal Intensity Contour" have appeared before. The

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* Considerable difference of opinion exists on the importance of protein and other nutritional factors over the short run. Caloric sufficiency surely does not guarantee postattack health for all, but caloric deficiency insures ill health for many.

Table 10

SUMMARY OF RESULTS FOR IMPORTANT RESOURCES

Resource	Code	Fraction of Area (G)	Fraction Vulnerable (G)	Lethal Intensity Contour	Sensitivity	Fraction Lost 1,300 MT (G)	Efficiency† Potential (G)	Efficiency† 1,300 MT
Chickens	11	.84	1.00	225*	.07	.12	8.8	4.9
Hogs and Pigs	12	.84	1.00	127	.06	.17	16.2	5.1
Milk Cows	13	.84	1.00	135	.06	.17	10.2	4.6
Cattle	14	.84	1.00	135	.06	.17	7.2	4.0
Corn	21	.70	1.00	250	.06	.20	12.7	4.5
Wheat	23+24	.55	0.97	106	.06	.26	23.5	2.7
Soybeans	32	.22	1.00	304	.06	.18	29.8	5.3
Sugarbeets	56	.10	1.00	562	.06	.14	83.8	7.2

* In r/hr at one hour.

† The multiple by which damage is increased if the directed attack assumption is used instead of the neutral attack. The "potential" column refers to the limit of low attack weight.

lethal intensity is defined as $D_\ell/(M_t M_{\beta\gamma})$, with standard case values everywhere. Wheat* is the most vulnerable under this criterion, and sugarbeets the least. On the other hand, sugarbeets are most vulnerable on the basis of concentration (efficiency). Even so, the observed efficiencies for sugarbeets are not startlingly out of line, and the fractions lost for all eight at 1,300 MT (growing season assumption) are small and comparable. The sensitivities are also all small and comparable. If the calorie percentages are used as weights, the predicted loss of calories would be about 21 percent, which may be compared with 21 percent fatalities in the SRIA attack.[3]

The greatest sensitivity found in the analysis was the possibility of directing an attack specifically against agriculture. With efficiencies of the order of 4, a twenty percent loss could be turned into an eighty percent one. However, this possibility is considered very unlikely. The next most sensitive assumption appeared to be the length of the vulnerable season. A conservative approach would use the entire growing period as the season of vulnerability for future damage assessments. The suggestion that crops may still be vulnerable if planted after the date of attack is viable, but relatively few instances of such occurrences would be expected nationwide.

Although the results are equally sensitive to uncertainties in lethal doses, total/gamma dose ratio, and dose rate multipliers, the uncertainties probably increase in the order M_t, D_ℓ, and $M_{\beta\gamma}$. The last therefore would be most logical for additional investigations of the three. M_t is not a subject for research, but changes in D_ℓ (including establishment of a zero-yield dose) by a factor of five to ten might occasion a reappraisal of damage estimates.

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* Weighted averages for 75 percent winter wheat and 25 percent spring wheat were used.

The exact shape of the dose-response function for sublethal doses is of little consequence for national damage assessment, and any investigations in this area should be directed toward establishing a D_ℓ end point for zero (or more realistically ten percent) yield.

The results are, of course, quite sensitive to the magnitude of the postulated attack, but usually less than linearly so. The existence of anything dramatic enough to be called a break point with respect to agriculture is rather doubtful, but if it exists it is probably in the 1,000 to 10,000 MT range. Danger points of a similar order of magnitude seem to have been identified with respect to other widespread vulnerabilities.[12]

Part Two

THE IMPORTANCE OF FERTILIZER

by

Pamela G. Kruzic

I OVERVIEW

Within the context of national entity survival is the necessity continually to review and assess areas of vulnerability. Previous studies[1,2] in this series have outlined the principles of agricultural vulnerability assessment and have addressed the complex problem of identifying sensitive subsystem inputs. In the 1969 study[2] a selected group of agricultural practices was reviewed to determine their relative importance in agricultural production. The agricultural practices surveyed were the application of fertilizers and pesticides, irrigation and cultivation, farm use of petroleum and electricity, and trends in cattle and poultry production. Along with petroleum, the availability of fertilizers raised the most serious questions as to the validity of previous vulnerability assessments. The main food and feed crops were found to be quite responsive to changes in soil nutrients. There were also indications that with the increase in fertilizer application rate, some cropland areas now receive near-optimal* levels of fertilization. Further, it was postulated that without the application of soil nutrients, crop production could conceivably be cut in half. The immediate questions arise: How important are fertilizers? What are the critical factors in crop-yield fertilizer relationships? And finally: How vulnerable is the fertilizer industry, particularly from the standpoint of specialized technology and new distribution systems?

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* Optimal in relation to the cost of the fertilizer and the market value of the crop.

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The primary vulnerability from an agronomic standpoint is soil fertility. Factors that limit increased nutrient response and nutrients with high residual or carry-over fertility will be the main issues. From the industrial sector, the impact of technology has been so great as to cause a new configuration in fertilizer production and distribution systems. Although the distribution of fertilizer manufacturing and mixing plants will be of major importance, the impacts incorporate new areas of vulnerability; these include new energy sources and larger demand for high analysis material.* Accordingly, the present task will first examine the growing dependence of food and feed crop production on applied nutrients and then review the impact of technology on fertilizer manufacturing and distribution systems.

Growing Demand for Fertilizers

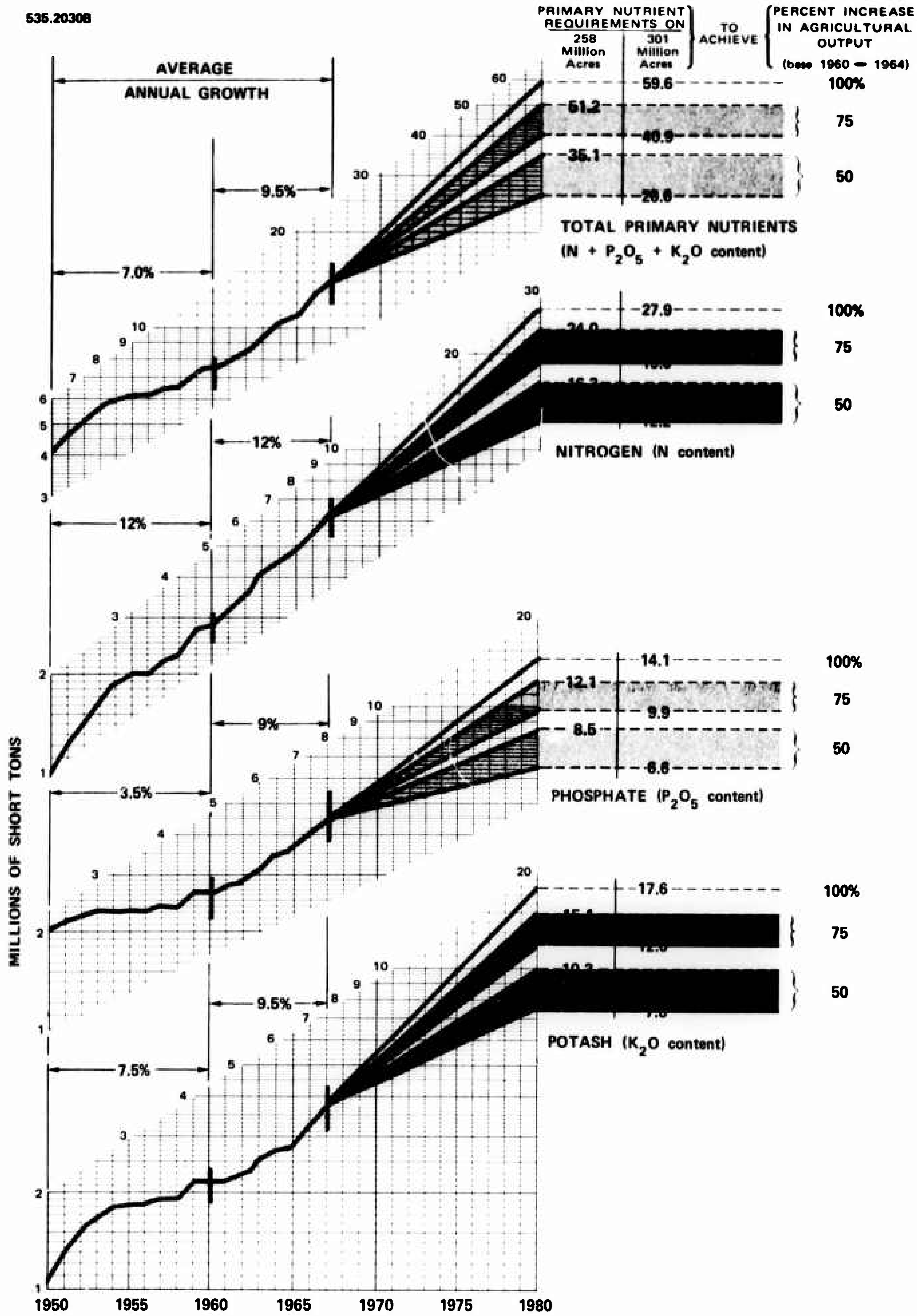
The tremendous increase in population has caused an escalation in agricultural productivity to meet the growing food requirement. Chemical fertilizers have and will continue to play the most critical role of all the technical agricultural inputs in meeting necessary nutritional demands. Changes in fertilizer use--kinds, amounts, time and method of application--have accelerated the demand for nutrients. Total fertilizer consumption increased from 24.5 million tons in 1960 to 37.9 million tons in 1968.

In 1968 the total primary nutrients consumption--Nitrogen (N) + Phosphate (P_2O_5) + Potash (K_2O)--reached 14,629,054 tons. This represents a nine percent increase over 1967.[13] With the use of higher analysis materials the tonnage of N, P_2O_5, and K_2O continues to increase faster than total fertilizer materials.

* Materials with high nitrogen, phosphate, or potash content.

The change in fertilizer use reflects the substitution of fertilizer and other technology for land--higher yields and fewer acres. Total crop production increased eight percent from 1960 to 1965. At the same time, cropland declined nearly 18 million acres, leaving 336 million acres used for crops by 1965. The fertilizer application rate in the United States increased from 58 pounds per acre in 1962 to 86 pounds per acre in 1966.[13]

In 1966 the Department of Agriculture published reports[14] providing (a) a projection of agricultural output by 1980 and (b) various combinations of land use versus fertilizer use that could be employed to achieve that level of output. These basic data have been adapted by SRI[15] to develop a slightly different graphic set of projections for domestic fertilizer consumption. In Figure 14 a range of fertilizer consumption potential is shown for varying levels of increased agricultural output by 1980 as well as for varying levels in land use. In this manner the sensitivity of fertilizer consumption to both land use and agricultural output can be more readily seen. The five branches in each curve of Figure 14 represent different assumptions about the course of agricultural production to 1980. Total production is assumed to increase by 50, 75, or 100 percent over the 1960-64 average; however, in the first two cases that increase could be achieved on cropland areas between 258 million and 301 million acres, depending on the amount of fertilizer used. A balanced mix of fertilizer application is assumed. The actual levels for nutrients, land, and output will be determined by such factors as growth in domestic and foreign demand for agricultural products, the evolution of agricultural technology, competing demands for land, and the replacement of natural products such as fibers by synthetics.



SOURCE: Reference 15

FIGURE 14 UNITED STATES FERTILIZER CONSUMPTION IN 1980—ALTERNATIVES

The results of TVA* research[16] were used to examine the validity of the less land - more fertilizer thesis. Cropland acreage and fertilizer usage data for 1968 from 48 states were used in a regression analysis to determine the gross relationship between total plant nutrient use and cropland harvested. Harvested acreage and fertilizer used were positively correlated at the 99 percent level of significance; 27 percent of the variation in plant nutrient use was associated with harvested cropland acreage. The seemingly conflicting theses that less land means more fertilizer and that more land also means more fertilizer are of course made compatible when the total output assumptions are shown to be different. Further investigation of the cropland fertilizer relationship will indicate whether the United States is currently using near optimum levels of fertilization, as is indicated in Ref. 2.

Industrial Expansion

To make a valid assessment it is necessary to examine developments in several areas and present them in proper perspective. The earlier discussion of growing fertilizer demand, together with an appraisal of factors influencing demand, helps provide this perspective. The reasons for industrial expansion in nitrogen technology and--to a lesser extent--in phosphate, sulfur, and potash technologies provide the background needed to investigate the implications of new developments in terms of vulnerability criteria.

The changes in fertilizer production technology have been a major factor behind the rapid growth in plant nutrient use. In recent years these changes have brought new processes and products to the market at an unprecedented rate. Concurrent with new technology changes--and of

* Tennessee Valley Authority.

primary importance in a vulnerability assessment--have been new developments and innovations in marketing and distribution systems.

