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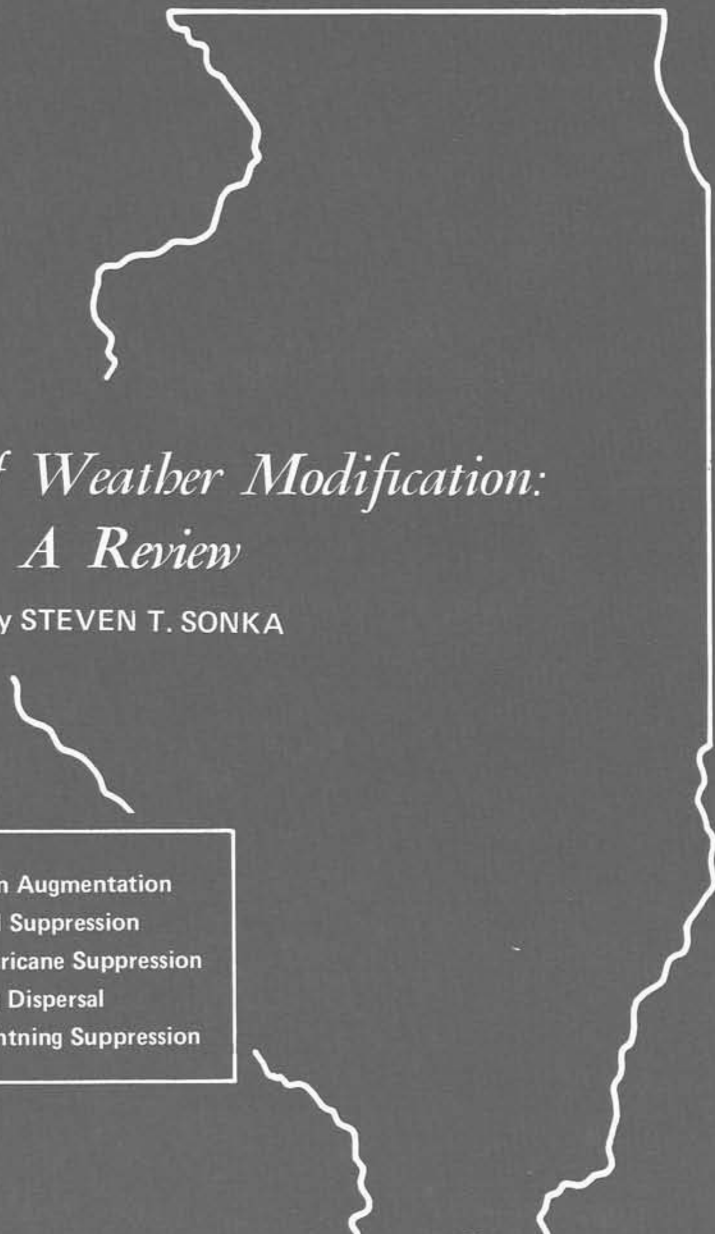

Economics of Weather Modification: A Review

by STEVEN T. SONKA

- $ Rain Augmentation
- $ Hail Suppression
- $ Hurricane Suppression
- $ Fog Dispersal
- $ Lightning Suppression

ILLINOIS STATE WATER SURVEY
URBANA
1979

REPORT OF INVESTIGATION 89

Economics of Weather Modification: A Review

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Title: Economics of Weather Modification: A Review

Abstract: This report first discusses gross benefits and costs of potential weather modification activities and the elements vital to a credible economic analysis of such activities. It then reviews and evaluates more than 60 existing studies relating to the economic impacts of five major modification activities: precipitation augmentation including snowpack enhancement, hail suppression, hurricane suppression, fog dispersal, and lightning suppression. Because weather can have severe adverse effects on economic activity, gross benefits of modification appear very high in relation to most operational costs. However, indirect costs may be great and, in general, those adversely affected are not the same individuals enjoying the gross benefits. A credible economic analysis of net bcnefits of weather modification requires consulting with atmospheric scientists to assure understanding of the physical factors involved, funding for a considerable amount of data gathering, considering effects of possible future changes in crucial factors, and orienting the analytical viewpoint to both negative and positive regional economic impacts. Most of the existing literature relating to the economics of weather modification addresses precipitation augmentation and hail suppression; very few attempts toward comprehensive economic analyses have been made. More is known about the economic impacts of weather on agriculture than for any other activity area.

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Indexing Terms: Cloud seeding, cost-benefit analysis, economic impacts, fog dispersal, hail suppression, hurricane suppression, lightning suppression, precipitation augmentation, snowpack enhancement, weather modification.

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CONTENTS

Economics of Weather Modification: A Review

*Steven T. Sonka**

INTRODUCTION

Two types of benefits are potentially available from efforts to modify the weather (Sewell, 1969). The first is to reduce losses from the occurrence of weather events. Hailstorms, hurricanes, lightning, and drought are some examples of weather phenomena which can cause severe losses. A second type of benefit arises when alteration of a particular weather factor can increase production of a desired good. Additional precipitation for crop production and power generation is an example of such a production consideration. Weather modification to produce either of these benefits could generate societal benefits.

A major problem in conducting an economic evaluation of weather modification technology arises from uncertainty about performance of the technology itself. As noted by Haragan (1974) considerable scientific controversy exists regarding the degree to which weather modification is thought to be successful. Haragan lists four questions which he feels must be answered before any cloud seeding effort should be undertaken. (These can easily be extended to other forms of weather modification.) These questions are paraphrased as:

1) Should it take place?
2) If so, how can a potential seeding opportunity be recognized?
3) How should a recognizable cloud be treated?
4) What did the seeding accomplish?

The first question is not entirely a physical question. Here, a complete set of physical, economic, legal, social, political, and moral factors must interact to reach a beneficial decision. This paper does not attempt to describe any of the non-economic variables alluded to, not because they are unimportant, but because of inadequate resources for their consideration here.

The second, third, and fourth questions relate to physical factors and measures of such factors. The unanswered questions diminish the outlook for general acceptance of cloud seeding. Haragan further notes that the public, not just the scientific community, must be confident of the answers to these questions.

Harmon (1976) details strong concern regarding the potential both to beneficially alter the weather and to assess those physical effects which result. He stresses that a dependable method of a cloud seeding must include a method to determine the modification potential of a cloud system and a technology to liberate this potential. He implies that sufficient understanding of clouds is not available to satisfy these two conditions. He also notes the difficulty of obtaining support for long-term experiments without a guarantee of certain social or societal benefits from successful research projects.

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But identification of physical effects is not the only potential problem in conducting an economic analysis. A second set of problems relates to the identification and quantification of the costs and benefits associated with weather modification. It is this second set of problems to which this report is addressed.

Organization of This Effort

The goal of this research effort is to review the existing literature dealing with the economics of weather modification and to delineate concerns which should be incorporated into future economic analyses. This effort is organized as follows: First, a general discussion of the costs and benefits of weather modification is presented. Second, several factors which are vital to the successful completion of an economic analysis of weather modification are discussed. The remainder of the report is a literature review of each of five main types of weather modification: precipitation augmentation (including snowpack enhancement), hail suppression, major storm suppression, fog dispersal, and lightning suppression.

Acknowledgments

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The input of the Illinois State Water Survey was instrumental in the preparation of this document. Stanley A. Changnon, Jr., played a major role in conceptualizing the effort and critically reviewing the report. J. L. Ivens edited the final manuscript and M. J. Innes prepared the camera copy. The relevance of the material to weather modification research in Illinois led to its publication by the Water Survey.

ECONOMIC EFFECTS OF WEATHER MODIFICATION

Few studies have extensively addressed the economic aspects of weather modification. What are the costs and benefits? Only when that is known can responsible decisions be made.

Gross Benefits and Modification Costs

Weather caused losses

To help set the potential benefits in perspective, a few estimates of weather-caused losses in the United States are presented in table 1 for broad categories of national activities (Thompson, 1976). These dollar losses and the percentage they represent of that sector's annual gross revenues indicate that agriculture has by far the greatest stake in weather modification.

Note. The term "losses" is used with great trepidation. Certainly this usage is not consistent with Russell's comment, ". . .that loss measurements must bear some relation to intended action in order to be meaningful" (1968, p. 624). However, these estimates are used here to provide a crude indication of the magnitude of economic costs resulting from adverse weather events on particular economic sectors.

Weather losses can also be viewed by types of weather. Hendrick and Friedman (1966) estimate the ranges of insured property losses in the nation as given in table 2.

Latest calculations of hail losses in the U.S. show $773 million for crops and $75 million for property (Changnon et al., 1977). Fog causes an estimated loss of $70 million to the aviation industry (Tschupp, 1970).

More is known specifically about the economic impacts of weather on agriculture than for any other activity area. For example, specific crop yield reductions due to all forms of weather hazards appear in table 3 (Changnon, 1972). These data demonstrate the regional differences in losses for two major crops and also the general importance of rainfall, either too little or too much.

In general, the gross benefits from the utilization of effective weather modification techniques appear very large. In some cases, however, these gross benefits would be considerably offset by direct and indirect costs. Although these costs are detailed later in this report, the reader should keep this caution in mind when evaluating the

Table 1. Annual Weather Caused Losses in the United States and Percent of Annual Gross Revenue

Activity	*Losses (millions of dollars)*	*Percent of that sector's gross revenues*
Agriculture	8,240	15.5
Commercial Aviation	92	1.1
Construction	998	1.0
Manufacturing	598	0.2
Transportation (rail, highway, water)	96	0.3
Communications	77	0.3
Electrical Power	46	0.2
Energy Fossil Fuels	5	0.1
Other (general public, government, etc.)	2,532	2.0
Total	12,684	

Table 2. Annual Insured Property Losses due to Weather in the United States

	Range (millions of dollars)		
Hurricanes	250	to	500
Thunderstorms (lightning, hail, and winds)	125	to	250
Tornadoes	100	to	200
Windstorms (extra-tropical)	25	to	50
Total	500	to	1000

Table 3. Annual Estimated Corn and Soybean Yield Losses due to Various Weather Conditions in the Midwest Corn Belt Area

	Average annual loss (bu/acre)					
	Western Corn Belt (Nebraska, Western Iowa)		*Central Corn Belt (Eastern Iowa, Illinois)*		*Eastern Corn Belt (Indiana, Ohio)*	
	Corn	*Soybeans*	*Corn*	*Soybeans*	*Corn*	*Soybeans*
Hail	3.5	2.4	1.9	1.4	1.2	0.9
Wind	3.7	1.0	3.9	0.9	3.8	1.2
Drought	7.3	2.7	5.4	2.7	8.7	3.7
Excessive moisture	2.7	1.6	4.9	2.6	6.9	2.8
Excessive heat	3.5	0.8	2.3	1.1	3.0	1.7
Excessive coolness	0.3	0.3	1.5	0.4	1.5	0.7
Freeze or frost	1.1	0.6	0.9	0.4	1.4	0.4
Total loss	22.1	9.4	20.8	9.5	26.5	11.4
Total as percent of total yield	38	32	28	31	36	38

gross benefit estimates of the next few paragraphs. Also the benefit figures presented were not estimated for the same year. Because of the relatively substantial inflation rates of the past few years, the reader should note that a dollar estimate for the 1960s might be considerably higher if converted to a current dollar basis.

Economic benefit estimates

One of the most carefully developed estimates of the economic benefits of very successful future weather modification (80% reduction in hail with 16% increase in growing season rainfall) shows that by 1995, with wide usage in the western United States, the benefit in reduced food costs would be $890 million (Changnon et al., 1977). Notably, this would be only a 5% reduction in farm production costs of food. The benefits from a lesser but still optimistic modification capability (—54% to hail, +9% in rain) would produce only a 2% reduction in production costs. These estimates include a careful analysis of the direct operating costs associated with the technology.

A recent report of the National Academy of Science (1976) presented crop yield and forage increases resulting from a modest (10%) increase in precipitation over large areas of the nation. The direct benefits in the form of farm receipts would be $217 million yearly, but this estimate does not account for any costs. A 5% increase in precipitation in the Connecticut River Valley (over 9 months) would produce cost advantages (those gained in relation to the next best alternative) of $1.3 million because of increased water for domestic and industrial users (Aubert et al., 1972).

One estimate of the benefits from hurricane modification (20% wind reduction with no rain change) showed $100 million gained annually in the United States and $800 million globally (Gray, 1973). These reductions represent benefit/cost ratios ranging from 30/1 up to 60/1.

The average annual increase in the runoff of a California (Sierra) river basin, due to snowpack enhancement conducted over a 19-year period, was estimated at 67,300 acre-feet of water, a 4% increase (Williams, 1971). This added water has local values ranging from $340,000 yearly (irrigation costs of water) up to $1.3 million (a maximum for certian power generation considerations). Operational costs averaged $51,000 annually, yielding benefit/cost ratios of 6.6/1 up to 25/1, depending on the value (use) of the water. If potential costs for evaluation and monitoring are included, the benefit/cost ratios drop, ranging from 1.8/1 up to 7/1.

An extensive assessment of the potential enhancement of winter snowpack in the Colorado River Basin considered three economic outcomes against an annual cost of $9.5 million (Weisbecker, 1974). If no new water resource management facilities were built, the benefits (from a predicted 2 million acre-feet of added water) would be $12.8 million. Two other alternatives, based on different assumptions about the construction of new basin facilities, revealed in one case a benefit of $30 million and in the other case no benefits.

Ratios of benefits to cost

It is instructive to consider some of the benefit/cost ratios available from the more thorough economic studies of weather modification. The range offered represents differences due to different modification capabilities and economic valuations. For the simultaneous decrease in hail and increase in rain, the ratios varied from 1/1 up to 15/1; for added snowpack in the Colorado Basin they were 1/1 to 3/1; and for added snowpack in the Sierras they varied from 1.8/1 to 25/1. The less certain calculations for hurricane winds modification produced ratios from 30/1 up to 60/1. It is important to realize that the range of values for ratios is great, as is the diversity of underlying assumptions used in determining those estimates.

Weather-related losses occurring in the nation are often catastrophic and small percentage reductions in damages from major storm events would reap substantial rewards. For the more minor events, such as closing of a particular airport due to fog, annual benefits could also be sizeable with a benefit/cost ratio of 5/1 (Beckwith, 1966).

Cost of weather modification

The gross benefits of weather modification efforts appear even more attractive when compared with the associated modification (operational) costs. For rain and hail modification, $1 per acre can be considered as a reasonable cost estimate involving operations, evaluation, and informational services (Changnon et al., 1977). This compares with other non-land production costs of $40 to $50 per acre for wheat in the Great Plains. Additional water from snow augmentation in the western mountains is expected to cost $1 to $1.50 per acre-foot (Weisbecker, 1974). This could be compared to costs of $50 per acre-foot for providing additional water by interbasin transfers (Howe and Easter, 1971). Only in the case of hurricane suppression do operational costs ($10 to $20 million per hurricane) attain significant levels (Gray, 1973). But as noted in table 2, damages in these storms are correspondingly large.

Evaluation of only the gross benefits and costs suggests that particular economic sectors would be quite interested in weather modification. In general, those sectors might be expected to be concerned only with the trade-off between gross benefits and operational costs. If the desired weather modification technology is not considered sufficiently efficient, then those interested sectors might support research and development of that technology. Although such research might be complex and relatively costly, these interested user sectors would see the expectation of future benefits — especially if that research and development were conducted in the public sector.

External Effects

A major flaw exists in the process of comparing gross benefits and modification costs, one which is not corrected by the addition of expected research costs. This flaw arises when the external effects of a weather modification program are not considered. This is not really an oversight for the private sector affected; rather, the problem arises when public sector monies are involved.

