ROYAL COMMISSION ON FARM MACHINERY

FARM MACHINERY CAPACITY

Graham F. Donaldson

Study No 10

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CANADA

ROYAL COMMISSION ON FARM MACHINERY

FARM MACHINERY CAPACITY

AN ECONOMIC ASSESSMENT OF FARM MACHINERY CAPACITY IN FIELD OPERATIONS

by

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While this study was prepared by a staff member of the Royal Commission on Farm Machinery and is being published under its auspices, the views expressed therein are those of the author and not necessarily those of the Commissioner.

Dr. Clarence L. Barber – Commissioner
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FOREWORD

This study analyzes the operating capacity of alternative farm machinery systems in field operations on the Canadian Prairies. The assessment is made in economic terms, but is based on the technical variables of machine performance, biological tolerances, and weather effects that exist in actual field conditions. The general aim is to assess the machinery system, and hence the level of investment, that is best suited to the range of crop acreages found on different farms in specified locations.

The analytical procedure employed, known as *systems analysis*, considers the interacting mechanical, biological and weather effects as component parts of the over-all field operating system. The specific technique applied is that of computer *simulation*, which is used to reproduce in abstract models the effects resulting from the interaction of the system variables. These variables are considered in the form of independent but known probabilities, not as single values. The models employ existing data, available from various sources, that were not originally obtained for this particular application.

The primary purpose of the study is not to provide information for farmer decision-making, though, providing the data were acceptable, the output could be used for that purpose. Rather it is intended to demonstrate the feasibility and usefulness of making this type of assessment, and to indicate the value of obtaining the data necessary to facilitate its accuracy.

The more explicit objective is to use this analysis to explore some of the farm-level implications of continuing farm mechanization. To this end an attempt is made to examine: (i) the nature of the costs associated with the use of a range of different-sized machinery systems; (ii) the cost effects of introducing other machines (such as new larger-model combines and grain dryers in cereal harvesting) into seasonal operations; (iii) the comparable risk effects of using alternative systems to handle given acreages; (iv) the cost and risk effects of using specified systems in different locations; (v) the need for larger or additional equipment for existing operations; and (vi) the adequacy of machinery developed for international markets when used in Canadian conditions.

Because of the large number of available machines that might be combined into a system on farms, the study was restricted to the major models produced by the larger manufacturers. It considers the main machines used in cereal harvest (combine harvesters and grain dryers), and in tillage and seeding operations (tractors and selected attachments).

Chapter 1 outlines the broader context of the subject, identifies the major constraints, reviews previous studies, and defines the approach used.

Chapters 2 and 3 contain details of the cereal harvest and cereal-seeding models respectively. In each case the relevant variables are identified, the model specified and its operation discussed.

Chapter 4 presents an interpretation of the results as represented by the output from the simulation models.

As in all complex projects, many people contributed to the work behind the final documentation. In this case special mention is due to Mr. P. L. Rutledge, Research Assistant with the Commission, who assembled and collected much of the data used in the models; and to Mr. W. W. Bradbury, of the Central Data Processing Service Bureau, who coded and supervised computation of the models. Without the constructive help of both, the task could not have been completed.

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G. F. Donaldson

November 1969

1. FARM MACHINERY INVESTMENT

In recent years, Canadian agriculture (along with that of its western neighbours) has been characterized by an increasing capital stock due to an expanding investment in farm machinery. This is a reflection of more, larger, more complex, and to some extent better quality, machines being used on farms. All of these, together with the trend in production costs in the farm machinery industry, combine to ensure that the capital invested in farm machinery per farm is continually increasing.

The extent of this growth can be seen from the sixfold increase in the machinery assets held on farms over the 25 years, 1941-66. In the same period the number of tractors on farms has grown from some 158,000 units to 598,000, and of combines from 19,000 to more than 170,000 units, as shown in Table 1.1.