The recent changes in the fertilizer supply and demand situation have been revolutionary. The revolution began in the early 1960s and is still in progress. The major factors causing this revolution have been enumerated by Coleman and Douglas[17] as follows:

1. Unprecedented farmer demand for fertilizers
2. Government programs that encourage greater fertilizer use to produce more food
3. Improved technology in producing more economical fertilizers
4. New sources of supply
5. New methods of fertilizer distribution from manufacturer to farmer

Today's farmer has realized the potential profits available through increased fertilizer use. As he became more confident of crop nutrient response, his demands for fertilizer became more specialized. Moreover, the continual shifts in U.S. agricultural policy from eliminating surpluses in the 1950s, to the 1965 and 1966 growing boom, and then back in 1967 to restricting production, have added to the demand for new fertilizer compositions to alleviate the storage and handling problems. Another major factor affecting the overall demand for fertilizers is the existence of agricultural development programs in foreign nations. Recent emphasis has resulted in major increases in fertilizer use, requiring that more fertilizer produced in the United States be shipped abroad. This, of course, gives the United States a great impetus to increase capacity.

On the supply side changes are even more drastic. The technologies of production, transportation, distribution, and use are changing so rapidly that conclusions based on 1963 data are no longer pertinent.

In the area of nitrogen technology alone, changes have been so extensive as to bring about a new configuration of the industry in the last decade. In ammonia plants a 600-ton-per-day capacity was considered maximum in the 1960s. Yet by 1967 there were numerous plants of over 1,000-ton-per-day capacity being built close to the source of low cost natural gas. At the same time, very small plants continue to be constructed, but in special-use areas and for special sets of circumstances.

Suitable methods of supplying fertilizer require an awareness of the developing transportation problems. As one example of this, in 1966 a four state area--Arkansas, Louisiana, Oklahoma, and Texas--used only 667,000 tons of nitrogen fertilizers. At that time the area had productive capacity of about three million tons of nitrogen. Additional plants have been announced that, by the end of 1970, will bring this capacity to more than 5.5 million tons of nitrogen.[17] With such an excess of nitrogen in a small geographic area, attention should be directed to the question of the vulnerability of concentrated production facilities as well as to the postattack problem of transportation and distribution from the point of production to the areas of need. On the other hand, gas pipelines are also vulnerable, so that long supply lines are not only economically prohibitive but also do not solve the vulnerability problem.

II CROP DEPENDENCE ON FERTILIZER

It has been estimated that about one half of the food production in the United States may be attributed to applied fertilizers.[18] In the next decade an even greater portion of our production will be attributed to fertilizer usage. Agronomically, this means a more careful selection and use of fertilizers. No longer will the farmer be able to apply a fertilizer ratio that is not correct for his soil and crop and expect the soil to "buffer" the mistake. Moreover, crop-yield-nutrient response will be highly specific.

According to the USDA Statistical Bulletin 233, farm labor has decreased steadily since 1940, while farm real estate has increased only slightly. However, the largest increase in farm input between 1940 and 1965 has been in fertilizer materials.

An examination of the increasing productivity caused by applying more fertilizer to a given amount of land may help in assessing today's crop dependence on fertilizer.

There was a time when additional crop production needs were met by bringing more land under cultivation. Land was abundant and seemingly unlimited. This situation has changed a great deal, however, during recent years. Harold Walkup stated in his presentation The Effects of Changing Crop Acreages that "from 1950 to 1964 the land area used for crops actually declined from 387 million to 335 million acres. During the same period fertilizer use increased from 4.0 million tons to 10.3 million tons of plant nutrient. Thus one could easily conclude from these facts that when less cropland is tilled more fertilizer will be used." This conclusion is true only to the extent that gross production

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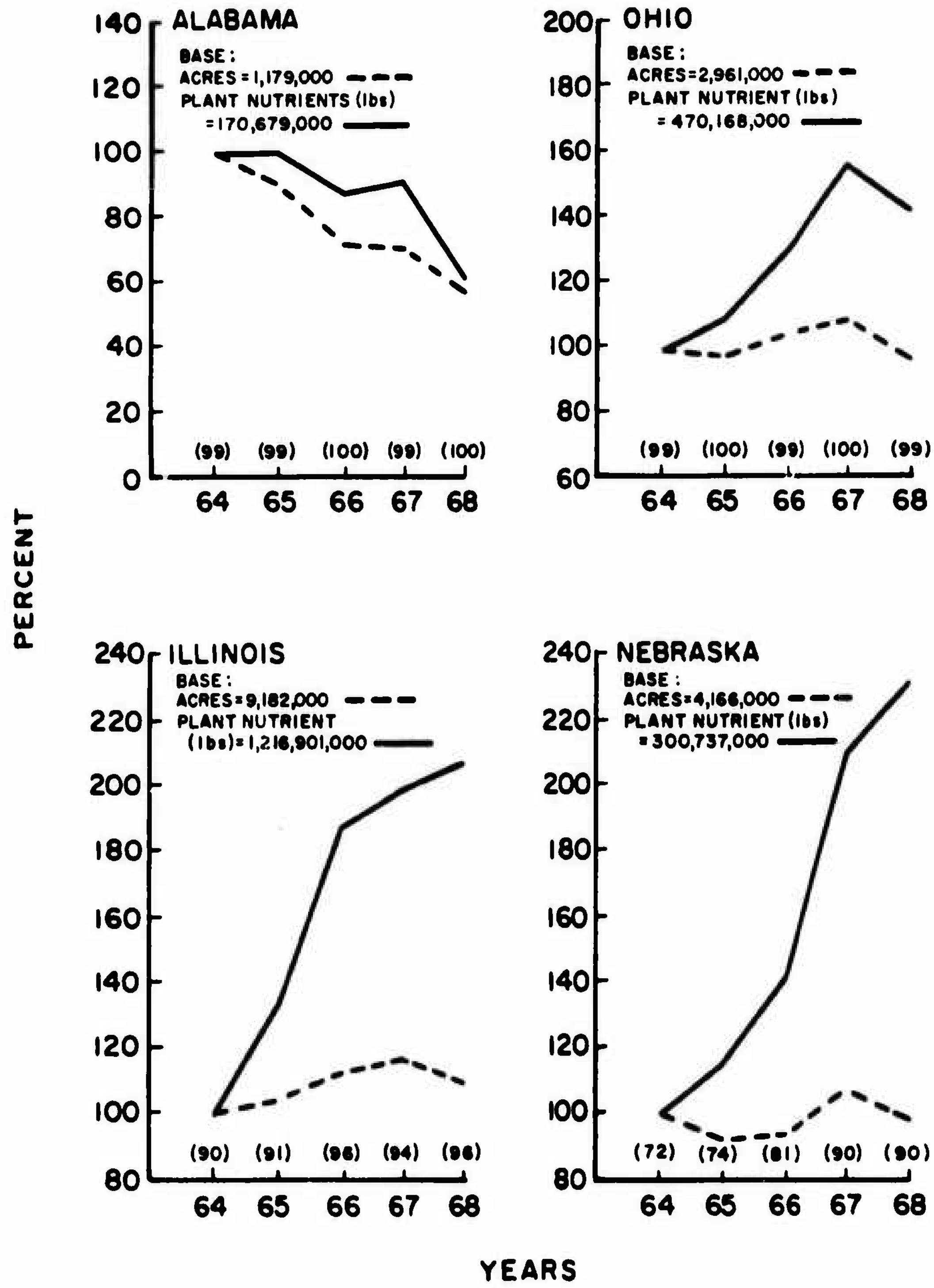
remains relatively constant. The analysis mentioned in Section I shows that when greater production demands are met by expanded land usage, more, not less, fertilizer is required.

Ibach[14] estimated that one ton of NPK (nitrogen, phosphate, and potash) would substitute for 9.4 acres of land at 1960-65 average crop and fertilizer prices and fertilizer use in the United States. If no fertilizer is being used, one ton of fertilizer would substitute for 13.2 acres of land. However, if fertilizer is being used at the economic maximum, one ton of fertilizer would substitute for only 1.9 acres of land. Tennessee Valley Authority workers[16] present a similar argument as follows: they hypothesized that in the older corn fertilizing areas a higher proportion of the corn acreage is fertilized, and that farmers on the average are fertilizing at closer to optimum levels. If so, changes in crop acres in the older fertilizer-using areas should influence use more than in newer fertilizer-using areas. To illustrate this phenomenon numerous graphs were developed. A composite of four of the graphs is presented in Figure 15. These show the corn acreage and the fertilizer used on corn--the index is based on 1964 quantities--for Alabama, Ohio, Illinois, and Nebraska. Also shown in parenthesis for each year is the percentage of the harvested acreage receiving any fertilizer. With a declining corn acreage in Alabama through the 5-year period, fertilizer use on corn declined similarly. In Ohio, also, fertilizer use on corn tended to increase and decrease with changes in crop acres. These relationships suggest that near optimum fertilization is practiced on corn and that almost 100 percent of the harvested acreage is fertilized by Alabama and Ohio farmers. However, in Illinois, and to a greater degree in Nebraska, fertilizer used on corn expanded rapidly during the 5-year period regardless of whether the acreage increased or decreased. The rapid increase in fertilizer use indicates there was a large segment of the market that still had not reached an optimum and



Numbers in parenthesis indicate percentage of harvested acreage receiving any fertilizer.

SOURCE: Reference 16

FIGURE 15 CHANGES IN FERTILIZER USE AND CORN ACREAGE stable level of fertilization. To the extent that a reservoir of unfertilized or underfertilized acreage remains in these states, corn production there has an outstanding growth potential.

The optimum situation in the United States depends on the cost of fertilizer and the price of the product. However, some perspective in this regard is provided by comparing the U.S. situation with that of other countries relative to fertilizer use and land area. In contrast to many countries, the United States has a small fertilizer application rate per acre. From the FAO* Population Yearbook--1967, Volume 21, we find:

Country	Population (thousands)	Cropland (thousands of acres)	Plant Nutrient (lbs/acre)	Wheat Yield (bu/acre)
Denmark	4,834	6,698	162	61.8
West Germany	59,676	20,425	310	48.4
Japan	98,865	14,930	284	36.1
United States	196,920	457,511	54	26.3

Although these yields are dependent on other crop necessities, such as rainfall, the United States is still relatively lower in productivity per acre than it could be under more demanding conditions. Thus, as our population increases, so also will our fertilizer requirements. However, this is a matter of long run trend, and we will continue to increase our fertilizer usage with either increasing or decreasing crop acres.

As soils are more heavily fertilized, continual yield increases will be maintained by optimizing a combination of factors in addition to

* Food and Agriculture Organization of the United Nations.

fertilization. Various factors other than soil fertility limit the ability of a crop to respond to fertilizer. Table 11 identifies the more important limiting factors. However, as Hildreth points out:[19]

> The removal of the limitation of one factor may cause another factor to become limiting. A good example is the response of crops grown in irrigated areas. Often, in dry areas, the supply of soil nutrients is adequate because lack of moisture is the first limiting factor. Once water is applied by irrigation, the supply of nutrients becomes limiting, and fertilization is necessary to make the use of water profitable. Attention to this principle, first set forth by von Liebig in 1840 and known as the "law of the minimum," is responsible for most of the increased agricultural production in this country. The actual yield response of crops in this country has moved steadily upward as the next limiting factor has been identified, studied, and removed. The use of fertilizer has become the most important way to eliminate the limiting factor of low soil fertility.

The agronomic evaluation of fertilizers provides valuable information concerning the various factors that limit the crop yield response to fertilizers. Of the 16 chemical elements known to be necessary for plant growth, 13 are called soil derived nutrients because they normally enter the plants through the roots. Customarily the soil derived plant nutrients are divided into three groups for the purpose of discussing their functions in plants. Table 12 provides a brief summary of the plant food elements.

As production goals are pushed higher and fertilizer usage is increased, the need for secondary and trace nutrients will also increase. Trace nutrient levels that were adequate to produce 10 bushels of corn per acre may be deficient if the yield goal is 150 bushels per acre or higher. This point has been demonstrated by crop experimentation.[21] Where no zinc was applied, corn yielded 134 bushels per acre, but an application of four pounds of zinc per acre as zinc sulfate increased the yield to 155 bushels per acre.