Disbenefits as well as benefits

As Castle and Stoevener suggest (1966), disbenefits as well as benefits can result from a purposeful effort to alter weather. One instance where a loss rather than a benefit occurs is when the intended physical change does not occur. The Whitetop Experiment in Missouri is an example of this concern. Decker et al. (1971) note that the initial analysis of this project indicated that precipitation in the target area was decreased rather than increased by augmentation efforts. These authors report a more sophisticated analysis which indicated that the seeding may have had no effect on rainfall. But the potential of decreased rainfall was not disproved, either.

Effects in unintended areas

Two external economic effects are especially important. One has to do with effects in areas other than the area intended for modification. An example is a snowpack augmentation program which results in considerably greater snowfall in the cities downwind of the intended region. The costs of additional snow removal and disruption of transportation in an urban area may be significant enough to be considered in an overall evaluation of the augmentation effort. A potentially more serious illustration involves the possibility of a hurricane with altered path. Although people in the original path may have considerable benefit from reduced damages, those people in the altered path area suffer considerable harm.

Diverse weather needs

A second type of external economic outcome concerns the diversity of weather needs within a modification region (Changnon, 1975). For example, additional water from Rocky Mountain snowpack augmentation may be beneficial for irrigation, power generation, and municipal uses in the Lower Colorado River Basin. But that additional snowfall may harm transportation, mining, and recreation activities in the Upper Colorado River Basin. It would seem that those individuals negatively affected in the Upper Basin might desire compensation from the sectors benefiting in the Lower Basin. This desire could lead to considerable controversy even for a program for which positive net benefits could be demonstrated.

In another example, in some parts of South Dakota both wheat and corn production are major activities. For wheat production, more rainfall than would normally occur in the spring months is beneficial. However, this same additional rainfall is detrimental to corn planting and hence production. A reverse relationship with rainfall is noted for these same two crops with respect to rainfall in July. This is an interesting example because in some areas individual farmers may grow both crops and, therefore, given adequate information, be able to choose (on some collective basis) if attempts to augment rainfall would be beneficial. In other situations, production of the two crops might tend to be so specialized that a potential for economic conflict is more likely (Changnon, 1975).

The crop production example above was interesting because competing water needs occurred in the same region and economic sector. However, in the cash-grain crop production regions of Illinois, both corn and soybean production are favorably impacted by additional July rainfall (Huff and Changnon, 1972). But non-agricultural endeavors may not desire additional summer precipitation. Among these are outdoor construction and recreation activities, both heavily affected by weather (see table 1).

Technical reversibility, mobility

One positive attribute of all types of weather modification is its reversibility, in a technical sense. Once a particular storm is modified it is not possible to undo the effects on that storm, but there does not appear to be any evidence that future storms will be affected. The seemingly independent nature of weather modification is attractive when considered as an alternative for major projects with long lasting effects (e.g., construction of canals for interbasin water transfers). In addition, present and foreseeable weather modification systems are quite mobile and can be installed or removed quickly and do not require sizeable in-place facilities.

Technical reversibility does not insure that weather modification programs can be turned off and on easily within a social context, however. If some economic sectors are benefited by use of a modification technology, those benefits are quite likely to be bid into the value of the fixed assets associated with that sector. Therefore, efforts to terminate the modification program would cause losses to the owners of those assets and could be expected to lead to controversy.

Natural and technical variabilities

A major factor affecting the economic benefits of weather modification, which has only infrequently been analyzed, is that of variability. Two types of variability are potentially relevant. One is the naturally occurring fluctuations of the weather event in question. The other is variability in the performance of the technology. Both of these factors can have an impact on economic benefits.

Although crop producers may believe a 20% increase in summer rainfall is advantageous, the expected benefit from that augmentation program may not be the same as the yield benefit calculated by measuring the impact of 120% of the average rainfall. In dry years, the 20% increase may have considerable yield-increasing effects or the additional rainfall may be so slight (20% of nothing is nothing) that the effect is not really measurable. Alternatively, if the augmentation program increased rainfall of a single thunderstorm from 2 to 3 inches, yield gains may not occur as the additional inch of water is lost as runoff. Indeed, for farmers in low lying areas such additional runoff may depress yields.

Variability in the performance of the technology, for example securing a 40% decrease in hail on one day and none on the next, is a major concern for assessing the economic potential of weather modification. Unfortunately, however, the present state of the modification science does not allow for its specification.

Negation by public responses

An additional economic ramification relates to public responses to successful modification. Because weather modification is often concerned with phenomena with major impacts, alteration of some behavior patterns of people might be expected. The potential of reducing building expenditures if hurricane suppression is successful is an example of such behavioral change. But hurricane suppression does not insure that tremendously destructive hurricanes will not occur. Even if all major storms could be reduced by some sizeable percentage, it is conceivable that, if buildings and structures were less well-built, similar amounts of damage would result as if no suppression existed and greater construction expenditures had been made. Thus economic benefits resulting from given shifts in average weather may be negated with time and the actions of affected people.

Although this last example might be an extreme case, it illustrates that claims of benefits from weather modification must be evaluated closely. Complete assessments of future benefits of weather modification programs must consider such secondary responses and their effects.

Important Factors for Economic Analysis of Weather Modification

A number of factors are especially important for anyone contemplating a comprehensive analysis of the net benefits associated with a particular application of a weather modification technology.

Consult physical scientist

For three reasons, close consultation and cooperation with atmospheric scientists is essential. First, their assessment of which physical phenomena will be altered by the modification process is crucial. This list of factors must not be limited only to those factors thought to be beneficial. For example, if the rainshadow effect is a likely possibility, then it, as well as the beneficial rainfall effects, should be noted.

Secondly, their information is needed regarding the two types of variability in weather modification, that due to uncertain technological performance and that due to natural weather fluctuations. The economist needs to have both the possible range of outcomes for the delineated physical factors and the likelihood function describing the relative probabilities associated with each possible outcome. As shown by Huff and Changnon (1972) for corn and soybean production, consideration of these variability factors can result in evaluations of a technology which are positive in some years but negative in others. Development of this type of information is essential if decision-makers are to formulate knowledgeable opinions.

The third type of data needed from the physical scientist is a listing of relevant aspects regarding the modification process. Such variables as when in the day, or in the year, such modification is possible are important factors to consider for precipitation enhancement. If the physics of storm clouds means that certain regions are more 'seedable' than others such information can be very valuable to set parameters around the range of economic analysis needed.

Analytical viewpoint important

After consultation with atmospheric scientists, the next most crucial feature of an economic analysis is its viewpoint. Too many existing studies have embodied the orientation "If we undertake this modification to benefit sector A, what exactly are the benefits to sector A?" The proper question is "If this modification process alters the weather in region X, what will be the impacts, both positive and negative, on the economy of region X?"

This latter orientation implies a considerable amount of additional effort. And to do the job well, such studies should be restrained to carefully conducted regional analyses. The proper size of the regions will be dictated in large measure by the information supplied by the physical scientist.

If a regional analysis is undertaken, it is important to clearly distinguish the net regional and the net national benefits. This is especially true if national research monies are involved. The reason is that a portion of projected regional gains is likely to be in the form of income transfers from other regions (Crutchfield, 1973). Such transfers should be specified so that national policymakers can be made aware of any unintended regional effects. This concern would seem particularly crucial when secondary benefits associated with proposed programs are being considered.

Regional gains should be presented, however. It seems plausible that national policymakers might think it proper to support a program in order to enhance development in a particular region. And policymakers in the affected regions would surely find information on both positive and negative potential effects to be of considerable interest.

Potential economic changes

Although it is important to know if a potential technology would be valuable under today's conditions, this knowledge is less useful when those conditions change. Therefore the role of potential changes in the economic environment in which the technology will perform is important. This does not mean the analyst should consider all possible societal changes and describe their impact on the value of the technology in question. Rather, the analysis should center on crucial factors and describe the impacts of changes in these variables.

For example, in snowpack enhancement, the level of demand for agricultural products and for energy has a major impact on the value of the augmented water. Therefore, it would be extremely valuable to know the potential value of snowpack augmentation under conditions of both low and high demand for these commodities. Users of the analysis could then evaluate the technology for the currently relevant demand level.

Basic data gathering

An often overlooked feature of economic analyses is that a proper result will require a considerable amount of data gathering. This type of research work is costly in terms of time and money and is often tremendously tedious. But funding agencies which do not allow enough time and money for basic information generation are dictating that the probability of receiving a valuable comprehensive analysis is very low.

PRECIPITATION AUGMENTATION

The prospect of augmenting precipitation has generated the greatest amount of economic study of the five weather modification technologies considered. However, a considerable amount of this discussion has been focused on crop production alone and then often on only one crop at a time. Relatively few studies have considered impacts of enhanced precipitation for a number of sectors, particularly where some of those sectors might be harmed by increased moisture.

For this section of the report three major categories of modification type have been delineated: 1) summertime augmentation, 2) fall augmentation of the Great Lakes, and 3) wintertime increases in snowfall in Western mountain regions. Summaries of studies pertaining to these categories follow.

Summertime Augmentation

A relatively large number of studies exist which detail relationships between summer rainfall and economic activity of various sectors of the economy. The majority of these, unfortunately, consider impacts on only one sector rather than on the several sectors which may have competing claims for moisture. This section contains a summarization of some of these studies categorized by sector affected.

Effects on Agriculture

Crop production is an obvious candidate to consider for precipitation augmentation. Therefore, a multitude of studies postulating the relationship between growing season rainfall and crop yields have been published. Ramirez, in 1974, presented estimates of the potential yield increases associated with provision of an additional inch of growing season rainfall in North Dakota. These results are summarized in table 4. These increases represent considerable gains in crop output for this major agricultural area. The assumption of 1 inch of additional rainfall is consistent with findings of Dennis et al. (1974) that such an increase would be possible in this area.

Effects of additional moisture

Borland and Snyder (1974) also consider the effects of additional moisture on Great Plains agriculture. They, however, use differences in land values as a measure of the effects of rainfall and hail on agricultural productivity. Using multiple regression techniques, they determine that a 5% increase in early season rainfall could be converted into cropland price gains of $10 to $12 per acre (in 1967 prices). This 5% increase equals about 0.25 inch of rainfall for the southwestern Nebraska and northeastern Colorado region evaluated. This analysis also indicates that the effect on land prices of a 5% increase in early season rainfall was nearly equivalent to a 20% decrease in crop damage due to hail in this region.

Table 4. Additional Crop Production per Acre Associated with an Additional 1 Inch of Growing Season Rainfall in North Dakota

	Region			
Crop	*West*	*West Central*	*East Central*	*Red River Valley*
Wheat *(bu)*	2.7	2.7	2.1	1.8
Barley *(bu)*	2.5	2.8	3.0	2.5
Oats *(bu)*	3.5	5.0	4.0	3.0
Range *(lbs dry matter)*	100	120	130	
Alfalfa *(lbs)*	275	300	275	300

Partin and Smith (1974) evaluated the effects of additional moisture on native rangeland in the Plains states. They indicate that percentage increases in rangeland production are roughly equivalent to percentage increases in growing season rainfall. Rates of increase tend to diminish, however, as rainfall increases exceed 40%.

One study indicated a desire for decreases in seasonal rainfall (USDA, 1975). Here reductions in per acre cotton yields were shown to be correlated with increases in August and September rainfall. This study also notes the possibility of using agricultural technologies other than weather modification, in this case earlier-maturing hybrids, to alleviate that seasonal rainfall problem.

Another instance of harmful effects of additional rainfall was cited by Struyk (1971). He compares land values in unprotected areas along the Missouri River with values in upland and protected areas. Reduced land values, on the order of 5 to 10%, were indicated for the most flood-prone areas. These price differentials are relative to 1970 land values of approximately $400 per acre. If rainfall enhancement led to increased flood potential, this analysis indicates that landowners in flood-prone lowland areas would suffer losses which may offset potential gains in crop production.

Changnon (1977) has evaluated net increases in crop production caused by additional inadvertent precipitation downwind of St. Louis. Here net yield increases of 2.6 and 1.3 bushels per acre were estimated for corn and soybean production, respectively. These projected increases are the combined effect of positive impacts of an average of 10% greater July and August rainfall and negative impacts of an increased incidence of hail.

Valuation of these rainfall increases in prices consistent with 1975-1976 conditions would be about $1.6 million for the region affected by the St. Louis anomaly. This additional crop revenue is earned through increased production of 100,000 bushels of soybeans and 400,000 bushels of corn. To indicate the effect of price assumptions on values of additional production, this same production would generate $1.15 million of revenue using reasonable expectations of fall 1977 prices ($1.75 per bushel for corn and $4.50 per bushel for soybeans). Changnon also notes that the additional rainfall has been linked to more flooding and more stream pollutants in this region.

Huff/Cbangnon consider variability

The studies cited previously consider benefits from average increases in rainfall. Huff and Changnon, in an excellent 1972 effort, incorporated the uncertainty characteristics of precipitation modification into the analysis. For the several crop production regions in Illinois, they evaluate the effects of different models of precipitation augmentation on corn and soybeans production. These models vary by the effectiveness characteristics they assume.

In most Illinois regions, these researchers found that soybean and corn production would have benefited from July-August rainfall increases of more than 10%. However, they also indicate that the value of any particular augmentation model varies considerably because of natural year-to-year rainfall fluctuations. One technology, which the authors felt was consistent with some claimed modification successes, would have helped both corn and soybean production in 26 out of 38 years modeled. This technology, with an assumed potential of delivering a 26% median increase over natural rainfall, would have led to reduced yields of both crops in one year and would have benefited one crop while harming the other in the remaining 11 years.

An important aspect of the variability question substantiated by Huff and Changnon is the effect of modification efforts in alleviating drought conditions. Huff and Semonin (1974) speculate that during drought periods the opportunity for seeding is so reduced that any resulting rainfall would be of minimal quantity. This hypothesis is reinforced by the Changnon and Towery study (1976) of a cloud seeding effort in Illinois in 1976. Although percentage rainfall increases of 12 to 50% are indicated, the magnitude of additional rainfall is approximately 0.1 inch. The authors do express reservations about the reliability of the results of this short-term operational effort, however.

Subsequent research by Huff and Vogel (1977) indicated that planned weather modification may be of benefit in alleviating growing season droughts. This analysis suggested that rainstorms during drought periods do extend over major portions of the drought area and would be candidates for rainfall enhancement activities. Further analysis to resolve the question of the value of modification during droughts would be quite beneficial.

South Dakota regional study

A study which considered the effects of additional rainfall on a regional level was done by South Dakota State University (1972). This study explicitly took into account:

1) Price declines generated by additional production
2) Costs of obtaining the additional precipitation
3) Associated increases in other production costs
4) The effects of induced shifts in types of farming

These effects were evaluated assuming an additional 1 inch of growing season rainfall was received in the Southeastern Crop Reporting District of South Dakota. Ten situations, assuming differing rainfall timing and differing price effects, were projected. The base model, assuming no modification took place, results in regional net farm incomes of $65 million. The rainfall and price variations considered generate income effects which range from 3.1 to 34% of the base.

A multiplier analysis was conducted to determine secondary benefits of the increased crop production. These secondary benefits were estimated to range from $4 to $67 million. The authors note that extreme care should be used in evaluating these indirect benefits. [Additional discussion on the topic of secondary benefits is included in the section of this report dealing with Snowpack Augmentation.]

The data utilized for this South Dakota study indicate the competitive aspects of additional rainfall on crop production in certain seasons. For example, wheat and rangeland production benefit from additional spring rainfall whereas such rainfall reduces corn production. Conversely, corn production shows very positive responses to additional July rainfall but such rainfall is detrimental to wheat production.