Table 1.1

INCREASED MECHANIZATION OF CANADIAN FARMING

Year	Total No. Tractors on Farms	Total No. Combines on Farms	Machinery Assets on All Farms	Machinery Assets per Improved Acre	Tractor Sales per Year	Tractor Horse-power Sales per Year
	(Thousands)		($ Million)*	$*	(Thousands)	
1941	157.8	19.0	596	6.50		
1946	225.2		905			
1951	399.6	90.5	1,932		18.1	578
1956	499.8	136.9	2,263	19.96	49.9	1,505
1961	549.8	155.6	2,566	21.86	23.6	945
1966	598.5	170.2	3,393	24.81	23.5	1,112
				29.03	30.9	1,959

* Values are in constant dollars (1935-39 base).

Source: Dominion Bureau of Statistics, Historical Statistics and Census of Canada, 1961, 1966.

That this expansion involves both more and larger machines is shown by the fact that sales of tractor horsepower have increased at a rate that far exceeds sales of tractors. The increase in total investment in farm machinery is reflected in the parallel growth in machinery assets per improved acre.

This trend has several implications. The increased machinery stock substitutes for other resources used in farming, particularly labour. Thus expanding mechanization is associated with adjustments in the structure of Canadian agriculture. Concurrently, changes in farm mechanization necessitate adjustments by manufacturers and dealers -- particularly in the type and size of machines produced, and in the services that must accompany their use on farms. But some of the most striking changes related to mechanization are those affecting farm management, both in the use of machines and in organizing the farm program in which they are used. Of the many decisions confronting the farmer-manager in this area, those concerning investment are perhaps most significant of all.

Investment Decisions

Associated with the larger capital stock of farm machinery there have been, not surprisingly, some changes in the purchasing of farm machines. As the annual purchases of farm machinery have enlarged both in number and value, so the yearly investment outlay has increased. The average outlay on new machinery per farm in Canada has exceeded $1,500 each year in recent years.

There are two implications of the increased level of investment. The first is the problem of capital formation. Whether the new capital is generated from internal savings or by external borrowing, the decision-maker is confronted not only with the organizational problems involved but also with the problem of allocating the limited capital supply between alternative investment opportunities. On farms with many enterprises this can be a complex problem. Because of capital scarcity the farmer is usually concerned with using as little as possible on any one investment.

The second effect of increased investment levels is that the amount of capital, and of consequent costs, riding on any decision is often also increased. Thus the cost of making a decision error is obviously expanded. For this reason a decision-maker is inclined to make a more careful assessment of the elements of each alternative available. Concurrently, because the possible cost is greater, the manager can afford to spend more time, effort and cash in exploring the decision alternatives available -- thus there is more attention paid to investment appraisal.

In addition to *larger* individual outlays, the increase in machinery investment often also involves a larger *number* of individual outlays in a given period of time. Thus decision-making involves an increasing number of decisions, as well as larger decisions. This effect also arises in two ways. First, there are more items of machinery used on farms -- thus there are more purchases. Second, there is a tendency to keep machinery for a shorter time. This may be because it is used more intensively, wears out more quickly because it is less sturdy or more complex, or because as wages increase it is cheaper to replace at an earlier date rather than repair. Whatever the reasons, this trend similarly ensures an increasing number of machine purchase decisions.

Concurrent with the increased size and number of decisions concerning farm machinery, there has also been an increase in the complexity of these decisions. In general, machines themselves have become more complex so that their operating capacity and efficiency, and their adequacy and durability, are more difficult to predict. Since their effectiveness is often closely related to changes in other aspects of the production process, a further element complicates the choice. Where machines are dual-purpose, or used in a sequence of operations, even more considerations are involved.

This situation is further complicated by the emergence of "machinery systems". The integrated nature of modern farm mechanization means that machines are seldom bought separately, or without consideration of existing equipment to which they must be matched. Thus a machine purchase decision involves much more than assessing the best machine or lowest investment to adequately do the job -- it necessitates consideration of the whole pattern of production, and the sequence of operations it involves. Often the problem may be so complex as to exceed the capacity of casual on-the-spot assessment so that more formal means of analysis become appropriate.