Table 11

LIMITING FACTORS IN YIELD RESPONSE

Limiting Factors	Description
Tillage practices	Poor tillage practices can reduce water availability, cause soil loss through erosion, and otherwise limit response to fertilizer. Yield increases from fertilizer will be greater with ideal tillage practices than with average practices.
Drainage	Excess water in the soil interferes with plant growth and limits yield response to fertilizer. The installation of a proper drainage system removes this limiting factor and usually greatly increases the response to fertilizer. Often, a drainage system will pay off only when combined with application of additional fertilizer and other improved practices.
Weed control	The present trend of using narrow row corn in the Corn Belt is paying off in part because of better weed control. The availability of effective herbicides to control weeds has made higher rates of fertilization profitable on many farms. Only with effective weed control does higher fertilization pay, and vice versa.
Insect control	In much of the world insects limit yields and production. Effective pesticides and other means of controlling insects remove this limiting factor on most U.S. farms. The increased yields from fertilizer can be harvested for income rather than lost to pests.
Variety	The classic example of hybrid varieties of corn illustrates how removal of varietal limitation can increase production. Many improved varieties are profitable only at high fertility levels. As with other limiting factors, once improved varieties are developed, they pay off when combined with other practices.
Climate	Most of the limitations imposed by climatic conditions still must be accepted as part of the uncertainty associated with farming. Research results are providing means of dealing with this difficult limiting factor. For example, the correlation of spring subsoil moisture and yields over a period of years is helping farmers make better judgments about how much fertilizer to use in a given year, based on the subsoil moisture in that year.

Table 11 (concluded)

Limiting Factors	Description
Irrigation	In large areas of the United States irrigation is removing the limiting effect of a shortage of soil moisture. This has made the use of fertilizer profitable in areas where little fertilizer was used before.
Soil pH	The soil environment has to be such that plant nutrients can be absorbed and effectively used by plants. This can be determined in part by pH, which indicates the acidity or alkalinity of the soil. Often, proper soil amendments to alter soil pH make the use of plant nutrients profitable.
Plant stand, planting date, and lodging	The economic necessity of sufficient plant population to best utilize higher levels of fertility has been amply demonstrated. Planting dates also influence fertilizer response. When high yields are accompanied by substantial lodging, the economic benefits from high yields are reduced. As with other factors, the proper consideration of these factors can increase returns to fertilizer.
Resistant varieties	Scientists have been able to develop varieties that are resistant to certain diseases. The reduction of the limitation imposed by disease means that crops can be profitably grown at high levels of fertilization.
Time and method of application	When and how fertilizer is applied affects yield response. The form and rate of fertilizer used also influence when and how it should be applied. By proper placement and timeliness of application, the yield response to a given quantity of plant food can be increased with the obvious increase in profits.

Source: Reference 19.

Table 12

SUMMARY OF PLANT FOOD ELEMENTS

Classification	Name	Symbol	Comment
Primary plant nutrients	Nitrogen Phosphorus Potassium	N P* K†	The primary plant nutrients are so called because the soil normally cannot provide them in the relatively large quantities needed for healthy plant growth.
Secondary plant nutrients	Calcium Magnesium Sulfur	Ca Mg S	The secondary plant nutrients are so called because they are also required by plants in fairly substantial quantities. Adequate amounts are present in some areas but lacking in others.
Trace nutrients	Boron Copper Iron Manganese Molybdenum Zinc Chlorine	B Cu Fe Mn Mo Zn Cl	Trace nutrients are so called because they are required by plants in very small quantities. These elements are available in adequate quantities in many soils. Sandy soils and peat and muck soils are most often deficient. When any trace nutrient is deficient, crop yield will suffer.
Micro nutrients	Sodium Vanadium Cobalt	Na V Co	Certain additional elements may be needed in minute quantities, and research is being conducted by plant physiologists on the subject

* In fertilizer, stated in terms of available Phosphate (P_2O_5).

† In fertilizer, stated in terms of Potash (K_2O).

Source: Reference 20.

Nutrient imbalance produced by heavy fertilization has also been shown to induce trace nutrient deficiencies. The problem of correcting deficiencies exists with identification and proper fertilization. It is doubtful that continued heavy application of primary nutrients with a random mix of trace elements can offer a satisfactory solution to the yield depression response due to nutrient imbalance. Specific identification and prescription fertilization to correct the deficiency are needed. The effective use of fertilizers is measured by the total crop uptake or the degree of recovery of applied nutrients by crops. This is particularly relevant since the uptake values correlate well with yield. Table 13 shows for specified yields the approximate quantities of the major plant foods contained in the harvested portion of the major crops. The yields in the table are well above United States averages in every case, but much below possible yields in many cases. Livestock products also contain significant quantities of plant food that comes from the feed or forage. The approximate values of plant food contained in animal product appear in Table 14.

Corn has been identified as the principle feed component (see Figure 13) and is also the most fertilizer dependent crop. The data in Figure 16 illustrate the high correlation between fertilizer use and corn yield in Nebraska. While the increase in corn yields cannot be attributed solely to increased fertilizer use, the rising use of nutrients and large yields that have occurred during recent years are similar. Nitrogen is the most important of the corn nutrient needs. Few soils have the required quantities unless the nitrogen from a previous legume crop has built up the soil's supply. (When a good stand of alfalfa or other legume is turned under, about 40 pounds of nitrogen per acre are made available.[20]) However, Barber[22] contends that "it is usually much more economical to use fertilizer nitrogen than legume nitrogen . . . ."

Table 13

APPROXIMATE POUNDS PER ACRE OF NUTRIENTS CONTAINED IN MAJOR CROPS

Crop			Acre Yield		Average Nutrients Contained in Crop (pounds/acre)									
Type	Kind	Part	bushels	tons	Nitrogen	Phosphorus as P_2O_5	Potassium as K_2O	Calcium	Magnesium	Sulfur	Boron	Copper	Manganese	Zinc
Grains	Corn	Grain	150	5.25	135	53	40	2	8	10	.1	.06	.09	.15
		Stover		4.5	100	37	145	26	20	14	--	.05	1.5	.30
	Barley	Grain	40	0.96	35	15	10	1	2	3	.04	.03	.03	.06
		Straw		1	15	5	30	8	2	4	--	.01	.32	.05
	Oats	Grain	80	1.28	50	20	15	2	3	5	--	.03	.12	.05
		Straw		2	25	15	80	8	8	9	--	.03	--	.29
	Rice	Rough grain	100	2.25	60	24	12	4	5	4	--	.01	.10	.08
		Straw		3	36	12	80	11	6	--	--	--	1.89	--
	Rye	Grain	30	0.84	35	10	10	2	3	7	--	.02	.22	.03
		Straw		1.5	15	8	25	8	2	3	--	.01	.14	.07
	Sorghum	Grain	80	2	65	35	20	4	5	5	--	.01	.04	.04
		Straw		3	85	25	125	29	18	--	--	--	--	--
	Wheat	Grain	40	1.2	50	25	15	1	6	3	.04	.03	.09	.14
		Straw		1.5	20	5	35	6	3	5	--	.01	.16	.05
Hay	*Alfalfa			4	180	40	180	112	21	19	.06	.06	.44	.42
	Bluegrass			2	60	20	60	16	7	5	--	.02	.30	.08
	*Cowpea			2	120	25	80	55	15	13	.21	--	.65	--
	*Peanut			2	91	22	83	39	15	14	--	--	.20	--
	*Red clover			2	80	20	80	55	14	6	.05	.03	.44	.28
	*Soybean			2	90	20	50	40	18	10	.01	.04	.46	.15
	Timothy			2	48	20	76	14	5	4	--	.02	.25	.16
Fruits & Vegetables	Apples		500	12	30	10	45	8	5	10	.01	.03	.03	.03
	Beans, dry		30	0.9	75	25	25	2	2	5	.12	.02	.03	.06
	Cabbage heads			20	130	35	130	20	8	44	.09	.04	.10	.08
	Onions			15	90	40	80	22	4	16	--	.06	.16	.62
	[a]Oranges			28	85	30	140	33	12	9	.14	.20	.06	.24
	Peaches		600	14.4	35	20	65	4	8	2	.05	--	---	.01
	Potatoes tubers		400	12	80	30	150	3	6	6	.05	.04	.09	.05
	Spinach			5	50	15	30	12	5	4	--	.02	.10	.10
	Sweet Potatoes	Roots	300	8.25	45	15	75	4	9	6	.05	.03	.06	.03
	Tomatoes, fruit			20	120	40	160	7	11	14	.14	.07	.13	.16
Industrial	Cotton	Seed & lint		0.75	40	20	15	2	4	2	--	.06	.11	.32
		Stalks, leaves & burs		1	35	10	35	28	8	--	--	--	---	--
	*Peanuts	Nuts		1	68	8	11	1	2	4	.03	.02	.01	--
	*Soybeans	Grain	40	1.2	150	35	55	7	7	4	--	.04	.05	.04
	Sugar beets	Roots		20	80	27	66	44	32	13	--	.04	1.00	--
	Sugar cane			30	96	54	270	28	24	24	--	--	--	--
	Tobacco	Leaves		1	75	15	120	75	18	14	.05	.03	.55	.07

* Legumes normally get the greater part of their nitrogen from the air. Computed from data in U.S.D.A. Misc. Pub. 369, Morrison's "Feed and Feeding," from a Spec. U.S.D.A. rept. by Lowe, U.S.D.A. Tech. Bul. 1009, Our Land and Its Care, The American Potash Institute, and other sources, by A. L. Mehring.

[a] Eight-hundred 70 lb boxes.

Source: Reference 20.

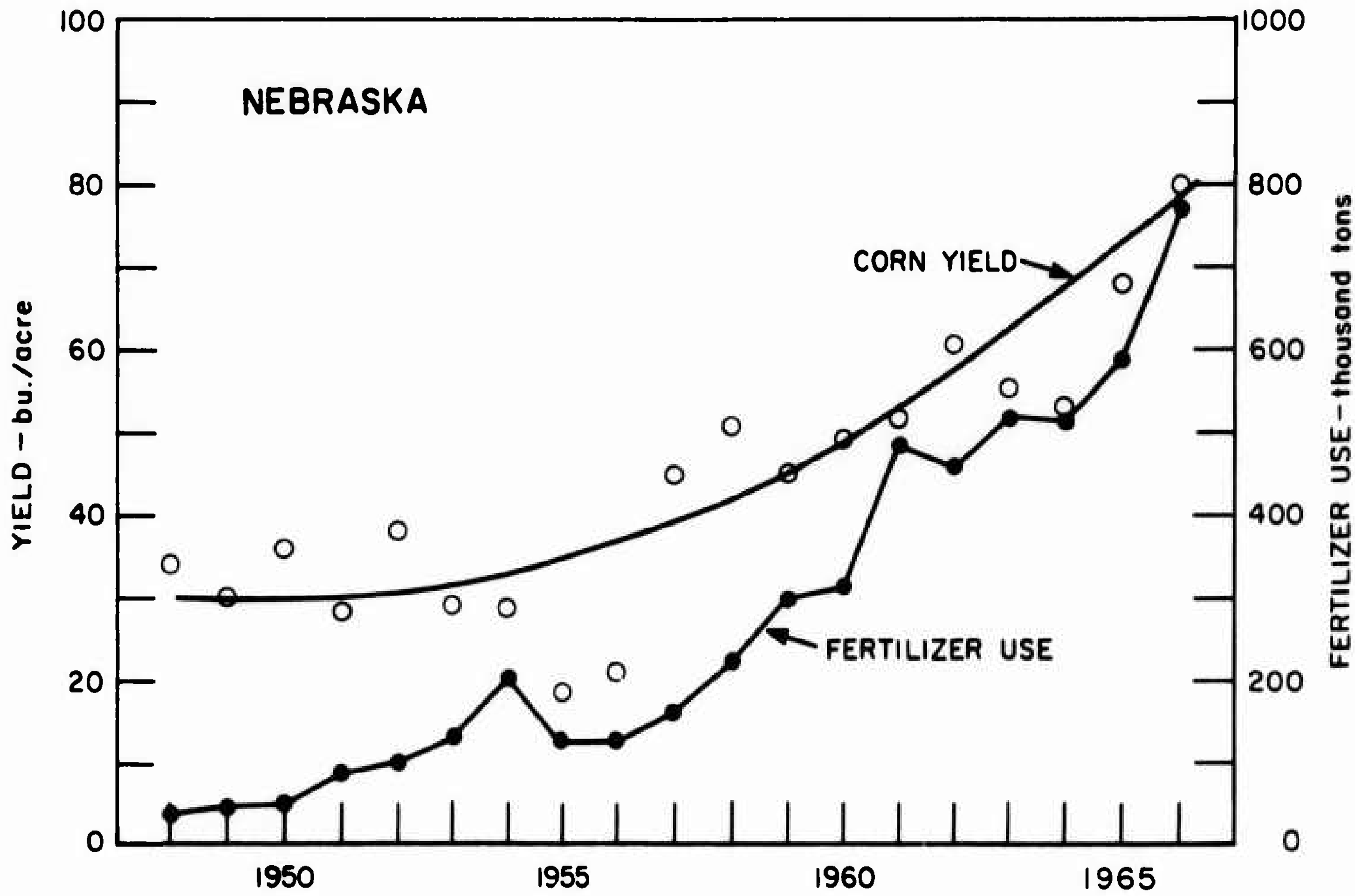
Table 14

PLANT FOOD CONTAINED IN ANIMAL PRODUCTS
(Approximate)

Product	Quantity	Pounds of Plant Food Removed			
		Nitrogen (N)	Phosphate (P_2O_5)	Potash (K_2O)	Calcium (Ca)
Milk	1000 lbs	6	2	2	1
Butter	1000 lbs	2	-	-	-
Fat cattle	1000 lbs (live weight)	27	17	2	13
Fat lambs	1000 lbs (live weight)	20	11	2	-
Wool	1000 lbs	*	10	50	-

* Unknown but probably high.