NAS, TASH national estimates

Two national studies will be cited. The first is the National Academy of Sciences work on climate and food (1976). This work's chapter on weather modification contains projections of annual average production increases due to 10% increases in rainfall in the major producing areas for each crop. These estimates are:

Commodity	*Additional quantity*
Corn	38 million bushels
Wheat	34 million bushels
Soybeans	18.4 million bushels
Western range	
Forage	52.5 billion pounds
Range cattle	4.4 billion pounds

To put these quantities in perspective, recent crop reports put 1977 national production levels for these crops at 6.1 billion bushels for corn, 2.0 billion bushels for wheat, and 1.6 billion bushels for soybeans (Good, 1977). Valued at prices of $1.75, $4.50, and $2.00 per bushel for corn, soybeans, and wheat, respectively, these production increases equal revenue increases of $217.3 million. However, it is not possible to determine from that report if competitive crop needs, such as cited for the South Dakota study, were considered.

Another national effort which should be mentioned is that contained in the Technology Assessment of the Suppression of Hail (Changnon et al., 1977). [This report is further detailed in the Hail Suppression section of this report.] The more optimistic technology described in that study assumed rainfall increases of 8 and 16% by 1985' and 1995, respectively. The major results of that analysis indicate these rainfall increases (coupled with sizeable hail damage reductions) would lead to slight decreases in production costs for food commodities. The analysis also indicates that landowners in regions adopting that technology could retain some of the resulting economic gains but at the expense of landowners in nonadopting regions.

Kansas study of impacts, alternatives

An excellent example of a multidisciplinary regional effort has recently been completed by a group of scientists at the Kansas Agricultural Experiment Station (1978). Although concerned primarily with agricultural production, this study does devote considerable attention to such crucial aspects as variability of rainfall, impacts on different types of storm systems, alternative economic conditions, and differential effects on the several agricultural areas included in the study. Because agriculture is a dominant economic sector in the region considered by this study, the failure to analyze impacts on other sectors probably does not greatly alter the benefit estimates generated.

As carefully noted in their report, this study does not attempt to project whether or not weather modification is technically feasible. Rather the study focuses on potential benefits, if such efforts are possible. To accomplish this, a 'plausible' model of rainfall alteration (from Huff and Changnon, 1972) was adopted. This model allows the impact of precipitation modification to be variable for different types of natural rainfall occurrences. The model adopted stipulates the following relationships: for natural rainfall occurrences of less than 0.10 inch, a 75% increase in rainfall occurs; for rainfall events of between 0.11 and 0.5 inch, a 30% increase occurs; and for rainfall between 0.51 and 1.0 inch, a 10% increase occurs. For natural rainfall events of more than 1 inch, a 10% decrease in rainfall is hypothesized.

Applying this stipulated rainfall alteration model to a 30-year series of rainfall observations indicates that a sizeable change in growing season rainfall could result. These effects were not uniform throughout the entire state of Kansas, however.

In absolute terms, rainfall increases ranged from 1.50 inches in southeastern Kansas to 2.25 inches in that state's northwestern region. These average estimates mask considerable variability in year-to-year estimates, however.

As would be expected, additional rainfall was found to be positively correlated with yields of grain crops and forages. An interesting result of this Kansas study relates to the regional change in comparative advantage in crop production caused by the stipulated rainfall changes. In general, these changes were found to benefit the western and eastern regions of the state relative to its central region.

Further, the level of benefits from altered rainfall was found to be strongly affected by the price conditions assumed. In the western region, which would receive the largest relative gains, benefit estimates ranged from *$99* million to $127 million. This benefit variation was in large part due to the price assumptions compared. The higher estimate was associated with no reduction in price due to increased production. The lower estimate was caused by a reduction in crop prices because of the additional output.

It should be emphasized that a price reduction implies a greater effect than simply less benefits to Kansas producers. These lower prices would be reflected in the entire market area of the crops affected. Therefore producers in areas not affected by the altered rainfall could be expected to suffer income losses if prices were lower because of the modification effort.

In contrast to results cited previously, this more detailed analysis indicates that the assumed rainfall alterations could have only relatively little effect on pasture stocking rates. Although some weight gains of calves were noted, these effects were considered to be generally of minor importance.

Weather Effects on Other Sectors of the Economy

Before presenting the articles dealing with selected non-agricultural sectors, an analysis of the extent of weather-caused losses to national economic activity will be discussed. This analysis is very heavily dependent on responses to a questionnaire answered by approximately 250 respondents (Thompson, 1976). This appears to be a relatively small number of observations for projecting national impacts for all sectors of the economy, however.

Thompson estimates that $12.7 billion of lost economic activity occurs annually because of adverse weather. Of this total, $5.3 billion is listed as losses which could be averted by perfect forecasting ability. More interesting to this report is the sectoral breakdown of weather-caused losses, listed as follows.

Sector	*Annual losses (millions of dollars)*
Agriculture	8240
Aviation	92
Construction	998
Communications	77
Electric power	46
Energy	5
Manufacturing	598
Transportation	96
Other	2532
Total	12,684

The preponderance of losses in agriculture would seem to justify the emphasis on this sector in weather modification research. However, these data do suggest significant levels of susceptibility to weather events in a number of other important economic sectors.

Outdoor Recreation. Several studies have considered the effect of precipitation changes on outdoor recreation and tourism. However, these discussions were in terms of qualitative rather than quantitative dimensions. Two of these papers are summarized below:

Two studies indicate pros and cons

Maunder (1970) presents a summarization of a survey of tourists and park officials at Banff National Park in Canada. He notes that tourism officials felt there was a correlation between weather events and tourism. However, no statistics were presented. This article also proposes that an intermittent day of adverse weather may be a bonanza to shop owners. Three major conclusions of this survey process are:

1) If outdoor activity is not conducted because of poor weather, it is often completed at another time
2) The effect of weather events on people's feelings regarding their vacation is a function of the prior expectations of those people
3) Weather has little impact on decisions to return to a particular area

Clawson (1966) also considers the possible impacts of weather modification on outdoor recreation. He speculates that many forms of outdoor recreation are dependent upon the occurrence of a certain range of temperature, sunshine, humidity, wind velocity, and other climatic factors. If these conditions are lacking, the demand for such activities would be diminished. He also notes that the supply of particular recreation activities is also dependent on climate. An example of this aspect is the relationship between snowfall and skiing. Earlier than normal snowfall allows a longer ski season and, therefore, provides benefits to the ski resort community. Once snowpack is down, however, unusually heavy snowfalls may cause economic losses to ski resorts.

Three additional important factors are cited in this paper. The first is Clawson's question as to whether adverse weather cancels or postpones outdoor recreation events. Determination of the answer to this question is crucial in projecting gains or losses from precipitation augmentation. Secondly, he postulates that weather modification to make the climate more attractive for outdoor recreation may intensify peak demands in already heavily utilized areas. The third factor is the hypothesis that, in general, precipitation augmentation would be detrimental to outdoor recreation. This relationship implies potential conflicts between this sector and other economic activities desiring more rainfall.

Construction. In the mid-1960's, Russo et al. (1965) completed an extensive study of the effects of weather on the nation's construction industry. Although the study was primarily oriented toward evaluating the benefits of improved forecasts, the data generated should be instructive in assessing the magnitude of effects for precipitation modification. From that study, an estimated $39.7 billion worth of annual construction activity was considered to be weather sensitive. This figure was 45% of total construction volume for four construction categories: 1) residential homes, 2) general buildings, 3) highways, and 4) heavy and specialized construction.

In this analysis, weather effects were separated into seasonal and intermittent components. The seasonal component, which is the more major factor, is probably not affected by precipitation modification. Thus this segment will not be expanded here.

'Halt' decision, site dry-out two problems

Intermittent weather events would seem to be very related to weather modification efforts, however. McQuigg and Decker (1962) note that precipitation augmentation would affect outdoor construction activities in two ways. The first is that the threshold level to halt operations would be exceeded more often. Secondly, more time would be required to dry-out construction sites if greater quantities of rainfall were to occur. To these two major factors, the Russo et al. study adds deterioration of perishable materials and additional equipment charges as losses generated by intermittent weather events. The sum of the losses for these four categories was estimated as equaling nearly $1.5 billion.

Evaluation of these intermittent effects is a complex function which ideally would incorporate quantity changes for moisture and the timing of those changes, temperature, work rules, labor agreements, and reliability of forecasts. Illustrative of these complexities is the finding of the Russo et al. study of the importance of the 7:00 a.m. decision point. At that time, the decision to commit resources for that day must be made. If construction is started and rain halts operations, non-productive wages must be paid and some materials may be ruined. If no construction is initiated and good weather occurs, expensive equipment will be idled and the completion date of the project will be needlessly delayed.

The breakdown of the estimated annual losses due to intermittent weather are given below:

	Annual losses (millions of dollars)
Non-productive wages	580
Equipment charges	265
Overhead and profits	280
Material losses	410
Total	1535

The equipment, overhead, and profit items represent fixed costs whose daily charges could be reduced if additional days could be worked.

Another complicating feature of any analysis attempting to estimate the effects of precipitation augmentation on the construction sector is that the incidence of the additional costs will vary among several economic sectors. These costs will be distributed in varying portions among employers, consumers, workers, and taxpayers depending on the particular circumstances in each situation.

Manufacturing. Water supply and, therefore, precipitation augmentation are generally considered to have some impact on manufacturing. However, there is thought to be little potential for economic benefits from weather modification for this sector (Bickert and Broune, 1966).

Unlikely manufacturers concerned

Garrison and Paulson (1972) note that plant location decisions at the macro level (i.e., What region in the nation to locate in?) are relatively insensitive to water supply issues. At this level factors such as markets, labor availability and wage, and climate are thought to be overriding. Micro level decisions (i.e., Where in the region to choose a site?) are thought to be more water supply sensitive. This consideration is particularly relevant for more water-intensive industries.

Bickert and Broune scrutinized the operations of five diverse manufacturing plants in Colorado to determine their weather sensitivity. They noted that the initial reaction of the manufacturers interviewed was that weather had negligible effects on operations. After examinations, the authors found that considerable precautions to offset weather effects were a routine part of the operations of these firms. In this region snow and low temperatures were the major disruptive weather factors with rain and high humidity the next adverse. Also, it was found that each of these five firms had somewhat different preferences for weather events.

Transportation. The effect of additional water supplies on shipping is discussed for the Great Lakes in the section on *Fall Rainfall Augmentation of the Great Lakes.* Additionally, augmented water on major inland rivers, such as the Mississippi, Ohio, and Missouri, would be expected to benefit the barge transportation sector.

The effects of snow on road and rail transportation are discussed in the *Snowpack Augmentation* section. Although those examples are only for the Mountain region, events of the past winters in the Midwest and East clearly indicate the potential for economic losses to transportation due to major snow storms.

Added water disbenefits transportation

Schwerdt (1970) discusses the potential for economic losses to water transportation because of augmented precipitation. The factor considered is additional costs of loading and unloading ships. Two effects are postulated. One is additional labor costs for non-productive wages. Work rules pertaining to minimum hours of pay required even if the weather is too inclement for work are a factor here. The other effect is additional moisture damage to perishable cargo resulting from greater quantities of rain.

Maunder (1970) notes a generally accepted relationship between rainy conditions and automobile accidents. He cites an Australian study showing that a 30% increase in accidents occurs on rainy days as opposed to clear days. Orne and Yang (1973) studied the relationship between weather conditions and traffic accidents in Michigan. They postulated the following equation:

$$z = 401 + 21X_3 - 4.7\ X_4 + 321X_5 + 207X_6 - 92X_8$$

Where z = number of accidents per 100 motor vehicle miles
X_3 = barometric pressure
X_4 = temperature
X_5 = precipitation
X_6 = pavement conditions
X_8 = lightning

Because precipitation and number of accidents are positively related, this equation would indicate that rainfall augmentation would lead to an increase in traffic accidents. This is certainly a serious consideration because of the injuries and loss of life associated with motor vehicle accidents.

Water Supplies. A crucial aspect of precipitation modification is the hydrologic consequences of increasing rainfall. Except for the agricultural sector Crawford (1966) speculates that precipitation augmentation will have its most major impact on water supplies. Offsetting the beneficial aspects of more streamflow, such negative aspects as sediment and flood damages must be recognized. Certainly natural year-to-year variations in runoff and streamflow should also be taken into account.

Extensive analyses for Connecticut

Aubert et al. (1972) evaluate the potential for precipitation modification in the Connecticut River watershed. The sectors of primary importance considered are municipal water supply, cooling for thermal power generation, and hydroelectric power generation. Their analysis assumes a growing population generating the need for additional water to serve those sectors. Their projections of water needs are based on a constant water price assumption which could inflict a scarcity bias into their analysis.

This analysis projects that cloud seeding would result in an additional 2 million acre-feet of runoff if seeding activities are conducted for the whole year. If seeding is only conducted for the months of June to February, only 1 million acre-feet of runoff would result. The shorter seeding period is considered because of the naturally plentiful water supplies in the spring months.

These additional water supplies are estimated to be providable with operational costs of $2.40 per acre-foot of additional water. At this price, domestic and industrial water supply sectors could realize a cost advantage from precipitation modification if precipitation is increased by 4%. If precipitation is increased by 15%, the cost advantage would be $1.3 million. Electric utilities are expected to realize cost advantages from rainfall augmentation if precipitation is increased by more than 8%. This advantage is related both to cooling for thermal plants and power generation in hydroelectric plants. (The term cost advantage refers to the cost of providing similar quantities of water using the next best alternative.)

Unfortunately, this study does not directly consider the benefits of multiple uses of water. Also, the negative impacts of this additional rainfall on other sectors are alluded to but not quantified. In a diverse, heavily populated region such as Connecticut, the economic losses from additional rainfall for eight months of the year could be substantial for such sectors as recreation, entertainment, agriculture, transportation, and construction.

Added water for electric power

The augmentation of water supplies can be economically attractive if these additional supplies can be converted to electric power through the use of existing power plants. Although estimates of benefits for additional power are also given in the Snowpack Augmentation section, a number of additional studies will be cited.

Eberly (1966) postulates that precipitation augmentation can be valuable for power generation in three ways. First, the efficiency of hydroelectric plants could be improved if dry years were not quite so dry. Second, fuel costs in thermal plants would be reduced by greater hydro-based output. And third, capital expenditures for new thermal plants could be delayed.

Eberly then suggests that the type of watershed and type of natural rainfall variation are important factors to consider in evaluating the net benefits of precipitation augmentation. Therefore he evaluated cost/benefit ratios for three hypothetical watershed types if they received a 10% increase in runoff. This rainfall increase is consistent with a finding of 8.5% additional runoff due to cloud seeding in the San Joaquin River basin (Elliott and Lang, 1967). The resulting ratios for the Eberly study are:

Cost/return ratios for a hypothetical 10% increase in runoff

Watershed	*Natural rainfall year*		
	Dry	*Normal*	*Wet*
Type I	1/4.6	1/9.0	1/14.1
Type II	1/3.0	1/8.3	1/8.0
Type III	1/0.4	1/1.2	1/1.4

This analysis indicates that in some watersheds the amount of benefit from additional runoff is very sensitive to the type of year. However, in other watersheds the value of the additional water is low in all types of years. Unfortunately, no effort was made to develop a weighted cost/return ratio over the naturally occurring rainfall years to determine an expected cost/return ratio.

Hydroelectric power *benefit*

Lackner (1971) presented a monograph in which the question of increases in the dependable water supply due to precipitation modification is considered. This discussion stresses that changes in the dependable water supply are a function of more than increasing the naturally occurring rainfall. Consideration of the present water supply system must be undertaken to determine the impact of more water, especially during drought conditions. Typically, hydroelectric power generation will benefit from augmented water supplies even if other sectors can not use excess water.