Apart from these problems, often there is also need to choose between different makes of equipment. In many cases different manufacturers produce a competing range of machinery so that there is a choice of make. Often this involves peripheral, though important, aspects such as nearness of the machinery dealership, or adequacy of service or spare parts supply. In other cases there may be a difference in price and in quality of the alternatives. All of these considerations add to the complexity and difficulty of investment decisions concerning farm machinery.

In summary, as annual farm purchases of machinery have expanded both in number and value, and as the investment outlay has increased, the complexity of the decisions involved has grown. The larger sized outlay means that the cost of a decision error is increased. Because larger machines are more complex, the choice between alternatives becomes more difficult. The fact that even small pieces of equipment may have complex interrelationships with other items in a machinery system further increases the problem. As the complexity of an investment decision is increased, the usefulness of some formal analysis of the decision alternatives is enhanced.

It is in this context that this study is set. The primary purpose is to demonstrate the potential benefits that may accrue from a formal analysis of decision alternatives. The aim is, first, to examine the interacting effects that may influence a machinery purchase decision in order to achieve some insight into the problem confronting the farmer in making machinery investments and, second, to assess the potential of formal analysis in aiding these decisions.

In an economic sense the farm machinery investment decision can be divided into two component questions. The first is that of *how much* to invest -- the level of investment to be made. In a farm machinery context, this is the *capacity problem*, relating to the size of the machine or system. The second is that of *when* to invest -- the best time to invest. In a farm machinery context, again, this is the *replacement problem*, concerning the time to replace a machine or system component.

In practice, more often than not, the two problems are closely related. Whenever a decision is made to replace a machine, the subsequent decision is whether to replace it with an identical unit, or whether a different size or type of machine would be preferable. Less frequently, when a farm business is newly established or when a reorganization of the production program is undertaken, the capacity problem may arise quite separately from that concerning replacement. However, because the time of replacement may depend on how fully the capacity of a machine is exploited, the expected time of replacement is of concern in capacity decisions. Similarly, because the relative adequacy of a machine may be a major reason for its replacement, the machine's capacity is often important in replacement decisions. Given recognition of these considerations, however, the two types of machinery investment decisions can be separated -- at least for the purpose of analysis.

Capacity Determinants

As used here, the term "capacity" is a time-related measure, and not a static physical dimension such as the capacity of a storage tank. Nor is it a simple measure, since when conditioned by an adjective we may refer to maximum capacity, expected capacity, excess capacity and so forth. In a farm machinery context, capacity is an operating characteristic determined by the rate of work achieved in operation, and by the amount of time over which the machine is operated. For an agricultural machine employed on a farm, these two parameters are determined by a number of constraints and variables, each of which is characteristic of the particular time and working situation being considered.

The rate of work is affected by the operating characteristics of the machine, the yield and conditions of the crop or product being processed, the weather or environmental conditions in which the operation is undertaken, and by various operating decisions that may be taken by the operator. Similarly, the time available for the operation is dependent upon the adequacy and extent of the machinery system under the operating conditions, the biological tolerances related to the particular product and operation involved, the prevailing weather or ambient conditions, and again, certain operating decisions made by the farmer. Therefore, in order to assess the machine capacity "required" (that is, the level of investment to be made), it is necessary to take account of the major variables and their determinants (13).

Rate of Work -- Of the several determinants of the rate of work of a machine, the first are the *physical characteristics* of the machine and its operating situation. These include the production characteristics of the machine, particularly its specifications and performance features. Clearly a higher horsepower or wider machine will be expected, *ceteris paribus*, to have a higher rate of work than a smaller one. In field operations, the rate of work will also vary according to the gear that is selected, and with the speed that is commensurate with effective operation of the implement being used. The rate of work that is achieved over time will also be affected by the service requirements of the machine and, when maintenance or repair parts are required, by the quality of service facilities available, since these determine the time lost through servicing and breakdowns. The frequency of breakdowns is, on the other hand, influenced by the age of the machine, and the way it is used.