Source: Reference 20.



SOURCE: Reference 19

FIGURE 16 CHANGES IN FERTILIZER USE AND CORN YIELD

The soil supply of nitrogen is replenished naturally by the combined action of organic matter decomposition, rainfall, and nitrogen fixing organisms. In many soils in the Corn Belt the total nitrogen supplied from these sources is less than 40 pounds per acre per year. Long time experiments on several soils indicate that these soils supply only enough nitrogen under continuous corn culture to produce 30 to 40 bushels of corn annually. Since corn will require 150 to 300 pounds of nitrogen per acre to produce a yield of 120 to 200 bushels per acre, most of the nitrogen has to be supplied as fertilizer.[22] When rates of nutrients that produce higher yields are used, a certain amount will remain to increase the soil fertility level of the next year's crop. The amount that remains will depend on the amount added, the yield, the harvesting method, rainfall, and soil effects. With sustained good management--including heavy rates of manure and commercial nitrogen or legumes, or both--turnover nitrogen in the soil increases substantially so that more of the nitrogen requirements of the growing crop are met by the "nitrogen cycle" in the soil.

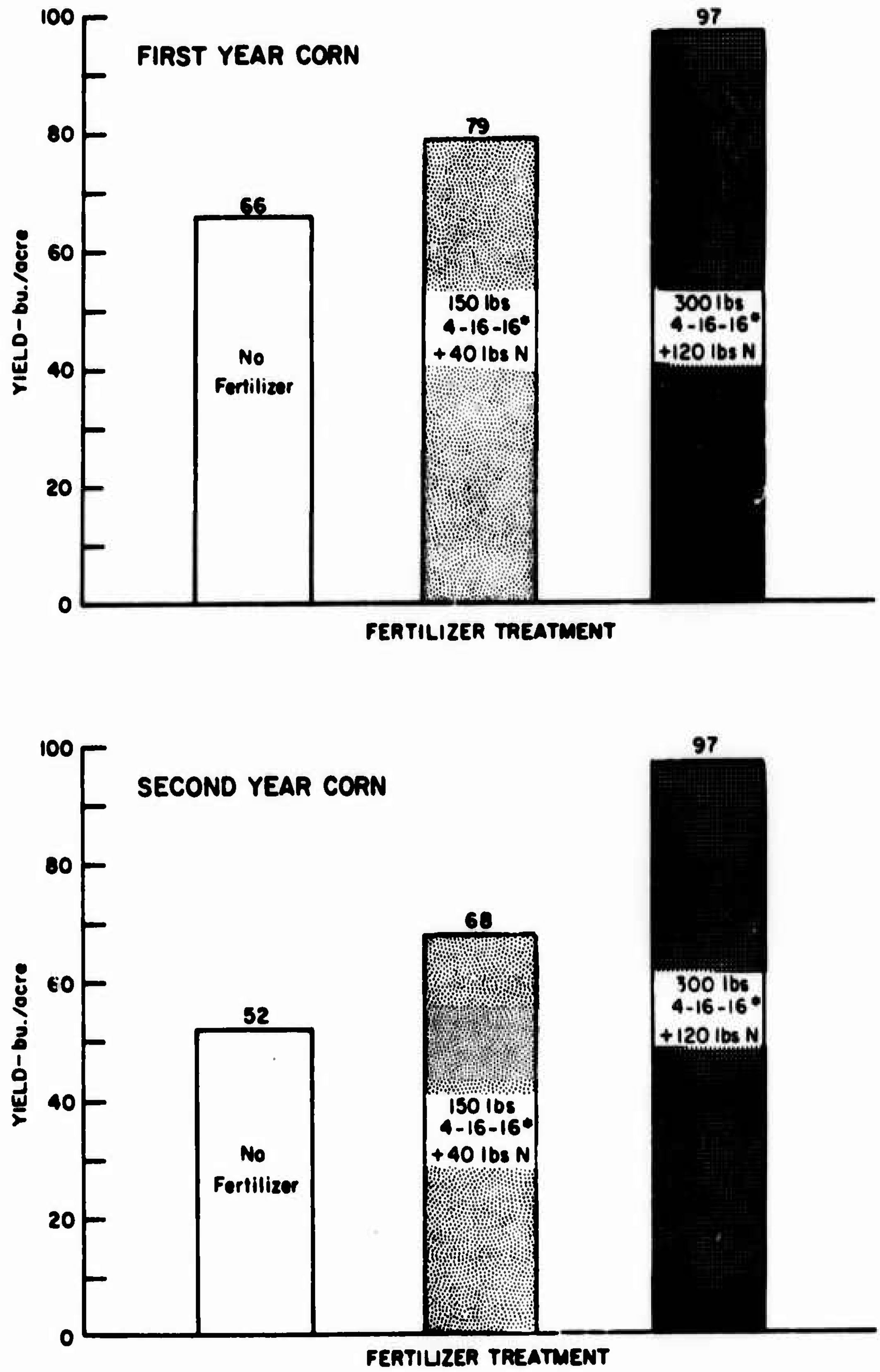
Barber[22] studied the carry-over of nitrogen on the prairie soil in Indiana with an annual rainfall of 35 to 40 inches. The residual effects of nitrogen applied in 1960-61 were considerable. Table 15 shows how the response in the corn yield to nitrogen applied in 1962 was influenced by the amount of nitrogen used in the previous years. The effect on the succeeding year's crop was as if about one-third of the amount applied in the previous year had been carried over in this silt loam soil. Figure 17 further illustrates the carry-over effects from the previous year's mixed fertilizer treatment. Without fertilizer, the continuous corn yield is decreased 32 percent the first year and 47 percent the second year. Low fertilizer application the second year represents a 30 percent loss in crop production.

Table 15

THE RESIDUAL EFFECT OF NITROGEN

Nitrogen Applied in 1962	Nitrogen Applied in 1960 and 1961: 0	50	100	150
	1962 corn yield -- bu/acre			
0	55	71	88	104
50	99	112	123	135
100	128	137	146	154
150	147	152	157	161

Source: Reference 19.



*Grade ratio, where the numbers refer to the percents nitrogen, available phosphate, and potash, respectively. This mixed fertilizer was supplemented by additional amounts of nitrogen as shown.

SOURCE: Reference 20.

FIGURE 17 RESIDUAL EFFECTS OF FERTILIZER ON CONTINUOUS CORN YIELD

It should be noted that harvesting only the grain results in far less stress on the soil's nutrient supply than harvesting the entire crop for silage. As indicated in Table 13, only nitrogen, phosphorus, and sulfur are contained in major proportions in the grain. Zinc and copper are about equally distributed between grain and stover; while potassium, calcium, magnesium, manganese, and boron are concentrated in the stover. Thus, soil fertility problems will occur sooner with silage production than when harvesting for grain only.

Since soluble phosphorus does not move appreciably in the soil and tends to revert to less available forms, plants seldom use more than 10 to 30 percent of the phosphorus in a fertilizer during the first season after application. This means that considerable residual phosphorus remains for future crops. The availability of this residual phosphorus varies with soils, but it is not influenced to any great extent by the initial source of citrate-soluble phosphorus. Even with the use of low rates on low testing soils, significant source defects are not commonly observed in the second season following application. In Minnesota the phosphorus soil test showed an increase from 8 pounds with no phosphorus to 170 pounds with 800 pounds of phosphorus per acre plowed down. In Iowa, an increase of 17.6 pounds of phosphorus per acre increased corn yields 18 bushels the first year and, with no further application, 15 bushels the second year.[19]

Potassium, a cation, attaches to negatively charged soil particles; hence, potassium stays about where it is put. Except in very acid, very sandy, or low exchange capacity soils, there is little chance of loss by leaching. Studies on several Illinois silt loams showed annual losses of only 2 to 5 pounds of potassium per acre.[19] As with phosphorus, some fixation may occur on some soils with a high mica content. However, such fixation is generally a reversible reaction and, except in soils very low in potassium, may be looked on as "storehouse potassium."

The carryover of trace and micro nutrients (see Table 12) depends on both the soil characteristics and the composition of the fertilizer applied. The shift from light application of mixed materials to heavy fertilization with high analyses primary nutrients causes nutrient imbalance. However, the relatively low trace element requirement of crops, combined with an awareness of the soil nutrient interaction, reduces overall the vulnerability of these elements. Nelson and Hansen[19] report that "a modest application of an element such as zinc may produce residual response three to four years after initial application." In a postattack recovery period of two to three growing seasons there would be little concern for anything but primary nutrients. Generally, in the United States crop response to applied nitrogen has remained high while crop response obtained with potassium and phosphorus has declined. The latter two elements accumulate in most soils as a result of fertilizer application. In contrast, nitrogen is relatively mobile, and removal by cropping, leaching, and volatilization tends to be high. Thus, nitrogen is more frequently a limiting factor in crop production than phosphorus and potassium.[23]

III CHANGES IN FERTILIZER PRODUCTION AND DISTRIBUTION

The accelerated use of fertilizers, technological breakthroughs, and the discovery of new raw material sources have called for reappraisal of the vulnerability of the fertilizer industry. Distribution and marketing systems have been in a state of continual change. New methods will continue to evolve as the industry adopts additional innovations. Although detailed statistics are not available to pinpoint all of the changes in production and distribution patterns, certain trends can be isolated and studied. This section will describe major trends in an effort to present a clearer picture of the industrial vulnerabilities.

Three distinct levels of traditional fertilizer marketing may be enumerated as follows:

1. Production of one nutrient by a primary producer
2. Mixing of various single plant nutrients by wholesalers
3. Distribution of mixed fertilizer to farmers by independent retail dealers

By 1950, however, new types of fertilizers and new demand patterns made it impossible to handle mixed fertilizers by the traditional method. J. R. Douglas[19] explains, that "new high-analysis multinutrient fertilizers dictated new shipping patterns with much greater use of freight cars and barges. This system of distribution made fertilizer marketing less dependent upon the mixer or wholesaler.

"The increased demand for fertilizer, especially in the Midwest, created a high-density demand for prescription fertilizers. Such fertilizers could be made economically by blending two or more high-analysis, multinutrient compounds near the areas of consumption. Thus,