Lackner concludes that, except for snowpack augmentation in the Rockies, precipitation modification would not be in operation on a scale large enough to affect National Water Commission operations by the year 1976. However, advances sufficient to lead to operational programs in the field of orographic precipitation modification were projected to be forthcoming shortly after that time. The outlook for the modification of convective and cyclonic storms is considered much less optimistic by this author. Further research on precipitation modification in areas where water scarcity is a significant problem is recommended.

Seely and DeCoursey (1975) have proposed a set of questions which they feel need to be answered before it will be possible to assess the effects of precipitation modification on stream hydrology. These major issues include:

1) What are the types of streams which would be affected and the magnitude of differential impacts by type of stream?
2) Would the increased rain come in the form of longer duration or as greater intensity rainfall during the same time period?
3) How much variability is associated with the expected rainfall increase?
4) In what season will the augmented rainfall occur?
5) Will the modification program have effects on streamflow in other seasons?

Fall Rainfall Augmentation of the Great Lakes

Stout and Ackermann (1977) have published an extensive study of the potential for augmentation of fall rainfall over the Great Lakes. They note that additional rainfall would produce economic benefits for power generation, shipping, recreation, and water supply, especially in years when the lake level is relatively low.

Aids power, sbipping, water supply

Power generation is important in this region for both Canada and the United States. Shipping has been on the increase between lake and international ports and efforts have been made to lengthen the shipping season to a full-year basis. Additionally, cities such as Chicago, Milwaukee, and Cleveland rely, at least partly, on the lake waters for municipal water supplies. The authors consider recreation to be a minor factor in this area and do not incorporate changes in this economic sector into their analysis. The only negative feature of increased lake levels incorporated into the analysis is associated with lakeshore property damage. This factor is especially important when lake levels exceed normal levels.

For their economic analysis, estimation of benefits is constrained to the value of additional water in Lakes Michigan, Huron, St. Clair, and Erie. Although the possibility of downstream benefits is mentioned, these benefits are not included because they are thought to be relatively small.

Results from two separate economic models are presented. One model was developed by Deininger of the University of Michigan while the other was generated by the Corps of Engineers. Both models considered only the impacts on power generation, shipping, and property damage. Changes in precipitation were constrained to 10 to 20% increases in the months of October, November, and December.

Four separate analyses, differentiated by historic time period and quantity of rainfall, were evaluated with both models. These time periods and the resulting range of benefits are as follows:

% Increase in *fall rainfall*	*Time period*	*Range of annual benefits (dollars)*
10	1950-1966	600,000-1,500,000
20	1950-1966	1,000,000-2,700,000
20	1955-1966	1,200,000-2,700,000
20	1955-1958 and 1960-1966	900,000-3,300,000

The range in estimated benefits results from the use of two separate models. Unfortunately, no definitive explanation is given as to the underlying assumptions of each model that cause these differentials. The bulk of the estimated benefits is derived from increases in the generation of electrical power. Benefits from shipping comprise only 15 to 25% of the gross benefits presented.

Damages to shore property

Damages to shore property are found to consistently reduce the benefits of the program. The two situations in which cloud seeding is assumed to occur only in some years excludes years when excess moisture naturally occurs. Surprisingly, the net annual benefits are not greatly affected by varying the number of the years included in the analysis. This equivalence results as increased property damages are, in general, offset by greater power benefits.

Seeding costs were not critically evaluated in this study. A 'ballpark' estimate of annual costs equaling $500,000 was presented, however. The authors do not indicate how extensive a monitoring and evaluation effort would be associated with this cost figure.

It is unclear from the study whether other sectors, besides lakeshore property owners, would be negatively impacted by increased precipitation and higher lake levels. For example, if farmlands near the lakes were to receive additional moisture from this program, the likelihood of yield reductions from harvesting problems would seem to be a potential concern. However, all benefits are probably not included in the figures presented earlier. No values are put on municipal uses of these lake waters even though water for these uses is noted as becoming more scarce in this region. Also, the possibility of using additional water as a diluting force in sewage treatment processes is alluded to, but no benefit estimates are provided.

Snowpack Augmentation

The question of augmenting winter snowfall for the purpose of generating additional water supply in Western regions has received a considerable amount of scrutiny. In this section a number of the more relevant studies are detailed and then a summary of the implications derived from them is presented. A major component of the section will make reference to the Technology Assesment of Snow Enhancement report (Weisbecker, 1974).

Williams study for Kings River

A study by Williams (1971) looked at snowpack modification and summer season precipitation augmentation for the Kings River region in California. This article notes that variation in average yearly flow is a significant problem in this region. The average annual flow is 1.7 million acre-feet. However, maximum yearly flows can reach 3.5 million acre-feet, indicating that yearly variations in flows can equal the average flow. Significant negative variations have also occurred. In this study weather modification is considered as a tool to help reduce the subnormal flows. However, it is also noted that management of water shortages involves a number of complex factors including expected flows on successive years, changes in demand for water, changes in water use practices, and carryover storage levels.

Average annual runoff was estimated as 1.7 million acre-feet in this region. Of this total amount, 1.5 million acre-feet are retained for beneficial uses in the region. Current crop demands, however, are 3 million acre-feet per year. Therefore 1.5 million acre-feet must be pumped from groundwater sources. These groundwater sources are in large part renewable. However, overpumping occurs at an average rate of 400,000 to 500,000 acre-feet per year.

A maximum of 2.2 million acre-feet of runoff is currently usable in any particular year. In years when natural runoff is in excess of 2.2 million acre-feet, the excess contributes to flood damages. Therefore, a precipitation modification program which generated water supplies in excess of this maximum amount would also increase flood damages.

Twenty-five-year data were used to evaluate the natural runoff in this region. For the years 1945-1970, excess water supplies occurred in 5 years, and flows of less than 1.05 million acre-feet occurred in 7 years. Other years were years without excess supplies but the levels never fell to the extreme 1.05 million acre-feet level. These records imply that 3 out of every 5 years in this region would involve potential water shortages.

In this analysis, it is hypothesized that a 10 to 20% increase in snowpack is feasible in this region. If a 20% increase is possible and no seeding were conducted in years of greater than 2.2 million acre-feet of natural flow, the following estimates of yearly flow would result.

> On the basis of the 25-year data on natural flow, adequate supplies would have been available with the augmentation program for 6 years. In 10 years, the additional water would have offset losses from groundwater pumping. In 3 years the water would have been utilized to reach capacity, and for the remaining 5 years no seeding would have occurred to avoid contributing to excess water supplies.

The value of water in this region is indicated by costs of irrigation water of about $5 per acre-foot. The value of additional snowpack to hydroelectric power generation varies from $1.50 to $20 per acre-foot. This variation in hydroelectric power benefits is dictated by where the increase in snowpack occurs in relation to the highest point in the basin. The costs of a weather modification program at the time the article was written were expected to be between 50¢ and $1 per acre-foot of water. The author suggests that evaluation and monitoring costs might increase that expenditure to $2 per acre-foot.

Even with the higher cost estimate, the benefit cost ratio varies from 2/1 all the way up to 10/1. This analysis does not, however, consider social disbenefits that may be generated by additional snowfall in the region.

Henderson (1975) evaluates the performance of a weather modification program conducted in the Kings River region of California over a 19-year period. This program was restricted to precipitation augmentation in the winter months. In 13 of the 19 years positive results were achieved and generated annual increases averaging 98,400 acre-feet of water. However, if we use the entire 19-year record as a base, the average increase in water supplies would be reduced to 67,300 acre-feet of water.

Alternatives to snow augmentation

In considering alternatives to snowpack augmentation, Howe and Orr (1974) look at the effects of agricultural acreage reductions in order to supply more water for other uses in the Upper Colorado River Basin. The goal of this article was to estimate the impact of generating additional water supplies in the upper mainstream of the Colorado basin by reducing the amount of irrigated agriculture in the basin. This water could be used for non-agricultural uses or to reduce salinity problems in the river.

A diversion from agriculture of almost 600,000 acre-feet of water is considered. This proposal would reduce the salt level of the river by 1.2 million tons. However, the decreased economic activity by the agricultural sector results in a reduction of annual income of $56.5 million in the region. Here the effects of the total direct plus indirect output on 31 economic sectors in this basin are considered.

Several ways of determining the cost of this method of obtaining additional water are proposed. If the salt reduction is valued at $20 per ton, the cost of additional water supply to the non-agricultural sector is valued at $54 per acre-foot. If the salt reduction is valued at $40 per ton, however, water costs are reduced to $14 per acre-foot. But if we look at interbasin transfer as the alternative method of providing additional water and this process costs $50 per acre-foot of water delivered, then the salt reduction part of this project would cost only $22 per ton.

Cummings and McFarland (1977) emphasize the importance of variability of flow in assessing water problems. They first present contrasting estimates of the virgin flows of the Colorado River. These estimates range from 13.5 to 15 million acre-feet annually. Their analysis of water availability indicates that there is a strong likelihood of water scarcity before 1990 in the Upper Colorado River Basin. They also note, however, the strong impact of institutional forces in contributing to this water scarcity.

A major conclusion of the article is that the average virgin flow is a poor parameter on which to base rights to use water from the Colorado River. They propose that once commitments are made for water use, high costs result during periods of water shortages. But if the commitments are made at relatively low levels, opportunity costs to the region occur in terms of economic benefits foregone because some water is not used.

The impact of institutional arrangements is quite substantial in regard to water use in this region. Martin (1975) claims that the salinity problem in the lower basin of the Colorado River could be very much reduced by management alternatives of farmers. In contrast to these on-farm methods, he comments that a considerable capital expenditure would be needed to provide a desalting plant to reduce the salinity problem. But if better water conservation practices, particularly trickle and sprinkle irrigation systems instead of flood irrigation, could be adopted he speculates that the salinity problem would be nearly eliminated. Another way to consider this issue is Martin's note that the federal government could pay farmers in this region $114 per acre to not farm, not build the considered desalting plant, and still reduce salinity in this region as effectively as would be done with a desalting system.

Rudel et al. San Juan program

Two additional studies will be discussed which evaluate the economic potential for augmenting water supplies by weather modification in the Colorado River Basin. The first is by Rudel et al. (1973). (The second is the Technology Assessment of Snow Enhancement done by Weisbecker.) The Rudel et al. study relates to snowpack enhancement in a 3300-mile area of the San Juan Mountains in southwest Colorado. For this study the daily variable costs of the modification program were projected at $975 per day for a 200-day season. Therefore, if the water is worth $14.50 per acre-foot, only 80 acre-feet of additional water are needed to cover daily costs. The indirect costs of the program for avalanche control, mining delays, and snow removal are projected at $93,000 annually.

This program of weather modification is expected to add 600,000 acre-feet of water. If that water were used entirely in Arizona and New Mexico, an effective increase in water supply of 510,000 acre-feet would be attained in these areas. If that water were entirely used in California and Mexico, however, the effective water supply increase would be only 487,500 acre-feet. With estimates for both direct and indirect costs, the following modification costs are given. If the water was entirely used in Arizona and New Mexico, the acre-foot cost is $1.26. If the water is entirely used in California and Mexico, the cost is $1.32 per acre-foot.

Direct, indirect benefits

It is specified in this study that additional water use will be in agriculture, and benefits from agricultural usage of water in these areas are projected. If the water is used for irrigation in Arizona, the direct and indirect benefits are specified as $14.50 per acre-foot. If the water is used by agriculture in California, these direct and indirect benefits are $26.50 per acre-foot. In New Mexico only direct benefits are considered and are evaluated at $20.55 per acre-foot. In addition to agricultural uses, the water can also be used by hydroelectric power generation. In the California and Arizona areas an additional $2 per acre-foot benefit is added for such use. No benefits for power generation are given in the New Mexico region, however, because additional power generation is not considered possible in this area.

If the additional water is distributed between New Mexico and either California or Arizona, the total value of this water can be estimated. Apportioning 127,500 acre-feet of the water to New Mexico provides $6 million in direct benefits to that region. If the remainder of the water is used in Arizona, direct and indirect benefits are projected at $6.3 million. If, however, the remainder of the water not used in New Mexico is used in California, the direct and indirect benefits are $10.3 million per year.

These projected benefits from water usage result in attractive benefit/cost ratios for the weather modification program. These ratios are 13/1 in Arizona, 16/1 in New Mexico, and 21/1 in California. However, these ratios appear to be a comparison only between benefits and operational costs. No costs for research and development were specified.

Consideration of potential problems

Some additional considerations relative to snowpack enhancement are discussed by Rudel et al. (1973). It is estimated that the cost of traveler delays would be approximately $81,000 annually. These additional costs would be generated by an additional two days of conditions when travel on roads in this region would be impossible. The additional melting problem required by greater quantities of snow shouldn't delay either timber or grazing activities significantly according to this article. During periods when snow is already present, both of these activities are shifted to regions where snow is not a problem and additional snowpack shouldn't affect them.

They also consider the possibility of flash floods in the region. The greatest danger from flash floods appears to occur not when snow is melting from the mountains but rather when sudden summer cloudbursts cause the smaller streams to rise out of their banks. However, if snowpack reached levels which suggested a sharply greater possibility of flood damage, the authors speculate that the weather modification program could be shut down to reduce the possibility of generating additional snowpack.

Weisbecker technology assessment

The Technology Assessment for Snow Enhancement in the Colorado River Basin was designed as an extensive study to project the impacts of this potential technology (Weisbecker, 1974). A summary of the costs of a snowpack project would be as follows: Annual direct costs for the system are $5.4 million for operation of the weather modification system, $84,000 for avalanche control, $25,000 for forecasting, $1 million for environmental monitoring, $2 million for within-basin external effects, and $1 million for out-of-basin external effects. These costs total to a yearly figure of $9.5 million.

As just noted, the detriments to the area of additional snowpack are projected, but in a rather gross fashion. The adverse effects considered include increased costs of mining operation; timber cutting; interference with road, rail, and air transportation; and shortening of the tourist season. However, only the mine operation and ground transportation impediments are given much economic value in the study.

This analysis projects that slightly under 2 million acre-feet of additional water would be generated in the Upper Colorado River Basin by winter snowpack augmentation. The process used to value this water was somewhat complicated, but essentially three different situations were considered.

Value with no building projects

The first of these situations is one in which no new building projects are undertaken on the river. If this were to occur, the effects of the additional water would not be too substantial. The relatively minor benefits occur because the study shows there is currently no shortage of water in the river because all the water is not entirely used right now. Without construction of new facilities it is presumed that there is no reason for there being a shortage in the future. The chief benefits of additional water (without making improvements) are in terms of increased water quality in the river, greater reliability of flows, and use of additional hydroelectric power. The reduction of salinity is estimated to be worth $2.5 million. This figure should be offset somewhat by additional sediment trapped behind the dams, but no estimate of this detriment was made. Additionally, hydroelectric power is projected to generate $6.2 million worth of benefits from the additional 2 million acre-feet of water. No value for reliability of flows is estimated, although, as previously noted, Howe and Orr (1974) stress the major costs that can result from year-to-year water variation.

An additional complicating factor is that not all of the benefits of the additional water will be generated within the basin. Therefore $5 million in benefits from basin spillover was projected. In total, if no new projects are built, the benefits from the additional 2 million acre-feet of water are projected to be $12.8 million.

New building independent of added water

If new facilities are built, two alternative ways of computing the value of this additional water are considered. If the additional facilities are built whether the additional water is coming or not, the value of the water is then projected as being equal to the cost of obtaining that same amount of water in the least expensive way. They note that the easiest way to generate 1.5 million acre-feet of water for Mexico is by transferring water from upstream irrigation use. The value of this 1.5 million acre-feet of water is set at $30 million per year. Although this figure is said to include direct and indirect benefits, it would seem to be a conservative figure. If agriculture is considered to be fully employed, work by Howe and Easter (1971) would indicate total benefits as being considerably higher.