As the production characteristics of the machine interact with the operating environment, a set of operating characteristics are established that also affect the rate of work. The design of the machine determines its adequacy in the particular field situation, and this directly affects the rate of work achieved. The design quality and age of the machine both influence its reliability and hence the operating rate that can be obtained with minimum time lost. The quality of the machine also determines the comfort and safety of the machine in operation, and thus the willingness and ability of the operator to exploit the machine's physical capacity.

Apart from these characteristics of the machine itself, other physical features that influence rate of work include (i) the size and shape of fields, (ii) the type of terrain being worked, and (iii) the relative capacity of ancillary equipment that comprises the machinery system. Though not part of the characteristics of the machine, these features vary in their effect from one machine to another. Thus they constitute part of the physical determinants of the rate of work achieved.

In practice, the rate of work is, of course, also influenced by the *biological characteristics* of the material being handled. When the machine is one used in field operations this means the features of the crop involved. In this category the primary feature is the intensity of the cropping, as measured in the level of inputs (seed and fertilizer) and the yield (in the case of a harvest operation). Cropping intensity varies from location to location, often due to climatic or economic factors, and it involves differences in the type and variety of the crop being grown, and the number and quality of cultivations. In any one year, it may also depend on the prevailing seasonal conditions.

The type and variety of crop grown may also have direct effects on the rate of work attained. For example, some fodder crops are easier to bale and to chop than others, so that a higher rate of work is possible when they are being handled. Similarly, in the harvesting of cereals, some varieties may be more easily threshed than others. The quality of the crop, in terms of its husbandry features, will also affect working rates. A crop that is free of weeds and not tangled is easier, and therefore faster, to handle than is one choked by weeds, or badly tangled or lodged by weather effects. Often these characteristics are determined by the timing of the operation and the maturity of the crop.

The rate of work may be influenced, too, by various quality considerations. For example, a crop that is grown for seed or that has particular market quality requirements, or one that is particularly perishable, may impose restraints on the rate of work that can safely be achieved.

Similarly, the *environmental characteristics*, such as weather conditions, may have quite direct effects on the rate of work. The weather conditions preceding a field operation particularly affect soil conditions, and these determine the effectiveness of power transmission through the wheels of the locomotive unit. This directly affects the rate of work.

In the same way, the prevailing weather conditions during an operation influence its effectiveness and consequently the speed with which it is completed. Some operations are more extensively influenced than others, but where the biological material being handled is affected by temperature, humidity, or any of the conditions determined by weather, the effect is real. This applies not only to field operations, which are obviously open to the vagaries of the climate, but also to barn activities where the ambient temperature or moisture conditions can affect the material involved in storage, handling, or processing. This is true for, say, the storage, grading and packing of potatoes, or for the augering and drying of cereal grain.

Finally, the rate of work realized in machinery utilization is also governed by various *operating decisions* made by the farmer or his machine operator. In these decisions he may be influenced by his knowledge of the work situation as well as by his skill in the use of the machine. But, apart from his level of skill, every operator is to some extent affected by his attitude to risk. In all machine operations the rate of work can be increased at a cost in terms of the thoroughness and quality of the operation, and of comfort and safety for the operator. In certain situations, such as combine use in cereal harvesting, the cost may be reflected in a single variable -- in this case, the loss of grain that occurs in different parts of the mechanism.

In virtually all field machine operating situations there is a "trade-off" between the savings associated with faster completion of the job and the costs connected with a poorer quality operation. In assessing these "trade-offs" a farmer may be influenced by (i) his assessment of the risk associated with taking extra time over the job (particularly in terms of weather effects), (ii) marketing advantages, such as prevailing product prices or competition for storage space, and (iii) various alternative activities that may have to be completed, all of which may have their own time-cost effects.