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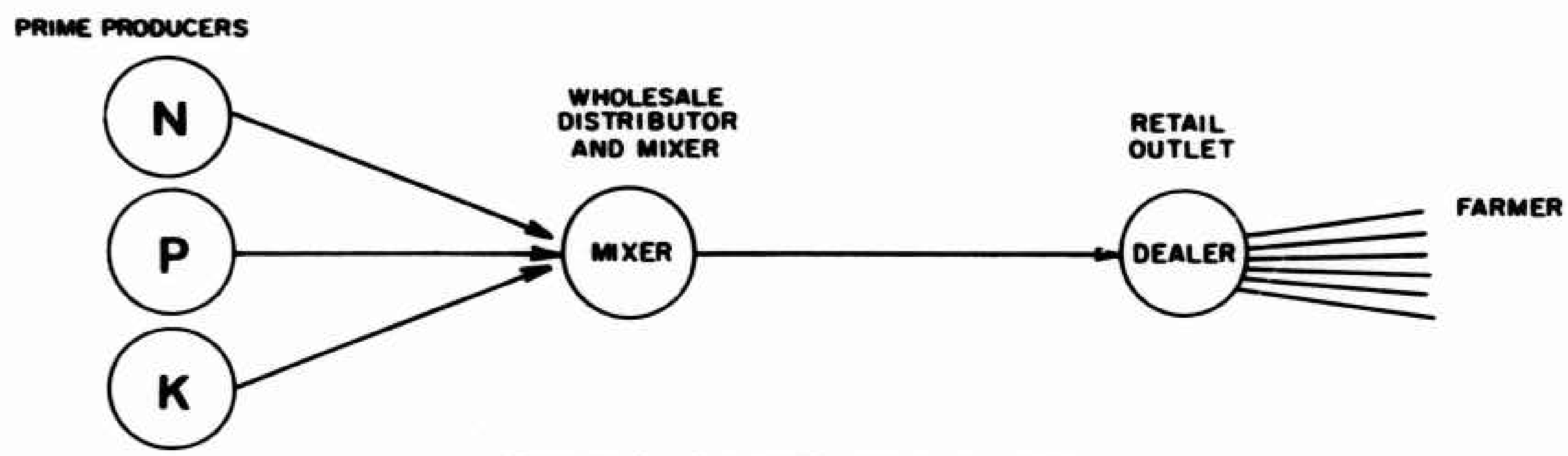
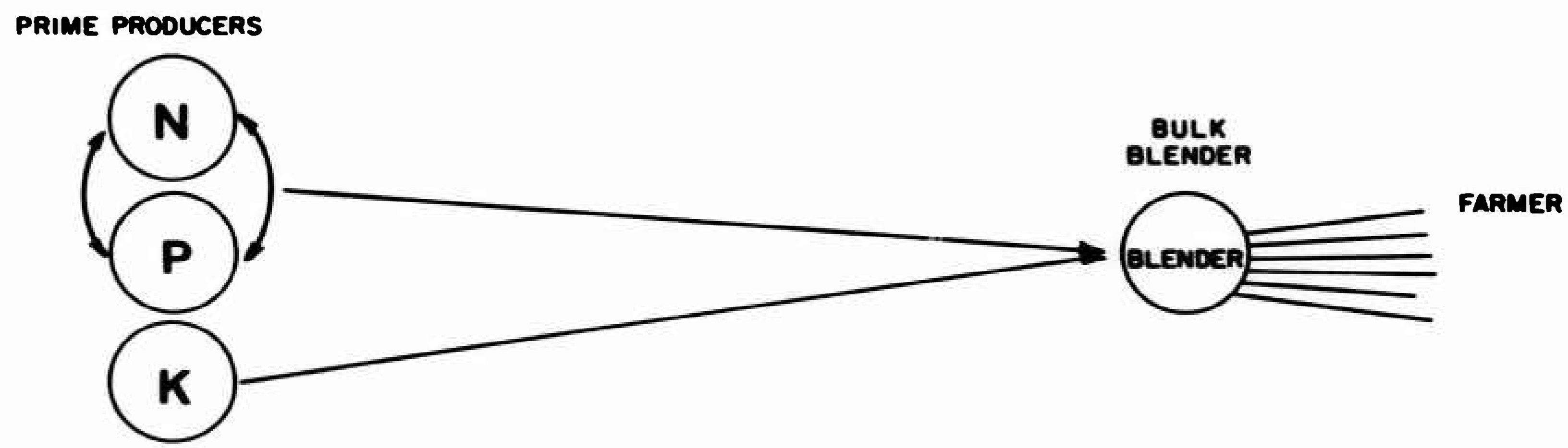
bulk blend plants became a part of the new distribution and marketing system. This system requires only a primary producer and the retail blender-dealer. The wholesale distributor is eliminated." Figure 18 illustrates the contrast between the traditional distribution system and the new system based on the retail blender-dealer.

From 1950 to 1960, the rapid growth of the U.S. fertilizer industry was primarily limited to the nitrogen sector. The 1962/1963 fertilizer year marked the beginning of a continuing period of rapid growth in phosphoric acid-based fertilizers. Fertilizer manufacturers felt the farmer demand for more fertilizers. This provoked a national boom in the construction of new fertilizer plants. Many of these new plants began production in 1966, thus creating adequate supplies. Phosphatic material was about 4,461,000 tons of P_2O_5, up 22 percent from the year before. The net supply of nitrogenous fertilizers was about 5,645,000 tons of nitrogen, up 14 percent, and potash for fertilizers was about 3,222,000 tons of K_2O, an increase of 19 percent over the previous fertilizer year. The total supply of fertilizers in 1965/1966 of 13,428,000 tons was 15 percent more than in the 1963/1964 fertilizer year and double that of eight years ago.[24] By 1966, production and consumption were in reasonable balance. In 1967, the revolutionary increase in fertilizer production created a surplus. This, coupled with lower than expected spring consumption resulted in the largest inventories of nitrogen, phosphate, and potash fertilizers in the United States that the industry has ever known.

The general picture for fertilizer production and consumption in 1970 is excess capacity. It is interesting, however, that in the last year there has been no indication of a major increase in production growth to meet future needs. Figure 19 shows the total announced plant capacity to produce nitrogen, phosphate, and potash fertilizers. These



TRADITIONAL DISTRIBUTION SYSTEM



BULK-BLENDING DISTRIBUTION SYSTEM

Source: Reference 19.

FIGURE 18 COMPARISON OF TRADITIONAL AND BULK BLENDING DISTRIBUTION SYSTEMS

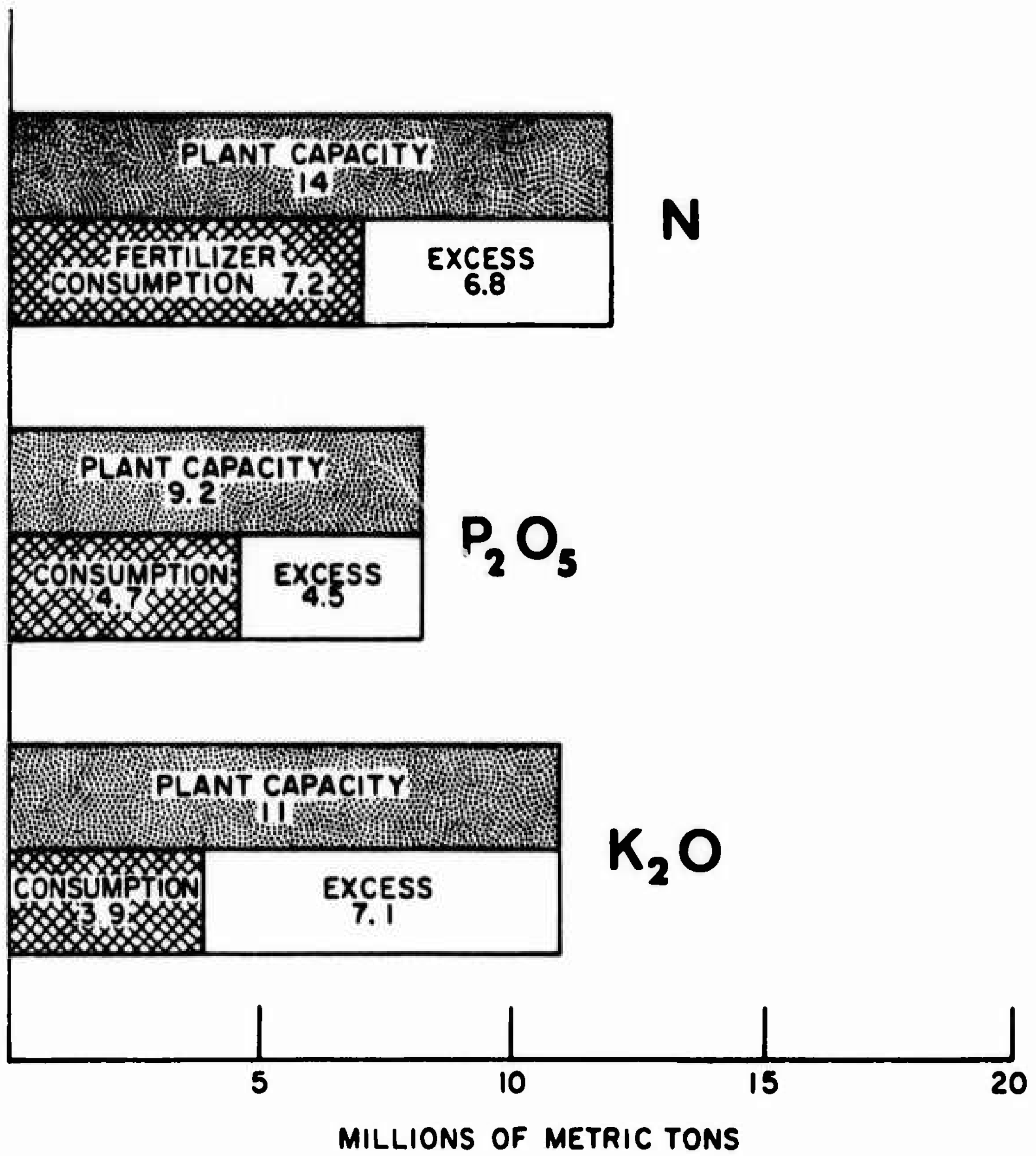


FIGURE 19 UNITED STATES PLANT CAPACITY AND NUTRIENT CONSUMPTION—1970

capacities can be considered as a reasonable measure of production potential. The figures are based on actual or optimum tons-per-day (tpd) rates, and represent the truest measure of capacity but not necessarily of actual annual output. The plant capacity is compared with estimated fertilizer consumption. This chart indicates that if no more plants are built there will be more than adequate plant capacity to meet anticipated fertilizer use in 1970. The excess includes three components--the non-fertilizer use (industrial and other), processing and shipping losses, and surplus and plant abandonment. Phosphate appears to be the only plant nutrient reasonably close to a supply-demand balance, because its surplus component is relatively small. Other factors must also be considered in evaluating the supply and demand situation. The plant operating requirements, the location and size of production units, and new raw materials sources will also have an effect on the postattack availability of fertilizer materials.

Nitrogen production facilities are located throughout the country, but recent trends indicate a clustering near raw materials resources. Ammonia, the major nitrogen fertilizer, consists of approximately 82.5 percent nitrogen. This nitrogen is drawn from the atmosphere. The other component of ammonia is hydrogen, which is 17.5 percent by weight of the total. The hydrogen requirement for ammonia in this country is manufactured from natural gas. Much of our gas comes from fields in the Gulf Coast regions and from the northern and southern plains states. The gas is transported in major pipelines to the north and east. Table 16 shows that the regions with increased ammonia capacity closely parallel the major gas fields and general gas producing areas in the United States. The ammonia fertilizer requirements in OCD Region IV[1] illustrate the supply and demand problems to be discussed later.

Table 16

SYNTHETIC AMMONIA CAPACITY COMPARED WITH U.S. AGRICULTURAL NITROGEN CONSUMPTION AND NATURAL GAS

OCD Region	Agricultural N Consumption (Thousands of Tons NH_3 Equiv.) Anhydrous[a] Ammonia	Total[a] N	Potential[b] N	Synthetic Ammonia Capacity[c] Tons (000's) 1968	1971	Natural Gas Equiv. 1971[d]	Natural Gas--1968 (BCF) Production	Reserve
Region I	3	161	226/ 407	160	110	3.3	5	124
Region II	86	577	798/ 1,129	1,530	1,943	58.5	461	5,672
Region III	152	1,211	1,251/ 1,573	2,444	2,611	78.2	138	1,434
Region IV	858	1,691	2,040/ 2,467	960	522	15.8	45	1,130
Region V[e]	362	992	1,402/ 2,217	5,912	8,342	250.1	16,623	243,243
Region VI	1,218	2,287	2,600/ 4,030	2,275	2,635	79.22	1,255	20,863
Region VII[e]	199	619	540/ 763	1,095	1,259	37.7	779	13,725
Region VIII	97	411	503/ 994	329	303	9.0	19	912
Total U.S.	2,975	7,949	9,356/13,580	14,705	17,725	53.8	19,325	287,103[f]

Table 16 (concluded)

Footnotes

a. Data are on a fertilizer year basis ending June 30, 1968.

b. Data are based on Recommended Nitrogen Application Rates and 1964 Harvested Acreage, by crops. Data were reported in the source on an N basis and have been converted here to an NH_3 equivalent. Data before the virgule (/) exclude hay and pasture; data after the virgule (/) represent total potential consumption including hay and pasture.

c. Data for 1971 considered only as optimum capacity that might be available for ammonia production.

d. Data are Chemical Engineering Handbook estimates based on an average of 30 million cubic feet of gas per ton NH_3. Data are stated in terms of Billions of Cubic Feet (BCF). Data represent Natural Gas requirement for total capacity although it is recognized that not all plants use natural gas as a hydrogen source.

e. Includes offshore reserves.

f. Includes reserves (a total of 245 BCF) not separately reported for Alabama, Arizona, Florida, Iowa, Maryland, Missouri, Tennessee, and Washington.

Sources: Chemical Economics Handbook, Stanford Research Institute, February 1969.

Consumption of Commercial Fertilizers in the United States (annual), U.S. Department of Agriculture.

Potential Fertilizer Consumption in the United States, Technical Bulletin No. 12, September 1965, The Sulphur Institute.

Minerals Yearbook (annual), U.S. Department of the Interior, Bureau of Mines.

Committee on Natural Gas Reserves, American Gas Association.

The technology of the phosphate industry has also been responsible for changes in regional production. There has been a trend to produce more phosphatic fertilizers at mine sites and ship intermediates and finished fertilizers to areas of consumption rather than to ship phosphate rock for processing. Production capacity for phosphate rock totaled 39 million tons in 1967, with Florida as the primary area. Further expansion will most probably occur in Florida. These new operations may well lead to a major shift in phosphate production facilities. Improvements in technology have reduced the production and distribution costs of wet-process phosphoric acid. Low prices and new supply areas, together with a growing demand for high analysis fertilizers, account for an expansion of this process, which will soon produce more than 80 percent of the phosphoric acid in the United States. Of the new plants being constructed only one is located in Florida.