New building because of added water

The third alternative is one in which new projects are built because of the additional water supply. If this is the case the additional water supply would not really generate additional benefits over the project benefits but would simply add to the cost of the project. This study then reviews the projected costs and benefits of the Colorado River Basin Project contained in Public Law 90-537 and considers that these projects are already not economic. Therefore, incorporation of the additional costs of the snowpack program would probably not be a wise idea.

HAIL SUPPRESSION

This section of the report will rely heavily on materials from the recently completed Technology Assessment of the Suppression of Hail (TASH) by Changnon et al. (1977). Although a number of other studies have been done which consider the economics of hail and its suppression (Changnon, 1972; Borland and Snyder, 1974; Summers and Wojtiw, 1971) none of them are nearly as comprehensive nor as current as the TASH effort.

Estimates of Crop Losses

One extensive analysis conducted prior to the TASH effort was that of Boone (1974). He estimated the average annual crop loss due to hail for the years 1966-1970 as approximately $403 million in 1968 dollars. The top ten states in terms of average annual loss (millions of 1968 dollars) are:

Texas	$51.0	North Dakota	$26.2
Iowa	39.6	North Carolina	16.6
Nebraska	35.8	Illinois	16.3
Minnesota	28.5	South Dakota	16.2
Kansas	27.1	Colorado	15.9

These estimates indicate rather sizeable reductions in crop production due to hailstorms. It is informative to note that six of the top ten hail loss states are in the Great Plains region, and two of the other four states are in the western Corn Belt. The high ranking for these states results both from a relatively high incidence of hail storms and the major agricultural orientation of these areas.

Property Damage due to Hail

The TASH report estimates property losses due to hail at $75 million nationally in 1975 dollars. Of the losses which could be attributed to specific regions, 38% were concentrated in the states of Iowa, Nebraska, Kansas, Oklahoma, and Texas. An additional 35% of these allocatable losses were attributed to the states of Illinois, Indiana, Ohio, Kentucky, Tennessee, Missouri, and Arkansas.

Individual Farmer and Hail Suppression

The TASH study primarily looked at the economic effects of hail suppression on agriculture in two dimensions. The first dimension was that of the individual farmer. The second dimension was that of the national economy and lost food production associated with hail damage. Through the use of adoption indices, these two aspects were integrated to estimate the extent of adoption of hail suppression for several assumptions regarding the effectiveness of future suppression programs.

The individual farmer's perspective toward hail as a production factor seemingly could be expressed as an average loss over a period of years. For example, historic data show that some areas of the Great Plains have suffered as much as 10% annual loss from hail over long periods of time. However, this average annual loss does not completely describe the detrimental effects of hail as a production factor.

Average loss, variability, alternatives

The variability of hail damage and associated losses in production are also factors which must be considered in estimating the effects of hail on the farmer. The losses which a farmer might suffer in any particular year can be much higher than the long run average loss. Losses of 30, 40, or 100% of a crop in any particular year can lead to serious cash flow problems for ongoing farming operations. Indeed such cash flow difficulties can have consequences for the individual farming operation which are very much more severe (in extreme cases even termination of the enterprise) than the level of average hail loss might imply. Therefore, the individual farmer analysis in TASH included variability aspects of hail damage.

A second factor which must be considered in describing the individual farmer's perspective is that of alternatives to suppressing hail. One such alternative is either hail or all-risk crop insurance. Of course, insurance does not offset national damages from hail because crop damages occur and food production is lost whether insurance is in effect or not. However, the presence of insurance could effectively offset the variability characteristics of hail damage at the farmer level and make the effects of a hail suppression program less attractive.

For TASH the detailed analysis of hail loss as it affects the individual farmer was conducted for six specific areas of the nation. These areas and the type of farming considered are: northwestern Kansas, wheat; southwestern North Dakota, wheat; north central Iowa, corn and soybeans; east-central Illinois, corn and soybeans; west central Texas, cotton; and central North Carolina, tobacco. These areas were selected because hail losses are relatively severe for the crops considered and each area is a significant producer of such crops. Also these areas have historically been susceptible to hail damage.

Self-insurance, insurance, suppression

To account for year-to-year variability of hail storms, this individual farmer analysis considered both the average income and the the variability of income for various strategies the farmer can adopt. Three major types of strategies were considered: self-insurance, insurance, and hail suppression. For the hail suppression strategy three levels of reduction of crop damage due to hail were considered — 20, 50, and 80% reductions in crop damage. In addition, three levels of rainfall variation were associated with each level of crop damage reduction — a 10% reduction, no change, and a 10% increase in rainfall in the hail season. (For the entire TASH analysis, only effects of rainfall changes occurring in those time periods when hail is a potential threat to crops were considered.)

Each of these strategies and options was evaluated through the use of a simulation model which estimated net income based on historical data for a period of time ranging from 20 to 40 years in particular areas. This simulation model used historic hail loss and production data (adjusted for current technology) to estimate the yearly net income. These yearly net incomes were averaged and the variability of this net income computed to arrive at estimates of the relative attractiveness of each strategy for each of the outcomes considered.

For the six farming areas considered, the estimated results in terms of average income are detailed in table 5. Here all figures are in 1973 dollars and relate to average net income per planted acre. Table 6 presents the corresponding estimates of income variability. For this analysis, the coefficient of variation was used as a measure of fluctuation in income. (The coefficient of variation is defined as the standard deviation of per acre net income divided by the average net income per acre times 100).

Insurance cuts income fluctuations

These estimates indicate that, in general, hail insurance tends to do what it was intended to do, that is, to reduce fluctuations in year-to-year income caused by hail loss but at some cost in terms of average income. An additional factor with regard to hail insurance is that it necessarily needs to be expensive in those areas where hail loss is a significant problem. In the western Kansas study area, for example, the hail insurance premium on the full value of production was estimated at more than $8.00 per acre. This cost compares with the tenant's non-insurance production costs of about $40 per acre. This relatively expensive cost of protection may inhibit some farmers from participating in a hail insurance program, even though those premiums may be justified by the loss history of that region.

A very pronounced regional difference in the attractiveness of hail suppression is evident from these data. Figure 1 expresses the outcomes for each of the six regions in terms of changes in net income and changes in certainty of income. For figure 1 both average income and certainty of net income are given index values of 100 for the situation assuming no hail suppression and no hail insurance. The hail suppression options are graphed as changes in both net income and certainty of income from the situation with no hail suppression. The letters H through P correspond to the estimates given in tables 5 and 6. These index values are also expressed in table 7.

Striking east-west differences

The most striking difference between regions is in terms of an east-west differential. For the North Carolina tobacco farmer and the Illinois corn and soybean farmer there is relatively little benefit in terms of either certainty or average income for hail suppression. These relatively small benefits indicate that the potential economic incentive for adoption in these eastern regions is probably not too great. Note, however, that a hail suppression technology insuring no reductions in rainfall and 50 or 80% reductions in hail damage would have slight, but positive, net benefits in these regions.

Table 5. Estimated Results for Crop Production in Terms of Average Net Income (dollars per acre)

Strategy			Northeast Kansas . wheat	Southwest N. Dakota wheat	N-central Iowa corn/soybeans	E-central Illinois corn/soybeans	W-central Texas cotton	Central N Carolina tobacco
A No hail insurance, no hail suppression			25.58	7.52	53.93	49.55	1.89	361.06
Hail insurance strategies								
B Value of production			25.25	7.08	60.05	50.05	3.12	330.13
C 40% deductible on value of production			25.91	7.42				
D Cost of production			25.44	7.18	57.04	49.82	3.99	331.21
E 40% deductible on cost of production			25.78	7.44				
F All-risk crop insurance			24.86	7.13	53.29			
G All-risk and cost of production hail insurance combined			24.52	6.69	59.42			
Hail suppression possibilities								
	Reduction in' crop damage	*Change in rainfall*						
H	20%	10% decrease	22.60	7.42	52.40	47.46	1.70	343.83
I	20%	no change	25.74	7.62	55.50	49.63	3.57	364.21
J	20%	10% increase	28.47	7.83	58.62	51.80	5.43	385.54
K	50%	10% decrease	22.34	9.18	56.35	48.33	9.01	350.32
L	50%	no change	27.35	9.40	59.45	50.50	9.86	370.71
M	50%	10% increase	30.11	9.62	62.58	52.67	11.75	392.03
N	80%	10% decrease	25.98	11.35	60.30	49.20	14.72	356.82
O	80%	no change	29.12	11.56	63.40	51.37	15.64	377.20
P	80%	10% increase	31.88	11.67	66.53	53.54	17.60	398.53

Table 6. Estimated Results for Crop Production in Terms of Coefficient of Variation

Strategy			Northeast Kansas wheat	Southwest N. Dakota wheat	N-central Iowa corn/soybeans	E-central Illinois corn/soybeans	W-central Texas cotton	Central N Carolina tobacco
A No hail insurance, no hail suppression			117	273	34	24	2715	100
Hail insurance strategies								
B Value of production			106	264	15	20	1592	108
C 40% deductible on value of production			105	256				
D Cost of production			106	257	18	21	1276	108
E 40% deductible oncost of production			109	253				
F All-risk crop insurance			116	269	30			
G All-risk and cost of production hail insurance combined			110	278	19			
Hail suppression possibilities								
	Reduction m crop damage	*Change in rainfall*						
H	20%	10% decrease	130	265	31	24	3047	104
I	20%	no change	115	258	29	23	1461	99
J	20%	10% increase	106	252	27	22	963	93
K	50%	10% decrease	119	205	20	22	598	102
L	50%	no change	107	201	19	21	551	97
M	50%	10% increase	99	197	18	21	464	91
N	80%	10% decrease	111	168	14	21	390	100
O	80%	no change	100	166	13	20	370	95
P	80%	10% increase	93	166	12	20	330	90

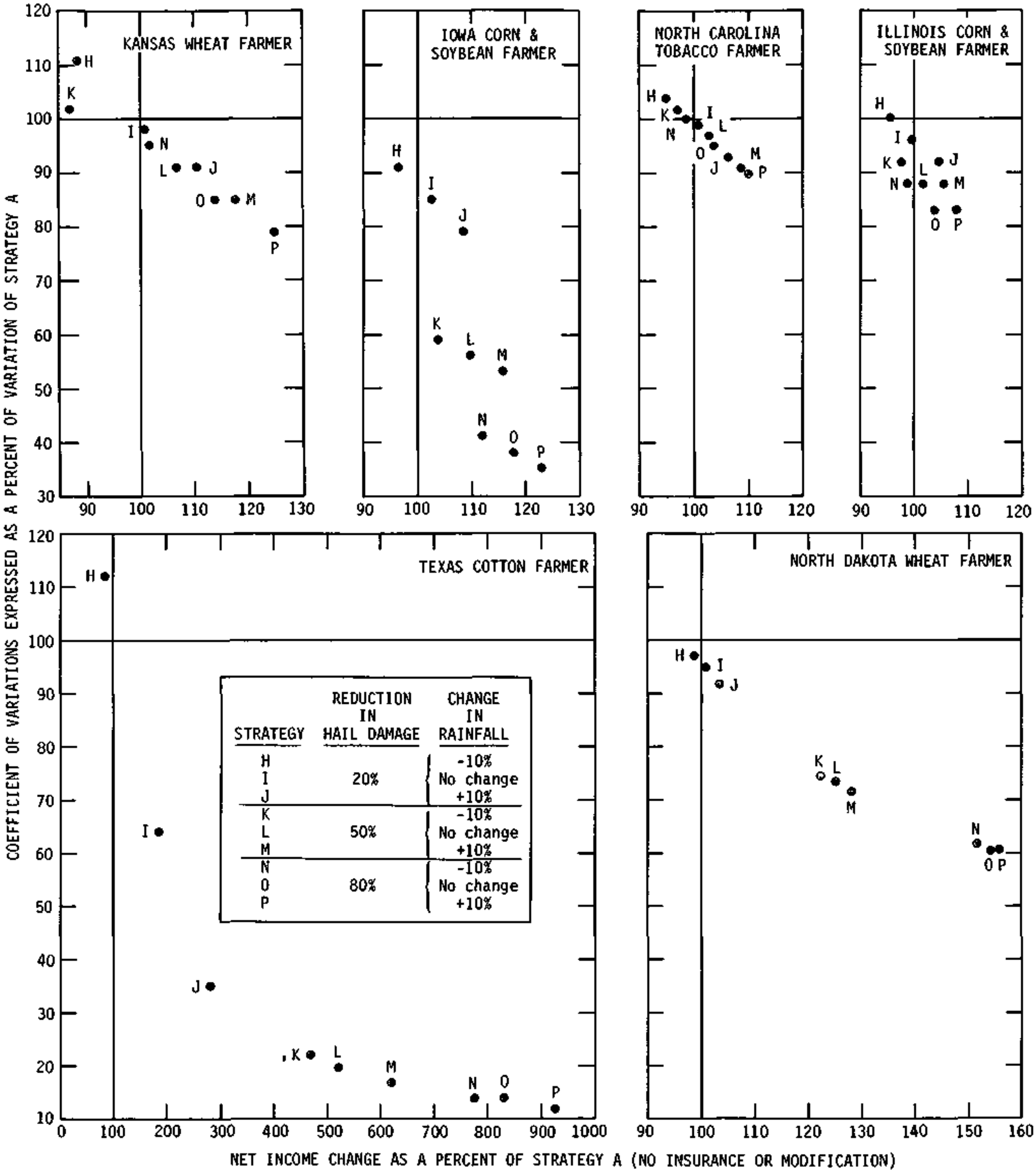

Figure 1. How net incomes change by strategies and regions

Table 7. Comparison of Average Incomes and Coefficients with Strategy A

Strategy			KS	ND	IA	IL	TX	NC
A	No hail suppression		100	100	100	100	100	100
			Percent average net income is of Strategy A net income					
	Reduction m crop damage	*Change in rainfall*						
H	20%	10% decrease	8 8	9 9	9 7	9 6	9 0	9 5
I	20%	no change	101	101	103	100	189	101
J	20%	10% increase	111	104	109	105	287	107
K	50%	10% decrease	8 7	122	104	9 8	477	9 7
L	50%	no change	107	125	110	102	521	103
M	50%	10% increase	118	128	116	106	622	109
N	80%	10% decrease	102	151	112	9 9	779	9 9
O	80%	no change	114	154	118	104	828	104
P	80%	10% increase	125	155	123	108	931	110
			Percent coefficient of variation is of Strategy A coefficient of variation					
H	20%	10% decrease	111	9 7	9 1	100	112	104
I	20%	no change	93	95	85	96	54	99
J	20%	10% increase	9 1	9 2	7 9	9 2	3 5	9 3
K	50%	10% decrease	102	7 5	5 9	9 2	2 2	102
L	50%	no change	91	74	56	88	20	97
M	50%	10% increase	8 3	7 2	5 3	8 8	1 7	9 1
N	80%	10% decrease	9 5	6 2	4 1	8 8	1 4	100
O	80%	no change	85	61	38	82	14	95
P	80%	10% increase	79	61	35	83	12	90

As the analysis considered more westerly regions, an increasing attractiveness of effective hail suppression was discerned. For the Iowa corn-soybean farmer the outcomes for the certainty of income variable were fairly substantial. For the Kansas and North Dakota wheat farmers increases in both certainty of income and average income were relatively large for hail suppression.

In the North Dakota case the change in hail season rainfall did not make a significant difference in the estimated attractiveness of the hail suppression program. For the Kansas wheat farmer, however, any reductions in hail season rainfall offset even substantial reductions in crop damages due to hail. To be economically attractive, therefore, a hail suppression program in this region would have to have very little likelihood of reducing rainfall as it reduced hail losses.