The rate of work achieved in machine operation is therefore not a simple deterministic factor, but a complex one dependent on the interaction of numerous variables. These may include any number of the physical, biological, environmental and human features, each of which may vary from place to place, year to year, and in many cases field to field and day to day.

Period of Operation -- Just as the rate of work is determined by the interaction of many variables, so the time taken or allowed to be taken is similarly determined. In this case the *physical characteristics* are perhaps less significant among the possible influences, but they are still relevant. For example, the adequacy of the machine, in terms of its design and quality, affects the way it will operate under particular conditions, and this may influence the hours during which the machine can be operated effectively. The reliability of a machine may also affect the extent to which the machine's capacity can be stretched.

The time available for any particular operation may depend, too, on the extent of the machinery system. For instance, a cereal-harvesting system that includes a grain dryer may be able to work for many more hours in a given number of days than a system without drying facilities. The same situation may eventuate for many operations, in those particular seasons when additional or alternative equipment would be useful.

The most significant determinants of the time allowed for operations are the *biological characteristics* of the product involved. For field operations, this means, mainly, the "husbandry dating tolerances" of crops. The nature of many crops is such that they require a particular length of growing season, or number of days of particular temperature, light or moisture conditions for their full growth and development. Thus there is frequently a short period during which they must be sown in order to be sure of obtaining these conditions. Often this period can be very narrow, though it can usually be extended both sides of the optimum range by accepting a varying proportion of yield loss. Plant-breeding programs can often alter or relax these constraints, but the general situation holds true for most crops.

Once the crop has successfully developed and reached maturity, or "harvest ripeness", another similar set of husbandry dating tolerances begins to become significant. The particular condition of "harvest ripeness" may not be an enduring one. For instance, hay is often made from crops at a preferred level of maturity when the nutrient content of the final product is known or expected to be at some desirable level. Once past this stage of maturity, the value of the finished product is progressively reduced. Similarly, with cereal crops a stage of ripeness is reached when the crop can effectively be harvested. Once this stage is reached, the quality and quantity of grain may begin to decline due to weather spoilage, pest or bird damage, or shelling from the ear. Thus there is, again, a non-rigid but limited time available for the economically successful completion of the operation.

Just as the seeding tolerances may be offset by the breeding of more flexible and particularly shorter season varieties, so action can be taken to ameliorate the restrictions on the harvesting operations. In practice, much of the skill of the farmer lies in his ability to select crops and varieties, and time of seeding, and even locations on his farm, in order to achieve a spread of maturing dates that is as wide as possible. But, however skillful he is at doing this, there are still limitations on the extent to which spreading can be achieved. These constraints, more than any others, limit the acreage that a given machinery complement can handle in a particular set of circumstances.

Closely related, and interacting with the biological tolerances in determining the time available for operations, are the *environmental characteristics* of the operating situation -- that is, in a field operation, the weather conditions. The weather prevailing during the period prior to the operation effectively determines the date on which the operation can begin. For example, in cold regions, spring tillage operations can begin only after the soil moisture has sufficiently thawed to permit them. Subsequently, seeding can start only when the soil has reached tolerable levels of temperature and moisture content. Eventually, the starting date of harvest is determined by the seeding date (which is previously determined by weather) and by the weather conditions that occur during the growing season.

Once an acceptable starting date has been reached for any operation, the time available for its completion is limited by the weather conditions that prevail during the operating period. Since weather effects determine soil conditions, the number of operating days may be dependent not only on the number of bad weather days, but also on the intensity of the weather effects (particularly rainfall) and their duration. Several days of light rainfall may defer all field operations for a longer period than one day of heavy rain. Nor is it only soil conditions that are affected in this way. The crop itself, particularly during harvest, may be the means through which the weather constraints are imposed on the operation. Excess grain moisture content, or even surface moisture on the leaves or straw, may be sufficient to stop the harvest process, even though soil conditions are not restricting.