Potash traditionally has been processed at mining locations. However, the location of potash mines in North America has changed considerably. While U.S. mining areas have expanded to the western states, several of the major reserves in New Mexico that can be mined economically are almost depleted. Canadian potash production, on the other hand, is growing rapidly. Potash production since its inception in 1962 has increased to over two million tons in 1966. By the end of the year, Canada is expected to be producing more potash than the United States. Since relatively small amounts of potash are consumed in Canada, the United States has become a major importing nation once again.[17,24]

Along with the tremendous manufacturing output, there have been significant changes in the size of nitrogen production facilities. In 1950, there were 20 producers of ammonia in the United States. By the end of 1970, there should be 67 producers at approximately 100 locations.[25]

Spurred by the strong growth in the total ammonia market and by the peaked in-season demand, larger capacity cryogenic storage facilities were designed to hold ammonia at atmospheric pressure.[17] A major innovation came when the centrifugal compressor was engineered into an ammonia plant design concept permitting substantial reduction in plant investment. There were, however, two important qualifications on the use of the centrifugal compressor. It was not practical in plants with a capacity below 600 tons per day, and the efficiency of such small plants dropped rapidly at production rates below 70 percent of capacity.

Thus, both existing and prospective producers scrambled to build more retail distribution and erect the storage facilities necessary to market expanding plant capacity. Today, most of the new plants are expected to be in the range of 1,000 to 1,500 tons per day--possibly 3,000 tons per day.

At the same time, however, at least 14 small plants of less than 100 tons per day were constructed. They were built with limited market areas in mind and were sized to fit a specific demand. They were not built for integration into large regional distribution areas. In comparison with the large ammonia plants, lower distribution and marketing costs partially offset the higher production costs.

Unfortunately, fertilizer cannot always be produced in the regions where it will be used. In order to be produced most economically, fertilizers must be manufactured near the cheapest source of raw materials. Thus, there will always be an imbalance in the regional supply-demand situation as long as production costs are considered the sole criteria for location of manufacturing facilities. This imbalance is well illustrated with the 1968 supply and demand of primary nutrients in Figure 20. The representative data for this are presented in Table 17.

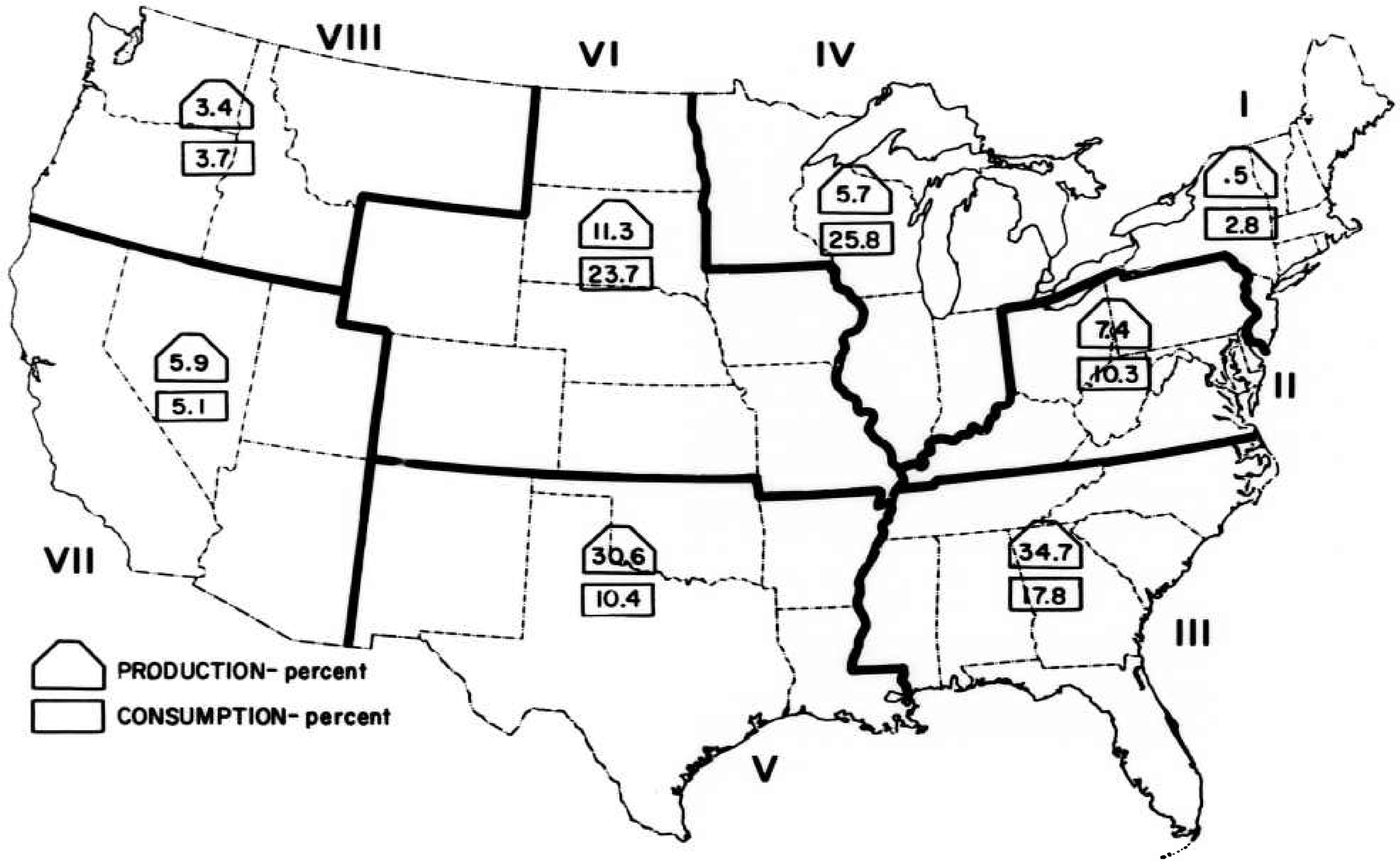


FIGURE 20 PRODUCTION AND CONSUMPTION OF PRIMARY NUTRIENTS—1968

Table 17

SUMMARY OF TOTAL PRIMARY NUTRIENT PRODUCTION CAPACITY AND FERTILIZER CONSUMPTION--1968

Region	Production Capacity: 10^3 tons $N+P_2O_5+K_2O$	Production Capacity: Rank Order	Production Capacity: Distribution (percent)	Fertilizer Consumption: 10^3 tons $N+P_2O_5+K_2O$	Fertilizer Consumption: Rank Order	Fertilizer Consumption: Distribution (percent)	Regional Situation 10^3 tons $N+P_2O_5+K_2$: Surplus	Regional Situation 10^3 tons $N+P_2O_5+K_2$: Deficit
I	160	8th	0.5	419	8th	2.8		- 259
II	2,239	4th	7.4	1,542	5th	10.3	+ 697	
III	10,386	1st	34.7	2,656	3rd	17.8	+ 8,730	
IV	1,731	6th	5.7	3,852	1st	25.8		-2,121
V	9,177	2nd	30.6	1,562	4th	10.4	+ 7,615	
VI	3,395	3rd	11.3	3,543	2nd	23.7		- 148
VII	1,778	5th	5.9	771	6th	5.1	+ 1,007	
VIII	1,042	7th	3.4	557	7th	3.7	+ 485	
Total U.S.	29,908			14,911			+14,997	

This table compares the total primary nutrient (N, P_2O_5, K_2O) capacity and consumption. Over 34 percent of the nutrients are produced in the southeast region. This makes Region III the primary producer but only third in 1968 consumption. Regions I and VIII are generally identified as areas of low production and consumption. However, while Region IV is one of the smallest fertilizer producing areas, it demands over 25.8 percent of the consumed nutrients. This highly agricultural area is generally referred to as the Corn Belt. The regional supply and demand figures for nitrogen, phosphate, and potash are presented in Table 18. Again, Region IV shows the largest production deficiencies. There are no facilities for potash production, and area production capacities for phosphate fall short by 19[illegible] 000 tons. With a nitrogen production capacity only 725 thousand tons, over half of the nitrogen consumed must be supplied from other areas.

Ten years ago fluid fertilizers and bulk blends were just beginning to develop. Now both are playing a very important part in the marketing of fertilizers. As bulk blends became more popular, companies with regional granulation plants developed granulation bulk handling systems to help them market fertilizers on a more competitive basis. In such a system, a few granular fertilizer ratios are produced, shipped to a low-cost bulk handling station, then marketed as bulk complete mixtures. Also, new raw materials are beginning to appear--like superphosphoric acid--to increase the utility of small granulation plants.

Bulk blend continues to grow in importance as a fertilizer distribution system. It began in the Midwest, to satisfy the farmers' demand for fertilizers at low costs. In 1959, there were less than 200 bulk blend plants in the United States. Most of these were in the Corn Belt region. By 1966, an estimated 3,149 bulk blend plants were scattered across the nation.[24] Over 60 percent of these were located in the North Central areas, as shown in Figure 21.

Table 18

REGIONAL SUPPLY-DEMAND OF PRIMARY NUTRIENTS--1968
(Thousands of Metric Tons)

Region	Nitrogen (N)		Phosphate (P_2O_5)		Potash (K_2O)	
	Supply	Demand	Supply	Demand	Supply	Demand
I	160	138	0	153	0	128
II	2,204	481	35	519	0	542
III	2,979	1,009	7,407	720	0	927
IV	725	1,375	1,006	1,200	0	1,277
V	8,130	909	1,047	435	3,320	218
VI	3,183	1,971	212	1,015	0	557
VII	1,338	511	440	204	921	56
VIII	346	337	696	181	4,251	3,748
Total U.S.	19,065	6,736	10,843	4,427	4,251	3,748

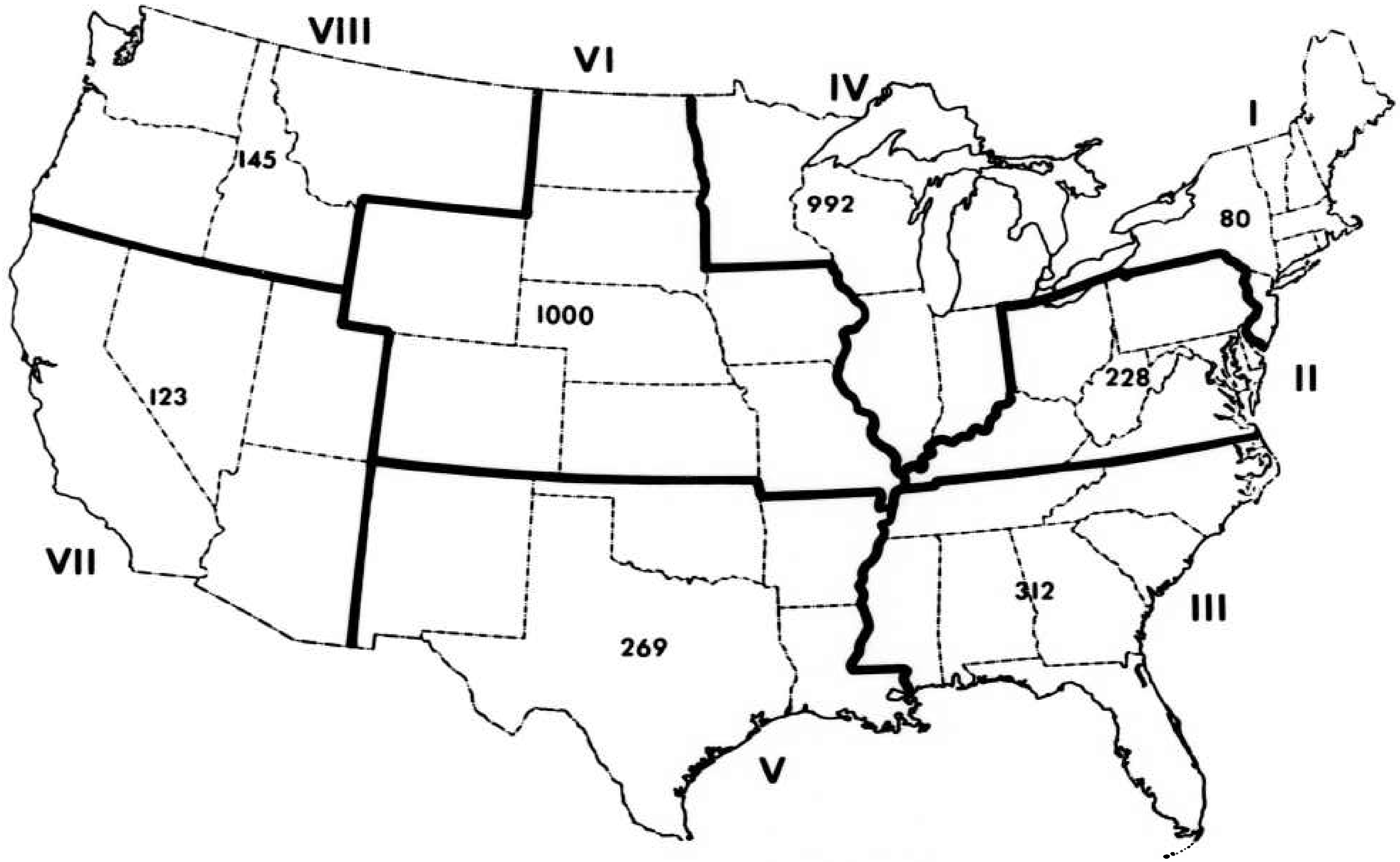


FIGURE 21 ESTIMATED NUMBER OF BULK BLEND FERTILIZER PLANTS

Farm Chemicals magazine has conducted intensive surveys of bulk blend facilities in the country. Douglas and Coleman[19] report these surveys show that "one of the current major objectives of the bulk blender is to add complementary enterprises to utilize personnel and facilities more effectively throughout the year and thus increase sales and profits while decreasing overhead costs per ton of fertilizer handled.