For the Texas cotton farmer considerable benefits were estimated for both certainty of income and average income. This area suffers severely from hail-induced fluctuations in income and also from other natural fluctuations in production. Benefits in terms of reducing loss in this area were quite large. [Note. The quality of data used for this area was the poorest of the six areas examined. This data problem may have contributed to overstating the benefits from hail suppression in this region.]

For the entire individual farmer analysis, the costs of the hail suppression program were assumed to be $1 per planted acre and the average income estimates were net of this operational cost. Although this figure was thought to be high relative to the direct operational cost of the hail suppression program, other costs such as program monitoring and insurance for the hail suppression operator were also considered to be included in this $1 per acre figure.

Estimates of the Adoption of Hail Suppression

A major emphasis of the TASH effort was to indicate the areas in which a hail suppression program was most likely to be adopted in the future. To conduct this analysis, estimates of possible effectiveness levels for hail suppression were needed. These estimates are given in table 8 for the most optimistic and most pessimistic effectiveness levels considered. Here an east-west division of the nation was made to reflect differing storm types and modification potentials. This division is depicted in figure 2.

The estimates of technological capabilities were then combined with the results of the individual farmer analysis and a number of social, political, and legal factors to estimate the areas in which hail suppression would be most likely to be adopted in the next 20 years. Here adoption refers to the utilization of hail suppression technology either experimentally or operationally. The geographic patterns of adoption resulting from this exercise are given in figure 3.

For both of the technological effectiveness levels, predicted adoption is limited primarily to the Great Plains area. The more optimistic technology model is predicted to have a much greater extent of adoption, covering a major portion of the Plains states. For the more pessimistic model no areas are shown as adopting in 1985. And only a smattering of areas in parts of the Dakotas, Nebraska, Montana, and Idaho are considered as adopting regions by 1995 for this assumption.

National and Regional Economic Impact

The national economic analysis used these adoption estimates to parameterize the extent of future usage of the hail suppression technology. For this national analysis, a mathematical model (linear programming, spatial equilibrium) was the framework used to estimate the benefits of hail suppression to crop producers. The model estimates the economic impact of reductions of hail loss and increases of hail season rainfall by taking into account the changes in the comparative advantage of crop production among regions.

Table 8. Estimates of Future Hail Suppression Capabilities

		Model I {optimistic)		*Model II (pessimtstic)*	
		Western U.S.	*Eastern U.S*	*Western U.S.*	*Eastern U.S*
1975	Hail	-30	0	0	0
	Rain	+6	0	0	0
1985	Hail	-40	-30	-15	-11
	Rain	+8	-5	-10	+5
1995	Hail	-80	-60	-30	-21
	Rain	+16	+10	0	+9

Figure 2. West-east division for scientific assessment

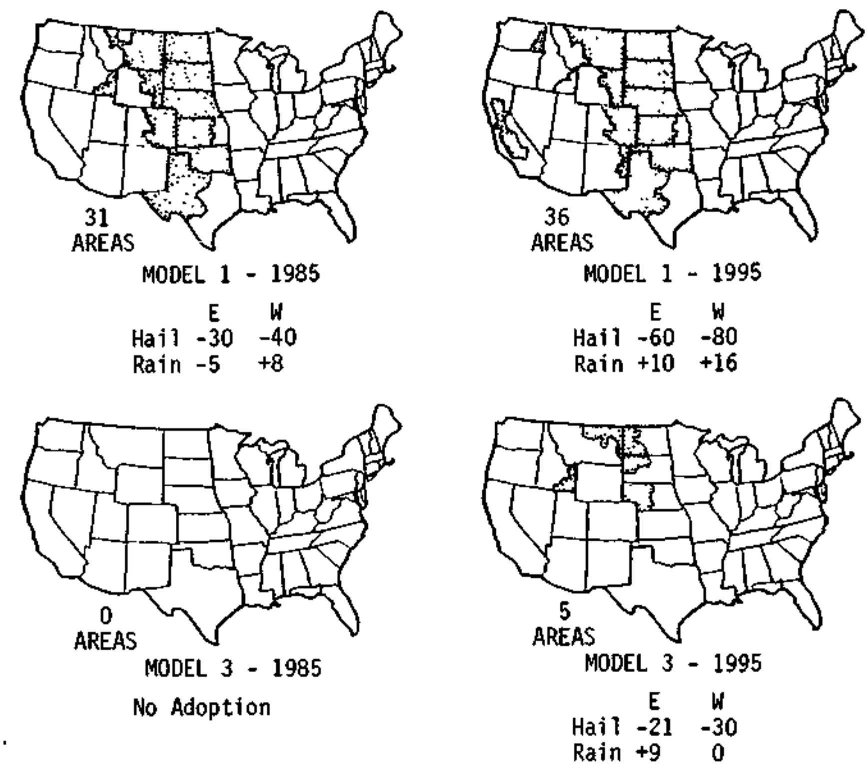

Figure 3. Maps of projected adoption areas

Eight crops were considered in this model: corn, sorghum, barley, oats, wheat, rye, cotton, and soybeans. These crops suffer about 80% of the hail damage occurring in an average year in the nation.

Estimates future impacts

The basic orientation of this assessment was to estimate future impacts of a viable technology. Therefore, the major emphasis of the national economic model was to project impacts for the years 1985 and 1995. For each of these time periods a benchmark model was first estimated. This benchmark model characterizes a continuation of the present situation with respect to usage of hail suppression. This solution represents one in which hail suppression in 1985 and 1995 would occur with the same effectiveness as in 1975.

Table 9 provides estimates of potential costs of producing and transporting the eight crops considered in the model for each suppression effectiveness level and the benchmark situation. In this table, production costs include land rents accruing to owners of farmland. Therefore these cost decreases would correspond to the reductions in food production costs which might occur for each of the levels of hail suppression technology. However, part of these benefits would be made up of losses in economic returns to landowners. Therefore, the estimates of table 9 overstate the true national value of the hail suppression program because they are partially composed of income transfers between segments of the national society. An apparent result given in table 9 is that the reductions in costs would not be very large for the 1985 situation. Even under the most optimistic assumption regarding hail suppression effectiveness, only a 1% cost decrease was estimated.

Note. This result should not be interpreted as a promise of reduced food costs in in the future. Rather this estimate should be considered as indicating that hail suppression at the indicated effectiveness level implies costs 1% lower than they would be without that hail suppression technology being in effect.

However, for 1995, a more optimistic situation with regard to hail suppression was projected. Here under the most optimistic assumption regarding technology effectiveness, cost decreases reached a 5% level. This 5% reduction was estimated to be equivalent to almost $900 million. But under the least optimistic assumption, insignificant cost decreases were estimated. These results imply that modest reductions in production costs could result from development and application of an effective hail suppression technology.

Table 9. Potential Production and Transportation Cost Decreases due to Future Hail Suppression*

Year	*Benchmark*	*Model 1*	*Model 2*
1985 *(billion $)*	18.915	18.695	18.915
Cost decrease		0.220	0
Cost decrease *(as % of benchmark)*		1	0
1995 *(billion $)*	18.744	17.853	18.741
Cost decrease		0.891	0.003
Cost decrease *(as % of benchmark)*		5	0

**Includes reduction m returns to cropland*

Gains to Crop Producers

By acting to reduce crop losses due to hail, the hail suppression technology is in effect an output-increasing mechanism. But crop production is conducted in an economic environment which approximates that of a perfectly competitive industry. Therefore, increases in output because of the introduction of a new technology will result in a lowering of the market price for the commodity produced.

Producers affected unequally "

But the TASH study indicated that the hail suppression technology would not be adopted throughout the nation. This characteristic means that the nation's crop producers would not be equally affected by the development of an effective hail suppression technology. Rather crop producers could be divided into two categories — those residing in areas where adoption takes place and those residing in areas where adoption does not occur. The economic impacts of this technology on the crop producer would be expected to differ for individuals in these two categories.

Larger output, lower price

As output becomes larger than it would be if a more effective technology had not been developed, the market price for crops produced would be expected to be lower than without the technology. But these crops are produced for national and international markets and no price differentiation will be made for crops produced with or without the benefit of hail suppression. Therefore, the individual farmer in a region where hail suppression is adopted will have more output to sell because of the technology but the price will be slightly lower than if the more effective technology did not exist. Thus, producers in the adopting regions should be no worse off and possibly might be better off than if the more effective technology was not available. Of course, consumers would be better off because of the resulting lower crop prices.

But the crop producer in a region in which hail suppression is not adopted will also suffer from the lower market price. And no output increase from the more effective suppression technology will be forthcoming to this producer. Therefore, producers in this category would be made worse off by development of this more effective technology.

Land returns reduced

Because land is the major fixed resource used in crop production, economic theory tells us that the benefits and losses to agriculture resulting from implementation of a technology such as hail suppression would be reflected in the variable, returns to the land, and thus in the price of land. For the optimistic effectiveness level, Model 1, national returns to land are estimated to be 97 and 92% of what they would be without this technology for 1985 and 1995, respectively. But these national data mask the regional agricultural impacts alluded to in the preceding paragraphs. Unfortunately the regional impacts presented in the TASH report are too aggregated to accurately depict these regional impacts.

Regional economic impacts

However, an auxiliary analysis was done, using the same programming model as in the TASH study, which does provide results illustrating these regional aspects (van Blokland et al., 1977). In this analysis, the goal was to estimate the economic impacts on

Table 10. Returns to Landowners for Illinois and Nationally, 1985*

Returns as an index of benchmark returns 1985 = 100		*Hail and rainfall departures from normal m percent*			
	Hail	-30	-30	—50	—50
	Rain	+5	+9	+5	+9
		Index numbers			
Illinois		102	107	103	108
National		98	97	98	97

Only technologies witb rainfall increases

agriculture if the entire state of Illinois, but only Illinois, were to adopt hail suppression by 1985. Several levels of hail suppression effectiveness were considered. The resulting estimates of returns to landowners are given in table 10.

In this table, an index number of 100 indicates that the area would be as well off with the indicated hail suppression effectiveness level as without it. The differential impact for farmers in an adopting region as opposed to those not in an adopting region is illustrated as index numbers for Illinois are above 100 and those for the entire nation are less than 100. This describes the probable result for any region adopting an effective technology relative to those regions which do not, or can not, adopt that same technology. In the context of the TASH study, this result implies that those regions in the Great Plains where adoption was estimated to occur (figure 3) would gain relative to the other producing regions of the nation.

Rainfall associated with hail

Another interesting aspect shown in table 10 is the comparison of the benefits of the specified hail damage reduction relative to the rainfall increase associated with it. The shift from a 30 to 50% effectiveness level for hail damage increases the return to landowners only from index numbers of 102 to 103 and 107 to 108. But the increase from 5 to 9% additional hail-season rainfall changes the respective index numbers from 102 to 107 and 103 to 108. This result is consistent with the results detailed for the Illinois corn and soybean farmer analysis described previously. Also the TASH national model indicated similar values detailing the economic importance of any rainfall changes which might be associated with efforts to reduce hail damage to crops.

Benefit/Cost Ratios

An additional output of the TASH study was computation of benefit/cost ratios for the various effectiveness levels considered. For this benefit/cost ratio only the benefits from reductions of variable production and transportation costs are considered. Using this variable does not include the reductions in returns to landowners as a national benefit. These benefit/cost ratios are computed for a 40-year period using an 8% discount rate. For the optimistic effectiveness level assumption, the benefit/cost ratio is on the order of 15/1 for the period. For the pessimistic assumption the benefit/cost ratio is —0.4/1.

To provide a basis for comparison, estimates of benefit/cost ratios for other agricultural innovations were included in the TASH report. After presentation of these data, the report concludes that, "In summary, although data are not available to make a comparison between further investments in hail suppression and other candidates for research funding, . . . the benefit/cost ratios are such that hail suppression with attendant rainfall augmentation appears to warrant serious consideration" (Changnon et al., 1977, p. 285).

Basis for benefit estimate

To compute these benefit/cost ratios, the operational costs of the hail suppression technology were deducted from the gross benefits estimate. This result tends to overstate the resulting benefit/cost ratio; however, it does serve to isolate the cost estimate to expenditures in the public sector. For estimation of this ratio, the cost estimate is composed of projected expenditures for future research and development and for design, evaluation, and program information activities. Past expenditures for hail suppression research are not included in this cost estimate.

The cost portion of the ratio would also be understated because the detrimental effects of additional rainfall on all sectors of the regional economies affected are not included. To the extent such additional rainfall raises expenditures because of delayed construction, additional traffic accidents, postponed outdoor recreation activities, etc., such outlays should be included as costs for the hail suppression activities. Because hail suppression was assumed to be attempted only during normally dry parts of the year, the severity of this non-inclusion is reduced.

The benefit portion of these benefit/cost ratios would also seem to be understated for a number of reasons. First, no benefit for reductions in variability of income are included. That variability can be a significant consideration as indicated by the North Dakota, Kansas, and Texas individual farmer analyses. Indirect benefits associated with any increased crop output also are not estimated. Third, reductions in property damages in those adopting regions are not included, and fourth, benefits from increased livestock production on rangelands in these adopting areas are not estimated.

Property damage reductions

The TASH report details many of the complexities involved in attempting to compute the effect of the suppression effectiveness levels specified on reductions in property damage. These include the correlation of property hail damage and tornadoes. If hail suppression were not conducted on days when tornadoes were likely, only a reduced portion of the hail-caused property losses would be affected. Further, associated with hail losses are water damages caused by rainfall entering structures damaged by hail. If rainfall is increased this may lead to additional water damages. Also the TASH analysis assumed that hail suppression activities would be conducted only in time periods when crops were susceptible to hail losses. Therefore, hail which damaged property in other time periods would not be alleviated by the suppression models in the TASH report.

For the pessimistic model, adoption was only indicated for relatively sparse areas of the northern Great Plains. Therefore, it would seem proper to conclude that the benefit estimate for this model would not be greatly affected by not including property damages.

For the optimistic model, adoption is considered for almost the entire Great Plains region. The property damage figure discussed previously indicated that this region contains approximately 40% of the allocated property losses as a maximum. If the entire property losses of $75 million in 1975 are combined with the 40% figure, the property damage figure for the affected area would be about $30 million.

For this optimistic model, hail damage reductions of 30 and 60% are estimated for 1985 and 1995, respectively. Relative to the $30 million figure, this implies maximum reductions of $9. and $18 million dollars, respectively. Although these are crude estimates, it is instructive to compare them to the reductions in production and transportation costs used in calculating the benefit/cost estimates. When reductions in returns to landowners were not included, supply costs for the agricultural products still decline by $206 and $493 million in 1985 and 1995, respectively. Again it seems reasonable to conclude that inclusion of reductions in property damages would not have greatly altered the benefit/cost ratios presented.

Estimates for forage, rangeland

Because hail is normally not thought of as causing significant damage to forage production on rangelands, the specification of the economic model used in TASH did not include any rangeland activities. However, as the TASH project proceeded, it became evident that rainfall changes produced by attempts to reduce hail damage should also be considered in the economic analysis. However, by this point, time and budget constraints precluded the inclusion of forage activities in the modeling framework.

Auxiliary data do exist, however, which may provide insights into the magnitude of this factor. The National Academy of Sciences report on climate and food (1976) suggests that a 10% increase in critical season rainfall in the 17 western states would result in an increase of 52.5 billion pounds of forage. This amount of roughage is converted into a potential of about 4.4 billion pounds of range cattle, equivalent to about 4.0 million head of cattle.