The extent to which weather effects impinge on mechanical farming operations varies with the particular operation concerned and with the location of the work site. Certain operations may be very susceptible to changes in the weather. For example, spraying with chemicals is particularly dependent on favourable conditions. Others, such as fall cultivations, may be little affected, except by prolonged or torrential downpours. For those operations that are weather-susceptible, locational differences may be important. Even minimal removes, from one part of a farm to another, may involve changes in soil type, in terrain, in wind protection, and, because of different slope or aspect, in different light intensity. Each of these may affect both the time of starting field operations, and to a lesser extent the operations themselves.

There are a set of *market conditions* which affect available operating time too. Though this is not a problem with a storable crop such as wheat, it is very real for perishable crops such as lettuce. Such crops often have high price variability and a limited time over which profitable prices prevail, so that time of market constraints are significant.

Notwithstanding the effects of these many exogenous variables, the time available for the completion of a job may also be adjusted by the *operating decisions* of the farmer-manager. The first determinant variable is the hours worked in a day and the days in a week. This involves considerations of energy, fatigue and safety in the case of an owner-operator, and these plus the payment of overtime, or the employment of extra staff, where hired labour is used.

Apart from this, the total time available may be restricted not by the physical or biological constraints directly related to the crop being handled, but by those related to other products or enterprises that have competing requirements. Sometimes this may include the preparatory operations of next year's crop. The time allowed may also be circumscribed by the farmer's assessment of the likelihood of successful completion after a certain date -- based on the likely subsequent biological and weather effects. Market conditions and price patterns may also contribute to the farmer's decision to attempt to complete an operation in a given time, or by a certain date.

Thus, when determining the time allowed, there are "trade-offs" involved, just as there are when considering the rate of work of a machine. The actual time available is certainly not rigidly defined by outside effects. On the contrary, the time taken can very often be extended -- but at a cost. It may involve a loss in yield through shelling or bird damage, or a loss of produce quality. Alternatively it may result in lower market prices, or an increased possibility of not completing the operation; or a direct cost, such as grain-drying, to rectify the effects of untimely operations. Again this choice is part of the decision-making prerogative of the farmer.

Production Risk -- The many factors identified above may combine and interact in many different ways. In some instances the one effect may influence both the machine rate of work and the time available for the operation. In particular, the weather effects, such as a fall of rain, can affect both. However, the many variables that are involved are largely independent and can interact with one another in many different ways. Each combination tends to create a different set of effects on the operation.

In assessing the possible impact of the influencing factors involved, the farmer is confronted with the reality that each is a variable and so may have a range of values in any one year, and even in any one operating situation. Because of his lack of knowledge of the possible outcomes among these values, the farmer is confronted with a degree of uncertainty in his decisions concerning his farming operations. Since these variables determine the level of mechanization that is adequate, this means that machinery purchase decisions involve uncertainty.

The variables in any decision situation can be classified according to the way they vary. Those that have a known outcome or an outcome that can be forecast with certainty are called *deterministic* variables. Those that have a range of outcomes that can be predicted in terms of a frequency distribution are known as *probabilistic* variables. The remainder -- those that have no predictable pattern -- are recognized as *uncertain*. Most of the variables affecting a machinery operating situation can be specified as probability distributions, providing sufficient measurements or observations are available.

In his machinery purchase decisions the farmer has to take account of the probabilistic, or stochastic, nature of the variables concerned. Consequently, it is rarely appropriate to select the minimum machinery investment that might be required. More reasonably, the farmer will attempt to assess the amount of additional outlay necessary to obtain a system that will overcome some of the risk involved in his operation. In this way he extends his control over the operation, and "insures" against some of the risk involved.

The extent to which he can afford to do this depends on both the extent of the possible losses -- or the possible cost involved in not insuring -- and on the probability of the loss occurring. Because it is not possible to specify either of these exactly for any given year or series of years (even where a probability of outcomes is calculated), the decision has to be made on the farmer's subjective judgment of the possible outcomes. Because it is subjective -- in other words, based on his personal assessment or "feeling" about possible eventualities -- the preferred level of investment in a farm machinery system will vary, not only from situation to situation, but also from one individual to another.