"Some people connected with the industry over a long period of time believe that bulk blending is merely a return to a modified traditional distribution outlet which has been adapted to the new fertilizer materials available. It is accommodating itself to the farmers' demands for additional services. The emphasis is on a full line of services to furnish a total farming system for the farmer. This includes not only farm input factors, but also relevant educational materials."

Liquid mixed fertilizers are also emerging as a new distribution method. Recent innovations in distributions and handling have caused liquid mix fertilizers to gain favor with farmers and dealers. Although the increase in the number of liquid mix producers has not kept up with the number of bulk blend facilities, growth has been consistent and rapid. By 1966 there were 1,229 liquid mix plants in the United States.[24] As seen in Figure 22, the practice has spread to all regions of the country.

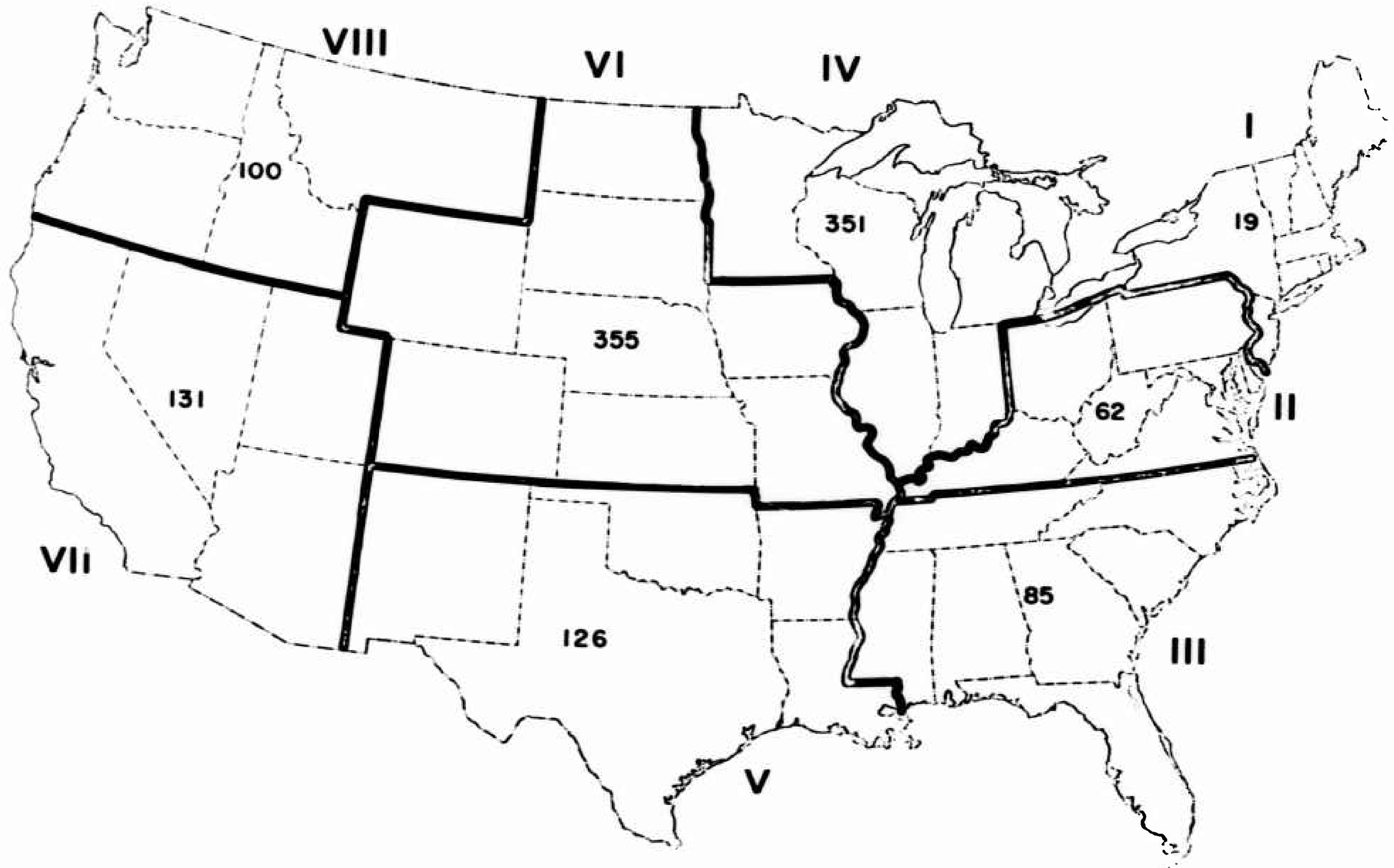


FIGURE 22 ESTIMATED NUMBER OF LIQUID MIX FERTILIZER PLANTS

IV VULNERABILITY IMPLICATIONS

Increasing agricultural production is sustained by nutrient application. Crops depend on fertilizer for high levels of soil fertility. Increased food and feed requirements demand heavy application rates and agronomically efficient fertilizers. At the same time, technological abilities have expanded the agricultural chemicals industry. Concentrated areas with large production capacities are evident. Abundant supply lessens national vulnerability, but regional excesses indicate trends toward sensitive distribution systems. Also, more specialized demands require selective inputs and refined processing techniques.

The decline in U.S. cropland plus the need to increase productivity create a greater crop dependence on fertilizer. Application rates are climbing toward the economic optimum and beyond. As primary nutrient demands are satisfied increasing increments in yield become more complex, the relative importance of other yield limiting factors is increased, and the crop yield response becomes highly specific. High productivity will be maintained by increasing amounts of fertilizer in combination with other agricultural practices.

The most critical soil nutrient is nitrogen. Phosphate and potassium are rather immobile nutrients and crop recovery is lower than for nitrogen. Corn, the major food and feed crop, does not require much phosphorus. Moreover, since phosphorus is relatively immobile in the soil, only 10 to 20 percent of the phosphorus added as fertilizer will be used by the immediate crop. The major portion remains in the soil to built up the phosphorus fertility level of the soil so subsequent crops can use it.

Potassium is required in large amounts by corn but is readily fixed in most soils. In contrast, nitrogen acts as a relatively mobile nutrient and crop requirement and removal tend to be high. Although there is little accumulation due to volatilization and leaching, some residual effects can be expected. Trends toward greater application rates will increase the residual or carry-over fertility. Approximately one third of the applied nitrogen should be available for the following year's crop. If continuous application of 150 pounds of nitrogen per acre produces about 160 bushels per acre, the second year crop with a 50-pound nitrogen equivalent carry-over might yield close to 100 bushels of corn per acre, even if no additional fertilizer were applied. The effects of residual power and the trend toward increased soil fertility indicate productivity losses of less than 40 percent without fertilization. However, as more optimal levels of fertilization are used, increasing increments in yield will become more difficult to attain. Thus, the general conclusion that complete loss of fertilizer would severely curtail yield remains valid.

Since corn does not have sufficient protein to form an adequate protein diet for animals, it is pertinent to note the change in corn quality with increased nutrient application. Fertilization with nitrogen will increase the protein content of corn grain where nitrogen is deficient although it may not increase the amino acids that often limit the feeding value of corn. Corn usually has about 9 to 10 percent protein. An application rate of 100 pounds of nitrogen per acre increases yield from 115 to 139 bushels per acre and increases protein content 7.8 to 9.6 percent.[20] The development of new varieties, higher in total protein and lysine, may increase the significance of nitrogen fertilization.

Accelerated fertilizer use coupled with demands for "prescription" fertilizers presents a new degree of sensitivity to the fertilizer industry. Anticipated changes in both soil fertility and agronomic needs will dictate new ways to increase agricultural production. As the technology develops the industry becomes more vulnerable in terms of recovery. New product innovations require a greater technological dependence.

The change in crop nutrient requirements has in turn caused divergent trends in the size of fertilizer production facilities. The complexity of new processes lead to the development of numerous large scale plants built close to the source of low cost natural resources. At the same time, very small plants continue to be constructed, but in special use areas and for special sets of circumstances.

The dispersal of small plants is valuable in terms of recovery accessibility. However the largest percentages of nutrient production are clustering in concentrated areas and represent increased vulnerability.

New locations of production facilities lead to new distribution and marketing channels. With large plants located far from the end use area, additional regional outlets were developed. This new growth tends to decrease vulnerability by providing storage for large quantities of material along short direct farm delivery routes.

Industrial vulnerabilities of primary nutrients vary. New potash sources will come from Canada, which tends to increase the vulnerability implication associated with transportation. In the case of phosphate, over 80 percent of the phosphoric acid production is concentrated in Florida, with the remaining phosphate facilities clustering in California, Alabama, and New Mexico. Although the production facilities are generally outside of SMSAs, the intense areas of concentration are quite vulnerable.

Although the nitrogen facilities are dispersed throughout the country, technological trends show the concentration of large scale plants near sources of natural gas. Louisiana and Texas alone account for almost 40 percent of the U.S. nitrogen capacity.

Table 19 shows the location and annual capacity of U.S. nitrogen facilities. Of the 134 nitrogen plants, 100 produce ammonia with an annual capacity of 17,725 thousand tons. Less than half of the ammonia plants are located within SMSAs with 44.5 percent of the total ammonia capacity.

A rank order attack directed toward population would destroy only 18.2 percent of the ammonia capacity at an attack level yielding over 50 percent damage to population.[12] An attack of similar size rank ordered for MVA (Manufacturing Value Added) would destroy 30.2 percent of the ammonia production and 70.0 percent of the total MVA. The ammonia industry is less vulnerable than the chemical industry for such an attack design.

If we were to suppose an attack directed specifically toward ammonia facilities, the industry would be easily incapacitated, as shown below:

VULNERABILITY OF AMMONIA PLANTS

Number of Plants Damaged	Ammonia Capacity Lost (percent of total preattack capacity)
10	28.3
20	46.3
30	60.5
40	70.8
50	79.0
60	85.7
70	90.9
80	95.8
90	98.2
100	100.0

Table 19

LOCATION AND CAPACITY OF UNITED STATES NITROGEN FACILITIES*

State	City	County	SMSA	Company	Annual Capacity† (Thousands of Metric Tons) Ammonia‡	Urea§	Ammonium△ Nitrate
Alabama	Birmingham (Watson)	Jefferson	Birmingham	E. I. Du Pont De Nemours & Co., Inc.			23#
	Bessemer	Jefferson	Birmingham	Hercules			23#
	Ketona	Jefferson	Birmingham	Ketona Chem (Joint Ala. By Prod. & Hercules)	48	10	44
	Wilson Dam	Colbert		TVA (U.S. Government)	83		
	Cherokee	Colbert		U.S. Agri Chemicals, Inc.	161	21	92
					292	31	187
Arizona	Benson	Cochise		Apache Powder Co.	14		60
	Chandler	Maricopa	Phoenix	Southwest Agrochemical Corp.	37	—	—
					51		60
Arkansas	Helena	Phillips		Arkansas Louisiana Gas Co.	200	64	96
	Blytheville	Mississippi		Continental Oil	320		
	El Dorado	Union		Monsanto	257	64	320
					777	128	416
California	Hercules	Contra Costa	S.F.–Oakland	Hercules	64	38	73
	Lathrop	San Joaquin	Stockton	Occidental Petroleum	89		
	Hanford	King		Reserve Oil & Gas	20		
	Ventura	Ventura	Oxnard–Ventura	Shell Oil Co.	152	124	22
	El Segundo	Los Angeles	Los Angeles	Standard Oil of Calif.	17		
	Richmond	Contra Costa	S.F.–Oakland	Standard Oil of Calif.	120		41
	Brea	Orange	Anaheim–Santa Ana–G.G.	Union Oil of California	320	51	55
	El Centro	Imperial		Valley Nitrogen	200	142	41
	Helm	Fresno	Fresno	Valley Nitrogen	162	32	—
					1,144	387	232