In 1975 the areas projected to adopt the optimistic hail suppression technology contained about 20 million head of beef cattle (USDA, 1977). This was about 75% of the total number of range cattle contained in the 17 western states. Partin and Smith (1974) indicate that a rough correspondence occurs between increases in precipitation and production of native grasses. Therefore, an *extremely* crude estimate of increased range cattle could be calculated as:

4 million cattle/10% increase in rainfall	X	30% increase in hail season rainfall	X	75%	=	9 million head

With 1975 national relationships, this increase in cattle numbers would produce 5.9 million 500-pound feeder cattle. If evaluated at 1977 prices, this would be $1.2 billion worth of production. These are very rough and crude estimates. A more thorough analysis of this issue should be attempted before these data are given substantial credibility; however, they do indicate a potentially important benefit of hail suppression activities.

MAJOR STORM (HURRICANE) SUPPRESSION

For four types of major storms, Hendrick and Friedman (1966) provide estimates of the range of annual losses for insured property by type of storm in the United States. They estimate losses of between $250 and $500 million dollars for hurricane storms. For tornadoes the losses would be between $100 and $200 million, for hail and wind thunderstorms $125 to $250 million, and for extra tropical windstorms, between $25 and $50 million. In total, they estimate insured property losses in the United States ranging from $500 to $1000 million as an annual average.

This article contained a very interesting analysis of hurricane modification although its major emphasis was related to insurance effects. The authors specify that hurricanes could be beneficially altered in terms of three parameters.

Alter severity, frequency, storm path

The first of these is intensity. Intensity, as they define it, refers to the severity with which winds and water reach the land and the amount of damage these factors can cause. The second parameter is the frequency with which storms develop. If a technique could be defined which would restrict the number of tropical storms or hurricanes that might occur, then beneficial results would be forthcoming. The third parameter was alteration of the path, or hurricane track, which might develop for major storms. They hypothesized that if hurricanes could be directed away from land areas or toward less populated areas there would be benefits in terms of reduction in damages.

Hendrick and Friedman hypothesize that a reduction of 15% in hurricane intensity could have reduced property damages by 41%. These reductions in property damages would come about because of fewer claims and less loss per claim. Secondly, they argue that a 10% reduction in frequency of occurrence should reduce property damages by about 10%. They then consider changing the path of the hurricane. They do note, however, that the uncertainty of predicting where the future path of this storm may be makes this modification effort much more uncertain. In spite of this uncertainty, they hypothesize that a 10% reduction in frequency plus a 15% reduction of intensity plus a 10% change in path of storms could lead to a 57% reduction in total property damage from hurricanes.

Benefits as well as damages

One of the concerns regarding modification of hurricane storms is the claim that there are beneficial aspects resulting from hurricanes. These benefits are primarily related to rainfall which occurs along with hurricane property damages. Hartman et al. (1969) consider the impact of rainfall from hurricanes on crop production in 11 southeastern states. They show that the impact of this rainfall on crop production is a function of the timing of the storm. Hurricanes which damage crop production occur in early fall. These crop losses are associated with flooding and damages involved in preventing harvest. However, this analysis shows that those hurricanes which occur in June and July tend to have more positive impacts on crop production because of the beneficial aspects of additional moisture for growing crops.

Using 1964 prices and yields, they estimate the net impacts of specific hurricanes on crop production for this region. This analysis indicates the range and diversity of impacts which individual storms can have on crop production. For one storm they estimate a reduction in crop production equaling $54 million. But for another storm, the impact of the hurricane was to increase crop production by approximately $8 million.

Howard et al. (1972) provide estimates of average annual property damage during the 1960's equaling about $440 million in the United States. However, they note that specific hurricanes have done considerably more damage. They cite Hurricane Betsy in 1965 and Hurricane Camille in 1969 which each caused about $1.5 billion worth of damage.

The overriding question addressed in this article is whether the policy (in force at that time) regarding the seeding of hurricanes should be changed in order to allow the seeding of hurricanes approaching a coastal area. For this analysis, the physical dimensions of the hurricanes are described entirely by surface wind speed. In addition, the analysis only deals with economic losses from property damage. Howard et al. suggest that injuries and loss of life are primarily a function of adequacy of warnings and not intensity of the hurricane.

Decision analysis made

This article is undertaken in the context of decision analysis. Those authors note that there are two factors of uncertainty addressing the question of whether to seed hurricanes. The first uncertain effect is that of natural changes in the development of a hurricane from a tropical storm to a property and people damaging event in the United States. The second source of uncertainty addressed has to do with the effects of the seeding process itself. That is, they do not treat a decision to seed hurricanes as automatically and in all cases providing a certain set level of physical change in that hurricane. Rather they claim that the parameter regarding suppression of wind damage should be treated more nearly as a random variable which has dimensions of variability associated with it.

A second factor stressed in addition to the uncertainty dimension is that a decision must be made. Agencies cannot escape this question because the choice of inaction is indeed a decision. If a viable suppression technology did exist, then that agency would be deciding not to provide the potential benefits from the seeding potential. Essentially what they are saying here is the old axiom that "no decision is a decision."

Howard et al. (1972) also note a problem of lack of data with respect to particular causes of losses from hurricanes. However, from historic data they estimate an equation to describe the hurricane property damage function. This equation is expressed as $d = c_1 w^{c_2}$ where d is property damage in millions of dollars, c_1 and c_2 are constants, and w represents the change in intensity of wind speed. The exponent, c_2, is estimated to be 4.36 on the basis of historic data. Therefore if a 15% reduction in maximum wind speed were to occur, the corresponding reduction in estimated property damage would be 51% .

Examine expected benefits

The analysis proceeds to examine expected benefits from seeding *a* hypothetical hurricane which without seeding would have resulted in property losses approximating $100 million. A sophisticated type of decision tree analysis is utilized to take into account all of the uncertainty aspects discussed above. Incorporated in this analysis is a probability distribution with respect to the natural phenomena regarding hurricane changes as hurricanes develop, grow, and approach land areas. Also probability distributions are used to describe the expected changes in physical characteristics of the hurricane due to the seeding process. For all of the outcomes simulated, the seeding decision stochastically dominates the no seeding decision. In all the cases considered, seeding hurricanes results in expected losses which are less than if the decision were made to not seed the hurricane.

It should be noted that in this analysis, the possibility is considered that seeding may actually result in more damages than if no seeding were to occur. However, the probability of this detrimental event is always considered to be small relative to the probabilities of no effect or beneficial outcomes.

A sensitivity analysis was also conducted to evaluate the effect of changes in the parameters in their model. The expected loss in terms of property damage appears to be about 20% less if the hurricane is seeded using their basic parameters. Varying the assumptions of the analysis causes this reduction to fluctuate between 10 and 30% but does not change the preferred alternative, the decision to seed hurricanes.

The final piece of information available from the analysis is the specification of a future experiment benefit/cost ratio of approximately 300/1. Although the magnitude of this ratio would be sensitive to varying assumptions, the authors indicate that using reasonable assumptions leads to benefits which very heavily outweigh associated costs.

Gray's 1973 study

Gray (1973) estimates annual damages of about $500 million from hurricanes in the United States. The basic philosophy behind the paper is expressed in the quotation, "Man should attempt to reduce this heavy storm disruption while not significantly reducing the beneficial rain from these storms" (p. 1). The suggested method with which to accomplish this goal is to reduce the intensity of winds in the core of the storm while maintaining the strength of the outer circulation which provides beneficial rainfall.

This study specifies that hurricane damages primarily arise from three sources. One source of damage is that of coastal flooding due to winds which cause high water along the coast. A second relates to direct wind force damages, and a third source of damage is the inland flooding associated with abnormally heavy precipitation. Maximum hurricane damage seems to be concentrated in the area of maximum sustained winds, to the right of the storm center. The study also makes use of the equation given by Hartman et al. (1969) where damages increase by a power of 4.3 with increases in wind speed.

Gray (1973) also noted that if storm rainfall could be more evenly distributed, then flooding damage would be greatly reduced and the storm's rainfall benefits would be enhanced. Also, storm winds and surge heights tend to be correlated. That is, as destructive winds intensify, the heights of the sea level which are attained also tend to increase.

International benefits included

An interesting aspect of this study is the inclusion of international benefits of the development of the modification technology. This is the only study which attempted to quantify this international dimension of weather modification research. However, it would seem that this concept is applicable to all the technologies considered in this report.

As noted previously, this study expresses hurricane modification as a goal. That goal is attained by reducing wind intensity in the center of the storm. Using the power of 4.3 as an exponential increase for wind damage, the study specifies, " . . . for 10 percent wind reduction of a cyclone with maximum sustained surface wind of 70 meters per second, the damage reduction would be about $50 million" (Gray, 1973, p. 85).

The analysis also estimates the potential for annual reductions in national property losses associated with varying levels of hurricane suppression capability. To accomplish this, it is assumed that:

1) Only one-fourth of the storms strike land, therefore the rest are not seeded
2) It is possible to reduce the maximum sustained surface winds by 20%
3) Damage relationships in the United States are applicable to the rest of the globe

Given these assumptions, projections of annual reduction in United States and global damages of about $100 and $800 million, respectively, are made.

Data are also presented which show the relationship between individual storm damage reductions and storm intensity as a function of the percent that the maximum surface winds are reduced. These relationships are shown in table 11. These data indicate that very great benefits occur for suppressing individual storms which have high levels of maximum sustained surface wind. In table 12 the relationship between the percentage reduction of maximum sustained surface winds and damage reduction for storms throughout the season in the United States are shown. This calculation assumes 1.6 treatable storms per year and expresses damage reduction in terms of millions of 1969 dollars.

Table 11. Individual Storm Damage Reduction by Storm Intensity and Percent that the Maximum Surface Winds are Reduced

(In millions of 1969 dollars)

Max. sustained surface wind (m/sec)	*Percentage wind reduction* 1	5	10	20	33	50
>80(avg 90)	15	70	140	250	330	400
60-80 (avg 70)	5	25	50	90	115	140
40-60 (avg 50)	1	5	10	20	25	30
25-40 (avg 33)	0	1	2	4	5	7

Table 12. Annual Damage Reduction for Various Percentage Reductions of Storm Maximum Sustained Surface Winds*

(In millions of 1969 dollars)

Percent reduction oj maximum sustained surface winds	*For U.S (1.6 treatable storms per year)*	*lor globe (12 treatable storms per year)*
1	~5	~35
5	~30	~220
10	~60	~450
20	~100	~800
33	~140	~1050
50	~170	~1300

**Only one-quarter of tropical cyclones witb maximum surface winds greater than 40 m/sec have been considered*

Gray's analysis presents operational cost estimates assuming the use of carbon dust for seeding material. The cost of operating a U.S. Air Force C5A for 8 to 10 hours is set at $30,000. The cost of the payload of carbon dust for this C5 A is approximately $10,000. Therefore, the cost of a single hurricane modification flight totals about $40,000. Adding overhead and support costs (which are poorly defined), the total cost of each flight is specified as being on the order of $100,000. If 10 to 20 flights are needed to suppress a single hurricane, operational costs would amount to about $1 to $2 million per hurricane. These relationships are further explained in table 13. In this table, the ratio of damage reduction to modification costs for different intensity storms and percentage wind decreases are shown. These data show that gains of an order of 10/1 to 100/1 are possible with 10 to 20% reductions in maximum sustained surface winds.

To consider the relationship between yearly average damage reductions and modification costs, table 14 is presented. The estimates of this table indicate that quite significant reductions in damages would result from reductions in maximum surface sustained wind speed. These estimates (again in terms of 1969 dollars) show benefit/cost ratios of 10/1 for a 5% wind reduction and 33/1 for a 20% wind reduction. It also should be repeated that these benefits do not attempt to include gains from reduced loss of life.

In the study Gray (1973) cites possible indirect benefits associated with development of a reliable hurricane suppression technology. Here he cites the opportunity to reduce building costs associated with hurricane damage. This factor refers to the additional expenses incorporated in normal building activities in hurricane-prone areas in order that the resulting buildings better withstand potential hurricane damage. Also

Table 13. Ratio of Damage Reduction to Modification Cost for Different Intensity Storms and Percentage Maximum Wind Decreases

Maximum sustained surface wind (m/sec)	*Percentage reduclton of maximum sustained surface winds*					
	1	*5*	*10*	*20*	*33*	*50*
>80 (assume 20 C5A aircraft)	7/1	35/1	70/1	120/1	160/1	200/1
60-80 (assume 15 C5A aircraft)	3/1	15/1	35/1	60/1	75/1	95/1
40-60 (assume 10 C5A aircraft)	1/1	5/1	10/1	18/1	25/1	30/1
25-40 (assume 5 C5A aircraft)	0	2/1	4/1	6/1	10/1	14/1

Table 14. Ratio of Yearly Average of Damage Reduction to Modification Cost for Different Percentages of Wind Decrease*

(In millions of 1969 dollars)

Percentage wind reduction	*Damage reduction/modification cost For U S*	*For Globe*
1	5/3	30/14
5	30/3	180/14
10	60/3	450/14
20	100/3	800/14
33	140/3	1050/14
50	170/3	1300/14

Only one-quarter of storms with intensity greater than 40 m/sec are included

reductions in government expenses for anti-hurricane construction of such things as sea walls and flood conduit channels are hypothesized.

Public response problems

However, this consideration may be rather suspect. In fact, if such precautions were lessened because of the possibility of use of hurricane suppression, then hurricanes of lesser intensity could possibly do as much damage as hurricanes of greater intensity did before the adjustment in building practices was made. In one sense, this possibility might be looked upon as a detriment to the overall hurricane suppression technology. Crutchfield (1969) notes that this aspect may be made more serious if people begin inhabiting areas which are relatively hurricane-prone because of the belief that hurricane damage has been lessened. And as noted in the Hartman et al. (1969) article concerning uncertainty, even though a hurricane suppression activity is available, that availability does not preclude the possibility of a very severe and damaging hurricane striking a particular area of the United States.

FOG DISPERSAL

As is also the case for lightning suppression, there exist only a few references dealing with the economic costs and benefits of fog dispersal. Of the ones reviewed, almost all dealt with the effects of fog on aviation. Although automobile transportation is also affected by fog, there seems to be little likelihood for a workable suppression technology to be developed for automobile transportation.

Fog-related costs for aviation

There are a few references which estimate fog-related costs for aviation. In a 1970 article, Tschupp estimates that fog-caused expenditures to aviation were between $66 and $75 million annually. He also gives an average cost per airport hour of approximately $47,300 for delays due to fog. He did note, however, that not all of these costs were out-of-pocket costs. Beckwith (1966) estimates that 1% of the uncompleted airline mileage in 1964 was caused by dense fog. He also notes that in 1964 there were 800 million miles flown in the United States. Maunder (1970) indicates that, in the United States, losses to aviation due to dense fog total $37 million for four winter months. These estimates all seem somewhat consistent with the figure derived by Thompson (1976) that $92 million in weather-caused losses occurred to aviation in the late 1960's.

But these articles also note that not all types of fog can be controlled with the same technology. Generally they imply that only super-cooled fog was amenable to control. And unfortunately, this fog-type is nationally the least prevalent type of fog. Warm-fog, which occurs much more frequently, was felt to be uncontrollable by weather modification methods.

Benefit/costs, Beckwith,

Beckwith (1966) presents cost and benefit estimates for a particular weather modification operation. He notes that there are three approaches to reducing losses from fog:

1) The development of electric landing devices
2) Expenditures to improve forecasting reliability
3) Development of effective weather modification technologies

He notes that fog dispersal was used extensively in World War II and was somewhat successful. However, that operation was found to be very expensive.

Beckwith also provides estimates relative to experiments by United Airlines in Oregon and in Salt Lake City. He notes that the annual problem with super-cooled fog in these areas is not frequently great. However, in these Northwest areas, super-cooled fog can occur for several days in succession, causing major transportation problems. Benefits from their operations in the winter of 1963-1964 are estimated to be worth $19,000. Associated costs are $3825. This would imply substantial incentive for commercial airlines to utilize modification programs.