Inevitably farmers have been confronted with this type of decision situation since time immemorial. However, there is some evidence to suggest that as the intensity and technical sophistication of farming has grown over the years, both the cost of unfavourable outcomes and the probability of their occurrence has tended to increase. For example, in cereal production, crop yields gradually increase due to improved varieties and both a greater number and more expensive inputs, including fertilizer and herbicides. As this happens, the value of a standing crop at harvest, in terms of either costs incurred or market value, is also increased. Consequently, the losses associated with an unsatisfactory or incomplete harvest will be greater than they would have been in a similar season a few years before.

In the same way, as yields are increased, the proportion of the farm under crop extended, or the acreage of the farm added to, the size of the crop to be harvested will be enlarged. Although the number of days available for harvesting is variable, there will be a maximum number of days that can be relied upon. As the size of the crop increases, the chances of finishing harvest in the maximum favourable period are diminished. Even with a bigger investment in machinery the farmer may be pushed into using more than the maximum number of days available. Consequently, the probability of not completing harvest successfully is increased.

With larger investment levels, more technically complex production relationships, increased potential losses, and possibly increased probability of losses, the machinery capacity decision confronting the farmer takes on a new significance. Given the pattern of adjustment occurring in Canadian agriculture, there must be growing pressures on the conventional pattern of farm management and a growing need for more formal analysis of management decisions. Since increased mechanization is a predominant feature of the adjustment process, it should not be surprising that the increased pressure is on machinery management decisions most of all.

Evaluation Procedures

Although farmers have been confronted with complex farm mechanization decisions for several decades, the extent of any formal analysis of these problems has been limited until fairly recently. In the last few years, however, there has been a marked increase in the amount of attention devoted to these questions, and accordingly a significant development in the quality of analysis made of them. This over-all trend applies particularly to the analysis of the farm machinery capacity decision.

Types of Studies -- From the outset there have been two types of studies made of mechanization problems, though the distinction between them has been emphasized only recently. The two types can be identified as *positive* and *normative* studies respectively. Positive studies essentially involve measurement and recording activities, and the making of inferences from the data obtained. Such studies include the assessment of actual parameters, either involving farm records and farm data collection or experimentation such as in machinery testing programs. These are direct assessments made in specific real situations, and this type of study is useful in providing a basic understanding of the process of farm mechanization.

Normative studies, on the other hand, involve the formulation of expectations for anticipated rather than actual events or situations. Inevitably, such analyses must employ observations and data obtained by positive studies, but they may be based on generalized situations and may include consideration of a combination of variables or events than cannot feasibly be studied in a positivistic way. Normative studies are indirect assessments based on expectations of probable events, and they are useful in predicting possible outcomes in future situations.

The key distinction between the two is that while positive analysis must refer to an actual and therefore a past situation, normative analysis is based on expectations and thus relates to future events. The results of normative studies are therefore directly useful in guiding future decisions, whereas those from positive studies can be used in this way only on the assumption that the future situation will be exactly the same as that existing in the past. Once this assumption is modified to take account of possible variations in the future, the analysis can be said to contain a normative element.

Earlier Studies -- The earliest studies of machinery use on farms were mainly positive in nature. Engineers made assessments of physical performance, including measurements of width of cut, forward speed, power output and similar machine parameters, for a wide range of locations. Concurrently, farm economists recorded the costs incurred in machine operations. Often the analyses were not exclusively devoted to farm machinery but to the operation of the whole farm or some enterprise on it. These studies provided information for direct application, and for use in other studies.