Table 19 (Continued)

State	City	County	SMSA	Company	Annual Capacity† (Thousands of Metric Tons) Ammonia‡	Urea§	Ammonium Nitrate$^{\Delta}$
Colorado	Louviers	Douglas		E. I. Du Pont De Nemours & Co., Inc.	—	—	17#
							17
Delaware	Claymont	New Castle	New Castle	Sunolin Chemical Co. (Joint Olin & Sun Oil)	—	83	—
						83	
Florida	Tampa	Hillsborough	Tampa-St. Petersburg	Cities Service Co., Inc.	137		
	Pensacola	Escambia	Pensacola	Escambia Chemical Corp.	92	23	92
	Bartow	Polk		International Minerals & Chemical Corp.	92		
	Tampa	Hillsborough	Tampa-St. Petersburg	Kaiser Aluminum Chem. Corp.			48
	Tampa	Hillsborough	Tampa-St. Petersburg	Nitram Chemicals, Inc.	—	—	137
					321	23	277
Georgia	Augusta	Richmond	Augusta	Columbia Nitrogen	119	26	190
	Bainbridge	Decatur		Kaiser Aluminum & Chem. Corp.			54
	Savannah	Chatham	Savannah	Kaiser Aluminum & Chem. Corp.	137	73	185
					256	99	429
Idaho	Pocatello	Bannock	Pocatello	J. R. Simplot Co.	50	—	—
					50		
Illinois	Marion	Williamson		Commercial Solvents Corp.			46
	Seneca	LaSalle		E. I. Du Pont De Nemours & Co., Inc.			180#
	Tuscola	Douglas		National Distillers & Chem. Corp.			37
	Cordova	Rock Island	Davenport-R.I.-Moline	Nitrogen Inc. (Joint Internat'l Minerals & Chemicals & Northern Natural Gas)	128	23	110
	Lockport	Will	Chicago	Texaco Inc.	71		92

Table 19 (Continued)

State	City	County	SMSA	Company	Annual Capacity† (Thousands of Metric Tons) Ammonia‡	Urea§	Ammonium Nitrate△
Illinois (Continued)	East Dubuque	Joe Daviess		Northern Ill. Gas Co.	200		
	Marseilles	LaSalle		Illinois Nitrogen Co.	—	—	137
					399	23	602
Indiana	Terre Haute	Vigo	Terre Haute	Central Nitrogen Inc. (Joint Boyden & Royster)	123	—	142
					123		142
Iowa	Fort Dodge	Webster		Farmland Industries, Inc.	200		
	Creston	Union		Green Valley Chemical Corp.	32		
	Clinton	Clinton		Hawkeye Chemical	124	21	132
	Muscatine	Muscatine		Monsanto Co.	92		
	Fort Madison	Lee		Sinclair Oil Co.	320		
	Fort Madison	Lee		Standard Oil Co. of Calif.	96		78
	Port Neal (Sioux City)	Woodbury	Sioux City	Terra Chemicals International Inc.	200	112	136
					1,064	136	346
Kansas	Lawrence	Douglas		Cooperative Farm Chem. Assoc.	173	49	246
	Dodge City	Ford		Farmland Industries, Inc.	200		
	Pittsburg	Crawford		Gulf Oil Corp.	173		315
	Wichita	Sedgwick	Wichita	Vulcan Materials Co.	22	—	—
					568	49	561
Kentucky	Henderson	Henderson	Evansville	Gulf Oil Corp.	—	71	92
						71	92
Louisiana	New Orleans	Orleans	New Orleans	Air Product & Chemicals	200		
	Geismar	Ascension		Allied Chemical Corp.	320	210	228
	Fortier	(Can't locate)		American Cynamid Co.	320	132	
	Geismar	Ascension		Borden Inc.	320	151	

Table 19 (Continued)

State	City	County	SMSA	Company	Annual Capacity[†] (Thousands of Metric Tons) Ammonia[‡]	Urea[§]	Ammonium[Δ] Nitrate
Louisiana (Continued)	Donaldsonville	Ascension		Central Farmers Fertilizer Co.	640		
	Lake Charles	Calcasieu	Lake Charles	Cities Service Co., Inc.	128		
	Sterlington	Ouachita	Monroe	Commercial Solvents Corp.	320		171
	Donaldsonville	Ascension		Gulf Oil Corp.	320	185	
	Donaldsonville	Ascension		Miscoa	320	385.	
	Luling	St. Charles			412		251
	Lake Charles	Calcasieu	Lake Charles	Olin	440	146	—
					3,740	1,209	650
Maine	Searsport	Waldo		W. R. Grace & Co.	—	—	27
							27
Michigan	Wyandotte	Wayne	Detroit	Pennwalt Corp.	32	—	—
					32		
Minnesota	Pine Bend	(can't locate)		St. Paul Ammonia Products Inc	—	—	83
							83
Mississippi	Vicksburg	Warren		Gulf Oil Corp.			27
	Pasagoula	Jackson		Miscoa	160		
	Yazoo City	Yazoo		Miscoa	320	78	275
	Pasagoula	Jackson		Standard Oil of Calif.	480	—	—
					960	78	302
Missouri	Louisiana	Pike		Hercules, Inc.	64	87	460
	Hannibal	Marion Ralls		American Cynamid Co.			121
	Joplin	Jasper & Newton		Atlas Chemical Industries	125	58	214
	Crystal City	Jefferson	St. Louis	United States Steel	90	—	92
					279	145	887
Nebraska	Omaha (La Platte)	Douglas	Omaha	Allied Chemical Corp.	185	128	105
	Fremont	Dodge		Central Farmers Fertilizer	44	19	36

Table 19 (Continued)

State	City	County	SMSA	Company	Annual Capacity† (Thousands of Metric Tons) Ammonia‡	Urea§	Ammonium△ Nitrate
Nebraska (Continued)	Beatrice	Gage		Cominco American			155
	Hastings	Adams		Farmland Industries Inc.	128		
	Beatrice	Gage		Phillips Petroleum Co.	200	51	65
					557	198	361
New Jersey	Gibbstown	Gloucester		E. I. Du Pont De Nemours Co. Inc.			46#
	Kenvil	Morris	Newark	Hercules, Inc.	—	—	19#
							65
New York	Olean	Cattaraugus		Agway, Inc.		55	67
	Olean	Cattaraugus		Felmont Oil Corp.	78	—	—
					78	55	67
North Carolina	Tunis	Hertford		Farmers Chemical Asso. Inc.	400	155	185
	Wilmington	New Hanover	Wilmington	W. R. Grace & Co.	—	—	185
					400	155	373
Ohio	North Bend	Hamilton	Cincinnati	Kaiser Alumium & Chem Corp.			96
	Lima	Allen	Lima	Standard Oil Co. (Ohio)	605	291	72
	Ironton (South Point)	Lawrence	Huntington Ashland	Allied Chemical Corp.	65	175	—
					670	466	168
Oklahoma	Pryor	Mayes		Cherokee Nitrogen	50		78
	Pryor	Mayes		Lone Star Producing Co.	96	160	—
					146	160	78
Oregon	St. Helens	Columbia	Portland	Shell Oil Co.	83	50	22
	Portland	Clackamus & Multnomah	Portland	Pennwalt Corp.	8	—	—
					91	50	22
Pennsylvania	Tamaqua	Schuykill		Atlas Chemical Industries			39*
	Seiple	Lehigh	Allentown-Beth-Easton	Commercial Solvents Corp.			5*

Table 19 (Continued)

State	City	County	SMSA	Company	Annual Capacity[†] (Thousands of Metric Tons): Ammonia[‡]	Urea[§]	Ammonium Nitrate[Δ]
Pennsylvania (Continued)	Palmerton	Carbon		Gulf & Western Industries	37		
	Donora	Washington	Pittsburgh	Hercules, Inc.			137
	Marcus Hook	Delaware	Philadelphia	Sun Oil Co.	121		
	Clairton	Allegheny	Pittsburgh	United States Steel Corp.	370	—	—
					528		181
Tennessee	Tyner	Hamilton	Chattonooga	Farmers Chemical Asso., Inc.	150	37	185
	Woodstock (Memphis)	Shelby	Memphis	W. R. Grace & Co.	232	114	—
					382	151	185
Texas	Deer Park	Harris	Houston	Diamond Shamrock Crop.	32		
	Dumas	Moore		Diamond Shamrock Corp.	146		
	Freeport	Brazoria	Galveston-Texas City	Dow Chemical	105		
	Beaumont	Jefferson	Beaumont-Pt. Arthur	E. I. Du Pont De Nemours Co., Inc.	320		
	Victoria	Victoria		E. I. Du Pont De Nemours Co., Inc.	92		
	Dimmit	Castro		Elcor Chemical Corp.	30		
	Odessa	Ector	Midland	El Paso Natural Gas Co.	105		
	Plainview	Hale		Farmland Industries, Inc.	4		
	Big Spring	Howard		W. R. Grace & Co.	83		
	Borger	Hutchinson		Hill Chemicals, Inc.	640		
	Kerens	Navarro		Lone Star Producing Co.	114	78	51
	Beaumont	Jefferson	Beaumont-Pt. Arthur	Mobil Oil Corp.	320	46	177
	Houston	Harris	Houston	Occidental Petroleum Corp.	320		
	Plainview	Hale		Occidental Petroleum Corp.	48		
	Etter	Moore		Phillips Petroleum Co.	192		168
	Pasadena	Harris	Houston	Phillips Petroleum Co.	210		16

Table 19 (Continued)

State	City	County	SMSA	Company	Annual Capacity† (Thousands of Metric Tons) Ammonia‡	Urea§	Ammonium Nitrate△
Texas (Continued)	Pasadena	Harris	Houston	Premier Petrochemical Co.		69	
	Deer Park	Harris	Houston	Rohm & Haas	46		
	Texas City	Harris	Galveston-Texas City	Standard Oil Co. (Indiana)	680		
	Houston	Harris	Houston	Tenneco Inc.	192	—	—
					3,679	193	412
Utah	Gomex (Springville)	Utah	Provo-Orem	Commercial Solvents Corp.			4#
	Geneva	Utah	Provo-Orem	United States Steel Corp.	64	—	92
					64		96
Virginia	Hopewell	Independent		Allied Chemical Corp.	357	—	287
					357		287
Washington	Dupont	Pierce	Tacoma	E. I. Du Pont De Nemours Co., Inc.			19#
	Tacoma	Pierce	Tacoma	Occidental Petroleum	20		
	Finley	Benton		Phillips Pacific Chemical Co.	142	40	50
	Kennewick	Benton		Standard Oil of Calif.	—	—	78
					162	40	147
West Virginia	South Charleston	Kanawha	Charleston	FMC	22		
	New Martinsville	Wetzel		PPG Industries	46		
	Belle	Kanawha	Charleston	E. I. Du Pont De Nemours Co., Inc.	320	187	—
					388	187	
Wisconsin	Barksdale	Bayfield		E. I. Du Pont De Nemours Co., Inc.	—	—	17#
							17

Table 19 (Concluded)

State	City	County	SMSA	Company	Annual Capacity* (Thousands of Metric Tons) Ammonia‡	Urea§	Ammonium△ Nitrate
Wyoming	Cheyenne	Laramie		Colo. Oil & Gas	167	46	74
					167	46	74
United States				Total January, 1968	13,602	3,089	7,580
				Total January, 1972-73	16,300	4,100	7,821

* Data are based on 1968 capacities. See Ref. 21.
† Annual capacity data are intended to be based on 330-340 stream days per calendar year.
‡ Data are on a NH_3-content basis.
§ Data are on a urea product basis--45%-46% N grades.
△ Data are on an ammonium nitrate product basis--33%-34% N grade.
\# End use other than fertilizer.

If one considers only nitrogen plants, fertilizer is much more concentrated and vulnerable than population or MVA. However, the plants are typically outside SMSAs, and would not likely suffer much collateral damage from the more usual countervalue attacks.

Most of the trends in the fertilizer industry described above will result in increasing agricultural vulverability. One factor argues for less concern, however. Even now nitrogen production capacity exceeds output by three to two, and a lot of fertilizer is exported. Manufacturers appear to be trying to develop further foreign markets, which will tend to encourage the building of even more capacity. In case of nuclear attack, then, a relatively small fraction of capacity surviving may be able to supply all domestic needs, assuming that distribution and management function properly.

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Stephen L. Brown
Pamela G. Kruzic

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13. ABSTRACT

Two separate studies of agricultural vulnerability are reported. One is a sensitivity analysis of agricultural damage assessment. Several important input assumptions are tested for their effect on the results of the damage assessment. The other study identifies trends in the production and utilization of fertilizers and relates them to changes in the vulnerability of agricultural production through potential loss of the fertilizer input.

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