To determine these net benefits, he defined benefits as the direct and tangible savings including revenue not lost because of cancellation or overflights, the cost of holding delayed aircraft, and reduction of the costs of providing other transportation, hotel accommodations, and extra meals for delayed passengers. It is unclear from the article whether any reductions in cost of flights not flown were included. If not, the benefits variable would be overstated.

Beckwith also cites data for United operations in the months from December 1962 to March 1963. For United Airlines, he estimates total revenue losses and added expenses of $9 million due to weather-caused delays. Of this total cost, he attributes $3.4 million to fog. He suggests that multiplication by a factor of five would provide estimates of losses for the entire nation, implying a $35 million national loss in these four winter months.

Benefits to general aviation from fog suppression are not evaluated in the benefits variable presented. Beckwith suggests these gains would primarily be in terms of improved safety records for non-commercial aviation.

Warm fog dissipation possibilities

Most recent articles have implied that the possibility of dissipating warm fog is becoming more of a reality. Kunkel (1973) tells of a designed system for heating air to dissipate fog, utilizing ground-based combustors to warm fog-laden air. He notes that plans are under way to develop an operational system by the year 1982. This operational system is then to be installed at a military air base. However, in a second article by Kunkel (1977) some of the apparent successes due to warm-fog modification are attributed in part to natural clearing conditions. This article cautions that natural clearing must be taken into account in any statistical evaluation of warm-fog dispersal operations.

In a recent article by Weinstein (1974) between 0.8 and 2.0% of traffic at selected U.S. airports was estimated to be affected by warm fog. These data are primarily based on experiences at military airports. In another part of this study Weinstein shows that in 1971, 21 civilian airports in the United States had over 200 arrivals affected by warm fog. Of these 21 airports, 11 had over 500 arrivals affected, and 4 airports had over 1000 arrivals affected. Cost of these delays caused by weather conditions are put at $3000 per incident, in 1973 dollars.

In evaluating the potential for weather modification to dissipate fog, these data suggest there would be considerable savings to be gained if fog could be dissipated at airports. Relative to most weather modification technologies another advantage of this system, as noted by Crutchfield (1969), is that this technology could be undertaken primarily by efforts in the private sector. Also, as noted by Sewell (1969), the external effects of this technology may not be too severe.

Service sector rights

An interesting comment is made by Maunder (1970), however, in proposing the idea that fog-created inconveniences might be looked upon as property rights of service-sector industries which have developed around airports. This is a concern which probably is true of all weather modification efforts. It has to do with industries developed over time, in answer to natural disasters which certain types of weather modification might attempt to alleviate. This becomes a perplexing and complex question as to whether these industries have property rights and whether the weather modification operations should be expected to, in some manner, compensate these industries for their reduction in property value.

LIGHTNING SUPPRESSION

Extent of lightning damages

Maunder (1970) quotes data indicating that lightning caused 27% of all forest fires in British Columbia in 1958. He notes that this figure understates the real effect of lightning because these fires caused 77% of the total fire damage to forests in that year and expenditures for fighting those fires should be included in the total costs of the lightning phenomenon. Included in the total effect of lightning is the lost timber associated with lightning damage to trees which do not burn.

Another indication of the extent of lightning-caused forest fires is given by Taylor (1971). He indicates that 60 and 40% of forest fires in the western United States and Canada, respectively, are lightning caused. This is considered to be about 6000 fires annually. Barrows (1966) cites a figure of 10,000 forest fires caused by lightning annually in the United States.

An additional aspect of the lightning fire is that the vast majority of such forest fires are small. Taylor (1971) indicates that 97% of the lightning caused fires are less than 10 acres in size. He also notes, however, that it is not known how many of these fires would have remained small without the intervention of man.

Along with the typically small nature of lightning-caused fires, it should be emphasized that not all forest fires are considered bad. Contrary to the popular opinion that the Forest Service would strive to extinguish every fire as rapidly as possible, Craig (1974) indicates that the Forest Service presently does not consider fire as a total menace. Rather, certain fires are allowed to burn on a prescription basis. This burning is allowed because of the relatively recent recognition of the beneficial ecologic aspects of fire.

But all lightning-caused fires are certainly not beneficial and are not allowed to continue to burn. The events of the summer of 1977 in West Coast forests are evidence of this. A *Newsweek* (1977) article reports 650 fires burning in one week's time. Many of these fires had been touched off by a lightning storm in California. One Alaskan fire burning during that week affected an area of 1500 square miles, an area larger than the state of Rhode Island.

Benefits of lightning suppression

Barrows (1966), although not providing detailed quantitative estimates of potential gains, does provide an excellent descriptive discussion of apparent benefits of lightning suppression. He notes that lightning fires cause more than damage to trees and timber. Additionally, long term damages occur to watersheds, wildlife, livestock forage, scenic beauty, and outdoor recreation. In some cases, losses are also inflicted on homes and lives are lost.

A most critical feature of lightning fires is the tendency for a very large number of such fires to occur in a short period of time. This aspect is evidenced by the recent California experience. Barrows cites three factors by which suppression of lightning would be beneficial:

1) The number of fires occurring in a short period of time could be reduced
2) The incidence of fires in critical places could be reduced
3) The number of lightning discharges could be reduced in those critical weather periods, such as in 1977, when the potential for catastrophic fires is greater

Sewell (1969) cites an additional attractive aspect of lightning suppression in that potential side effects appear to be minimal. Except for those people employed to fight fires, there seem to be few economic sectors benefited by forest fires.

Barrows (1966) does provide an estimate of the cost associated with lightning suppression. He projects that the cost of lightning control would be about 1/4 to 1/3 the expenditures for fighting fires. At the time that article was written, these fire fighting costs were about $150 million annually. However, this is given as a crude estimate and Barrows notes that there appears to be a lack of scientific understanding of lightning causes.

SUMMARY

This report considers the complex subject area which relates to the economic impacts of planned weather modification. Two rather separate efforts are included. The first focus of this report details those several factors whose inclusion is crucial to credible economic analysis of weather modification. Hopefully, specification of these factors will provide an initial framework for future economic analyses. The second is a review and evaluation of many currently existing studies relating to the economic impacts of weather modification. Five types of weather modification are considered: precipitation augmentation, hail suppression, hurricane suppression, fog dispersal, and lightning suppression.

The five modification activities were those thought to be most technically promising and/or to have considerable economic impacts. Brief sketches of the findings for each activity are included here.

Precipitation Augmentation

1) Several aspects of summertime precipitation are important in assessing economic benefits to crop production. In general, crop yields are increased by above-

normal rainfall only if the added rain arrives at the proper time. Additional rainfall at inopportune times can decrease yields. A further complication is that the time of beneficial effects typically does not occur simultaneously for all crops grown in a region. Variability, both with respect to natural rainfall and technological performance, is a crucial factor affecting the economic attractiveness of augmented precipitation.

2) Precipitation augmentation is not expected to eliminate droughts. However, the value of even relatively small increments of moisture for agricultural production and water supplies may be substantial during such periods.

3) Nationally, a 10% increase in precipitation in major crop producing regions has been estimated to increase farm receipts by $217 million (at 1977 prices). The crops considered were corn, soybeans, wheat, and rangeland forage. No price decreases because of this additional output were considered, however.

4) Regional analyses of agricultural impacts can be particularly valuable. Considering the southeastern corner of South Dakota as a target area for augmented rainfall, a range of increased farm income was estimated to be from 3 to 34%. Another study, which detailed the state of Kansas as a target area, found considerably different impacts among the several regions of that state. The western region would receive the greatest beneficial impact with net income increases to farmers of from 19 to 24%. In the central region, however, income impacts ranging from a 10% reduction to a 4% increase were estimated. In both these studies, the range in income estimates resulted from the use of alternative assumptions regarding technological performance and price reductions because of increased production.

5) The effect of augmented rainfall on rangeland, and therefore on beef production, is unclear. Gross estimates at the national level indicated a potentially substantial positive impact. The more detailed and comprehensive Kansas effort, however, indicated only minor impacts. This uncertainty is a matter of considerable economic importance.

6) If rain augmentation was effective in the Great Plains region but not adopted in other regions, slight decreases in consumer food costs would occur (Changnon et al., 1977).

7) Little quantitative work on the impacts of rainfall on tourism has been attempted. The crucial question for this sector is whether a rainfall event leads to a cancellation or only a postponement of a planned outdoor activity.

8) Additional rainfall can be expected to impact negatively on the construction industry in four ways:

a) The threshold level to halt operations would be reached more frequently
b) More time would be required to dry out construction sites
c) More damage would occur to perishable materials
d) Overhead charges for machinery and equipment would be higher as more idle time occurred

9) The sum of losses to construction due to intermittent weather events was estimated at $1.5 billion with mid-1960 prices. Evaluation of the effects of additional precipitation must consider the amount of rainfall change, when that change occurred, temperature, work rules, labor agreements, and forecast reliability. The incidence of losses from increased construction costs due to precipitation modification would be spread among employers, consumers, workers, and taxpayers.

10) Additional rainfall was found to contribute to increases in the number of automobile accidents.

11) Summertime precipitation modification would negatively impact on water transportation by increasing non-productive labor charges and the amount of damage occurring to perishable cargoes. However, additional water in streams and lakes might reduce shipping costs by allowing heavier cargoes to be carried.

12) The hydrologic consequences of precipitation enhancement are extremely important. Beneficial aspects would include increased streamflow for use by municipal water systems, power generation, and irrigation. Harmful aspects include increased flooding and additional sediment damage. A major question relative to water resource benefits is whether additional rainfall comes because of rainfall of longer duration with the same intensity or is the result of greater intensity for the same duration.

13) The type of watershed and amount of naturally occurring rainfall can greatly influence the benefits from increased streamflow for power generation. Therefore, different regions can have quite different benefits from the same quantity of increased rainfall. Cost-return ratios of 1/1.2 up to 1/14 for differing basins were reported.

14) An extensive study of hypothetical precipitation modification over the Great Lakes showed significant economic benefits to shipping and power generation. However, damage to lakeshore properties also occurs. Net annual benefits of $1 to $3 million were estimated for operations in the fall months only. Although the net benefits of such a program are positive, property owners would need to be compensated if their welfare is to be maintained.

15) Snowpack enhancement is a relatively inexpensive way to augment water supplies in mountain regions and areas which use these water sources. For average years, costs of less than $5 per acre-foot were estimated, including some indirect costs for people negatively impacted by additional snowfall. In one assessment, the operational costs of the snowpack program were less than 60% of the total costs.

16) Evaluation of the benefits of additional water from snowpack enhancement is an extremely complex problem. Irrigation and hydroelectric power would seem to be the prime beneficiaries of additional water. Any other demanders of water could bid water away from irrigation if they needed it. (In some instances, institutional arrangements would need to be altered to allow such transfers.) Therefore, estimating the future value of irrigation water and the secondary benefits of agricultural production is especially important. But these values are extremely sensitive to assumptions about the future demand for food and fiber. If future demands allow excess capacity in the nation's agriculture, the value of augmented irrigation water may be low. But, if future food demands lead to full employment of agricultural resources, the value of snowpack enhanced water may be quite substantial.

Hail Suppression

1) Property damage due to hail results in considerable losses throughout the nation. However, the dispersion of these losses over wide geographic areas and their relatively small value compared to crop damages indicate that initiation of hail suppression projects to alleviate property loss is unlikely.

2) Great regional differences exist in the potential economic incentives from hail suppression for the individual farmer. Major economic benefits, both in terms of increased average income and reduced variability of income, appear likely for crop producers in the Great Plains.

3) If the future capability for hail suppression is quite successful, adoption of this technology may be relatively widespread throughout the Great Plains. However, a low-level suppression capability would limit adoption and negligible economic impacts would occur.

4) Adoption based on a capability to suppress most hail could lead to consumer food costs slightly lower than if such a capability were not available. Part of these reduced food costs would come at the expense of landowners in regions not adopting the technology.

5) A benefit/cost ratio for research to develop a sizeable hail suppression capability was projected to be about 15/1 over a 40-year period. The annual national benefit would be $493 million.

6) Alteration of rainfall associated with efforts to reduce hail is an extremely crucial economic variable. In most areas, crop production was shown to be more sensitive to minor rain changes than to sizeable reductions in hail.

Major Storm Suppression

1) Hurricanes annually cause massive damage to the nation. Annual estimates averaging more than $500 million are generally agreed upon. Instances of particular storms which caused damages in excess of $1 billion have also been noted.

2) In terms of physical characteristics of the storm, the parameter which would be desirable to alter is wind speed. It would appear that alterations of wind speed would not greatly diminish the beneficial characteristics (usually rain) of hurricanes. However, diminishing the level of maximum sustained surface winds would seem to very strongly reduce the detrimental characteristics of the hurricane event.

3) There appears to be more than the normal uncertainty regarding hurricane modification. In this example, the additional uncertainty of the future movement of the storm is extremely important. But the decision to seed has to be implemented considerably before the final path and magnitude of the hurricane are known. Therefore, it would seem that errors could be made in deciding when to seed and which hurricanes to seed.

4) Another consideration is the public response to the knowledge that effective hurricane suppression would be utilized. If people did not continue to take present measures to offset hurricane losses, in terms of increased expenditures for buildings and sea walls, it is possible that modified storms of lesser intensity could cause equivalent amounts of damage as did more intensive unmodified storms. Also, if people and economic activity moved into more hurricane prone areas, losses in these areas would increase. These additional losses might offset the expected gains from hurricane suppression.

5) The potential for altering the path of a storm and damaging another area would seem to be a major factor in the utilization of this technology.

Fog Dispersal

1) Relatively few studies have attempted a comprehensive economic analysis of the fog suppression technology. The studies completed have focused on aviation effects with the possibility of fog suppression for ground transportation thought to be unlikely.

2) Supercooled-fog is the category of fog most easily suppressed. However, this fog type is the least common in the nation. The potential for warm-fog suppression exists but is terribly expensive.

3) If fog cancels airport operations, the direct costs to airlines can be quite substantial. Even not counting personal losses to affected travelers, potential benefit/cost ratios seem attractive.

4) But losses to airlines and travelers may be gains to service sectors and other transportation modes. Therefore, the national losses because of fog are somewhat ambiguous. Except for these market effects, other external effects of fog suppression do not appear to be substantial.

Lightning Suppression

1) Extremely few economic analyses have been done. Information and data on the relationship between suppression of lightning and reduction of losses from undesirable fires are needed.

2) Tremendous costs are associated with lightning fires in critical time periods. These costs occur in terms of lost timber production, disruptions to wildlife and scenic areas, watershed damage, and the cost of fire control as well as losses to human life and property.

3) The potential for harmful side effects of effective lightning suppression seem to be small unless rainfall is decreased.

CONCLUSION

Because weather events can have severe adverse effects on economic activity, the gross benefits of successful weather modification activities are apparently very high. And, in general, the operational costs of modification activities are small relative to those gross benefits. But the indirect costs of modification activities may be very great. The most important of these indirect costs is that, in general, those individuals suffering the adverse effects are not the same individuals who are enjoying the gross benefits. Therefore, even if the gross benefits of an individual project are greater than the sum of the direct and indirect costs, the existence of such positive net benefits does not insure that some individuals would not suffer substantial decreases in welfare.

It would seem that comprehensive economic analyses of various types of promising weather modification activities could provide useful information to the public and its decision-makers. To be credible, such an economic analysis needs to be based on a sound understanding of the physical factors which will be altered and the manner in which they will be affected. In general, this need implies that the advice and active cooperation of physical scientists are required.

Probably the most important aspect in determining the credibility of any economic analysis, however, is the viewpoint of that analysis. In conducting such an analysis, it should be clear that the goal of the analysis is to determine the effects of the modification activity on the entire economy of a region, not just impacts on those sectors which derive benefits from the planned activity.

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