Based on generalizations from the measurements obtained in this way, two types of assessment of a more normative nature were made. The first were estimates of the physical capacity of individual machines. This was calculated on the basis of the effective width of the machine and its average forward speed, with an allowance for lost "efficiency" through lost time, overlapping, turning, and so forth -- called an efficiency correction factor. Thus the relationship could be expressed as:

$$C = \frac{R.W.e}{8.25}$$

where C = effective capacity in acres per hour

R = forward speed in miles per hour

W = effective working width in feet

e = efficiency correction factor based on field observations

8.25 = constant derived from 43,560 sq. ft. per acre and 5,280 ft. per mile.

The field capacity estimate so obtained could be related to the hours worked in a day and the number of days available for the operation. In this way an estimate of the physical operating capacity of a machine could be obtained, and for a given crop acreage, the size and number of machines required could be ascertained. This projection was based on single value estimates, and assessed in terms of static physical criteria.

The second type of normative study made projections of the economic capacity of different machines. This was based on cost estimates drawn from recorded data, and recognized that the unit cost of an operation was a function of overhead or fixed costs incurred, regardless of the level of use of the machine, and of operating or variable costs that vary proportionally with the level of use of the machine. The average total costs were calculated by adding the fixed costs (depreciation, interest, taxes, insurance and shelter costs) to the variable costs (maintenance, repairs, fuels, lubricants and labour), expressed in terms of cost per acre. Since the fixed costs are spread as more and more acres are handled, the cost per acre varies from one level of use to another. Thus in economic terms the capacity of a machine might be considered as the acreage at which the cost per unit is at a minimum, or the acreage range over which the machine has a lower unit cost than its alternatives.

These two approaches have provided the basis for analyzing the farm machine capacity decision, and for advising farmers on the selection of alternative machines. Progressively the procedures used in these estimations have been refined, and the number of variables considered in the analysis has been extended. However, the two methods rarely give the same, or even a similar answer. This is perhaps not surprising in that they do not analyze the same parameters, nor are they assessed upon the same criteria. Further, neither method gives an answer that is fully acceptable to farmers. It is frequently observed that farmers often maintain machine capacity in excess of the level either formula would suggest. Consequently, it is sometimes held, on this basis, that farmers are irrational buyers of machinery. It might be argued, on the other hand, that these analyses underestimate the capacity level that farmers, by experience, find they need.

Advanced Studies -- With the advent and subsequent availability of electronic computers, new techniques became available that could be applied in analyzing farm machinery investment. This coincided with an expansion of work in this area and the development of new directions in analysis (15, 41). Though many of these studies employed developments of the two methods outlined above, the distinction became blurred, as even studies based on technical parameters had results expressed in terms of revenue effects, and economic studies took explicit account of physical and biological variables.

The first developments were the breakdown of the variables in the formulae used into their component variables, and the inclusion of other determinants not previously considered. Some of the pioneering work in this direction was done by Hunt at the University of Illinois (19, 20, 21). This work expanded the range of measurements employed in the analysis of alternative machinery systems, and subsequently extended the mathematical treatment of the problem. In later studies this approach culminated in the explicit formulation of the problem in the context of systems analysis.

Similar work was undertaken by Link, Marley, and others, under the auspices of Bockhop at Iowa State University (16, 27, 32). In their studies the operations analysis tools of PERT, and queuing theory, were combined in analytical models of the type known as network analysis. These took account of the interaction of several variables, particularly in the sequence of field operations on farms, and they included assessment of weather effects as stochastic variables. The studies employed data recorded over several years on the research farm of the university, which limited the generality of their findings. They also suffered from the disadvantage that "acceptable" risk criteria were assumed and specified.

Concurrently, more detailed studies were made of the costs involved in field operations. Though this type of study was undertaken at many centres, that done by Armstrong and Faris at the University of California is perhaps the most comprehensive (1). This presented detailed cost curves for alternative machinery systems and specified least-cost systems for different crop combinations. An extension of this type of work is seen in a study by Ihnen, done under the direction of Heady at Iowa State University (22). This takes explicit account of the cost of timeliness effects, and demonstrates the rise in costs associated with extending a given machinery complement over increasing acres.

In another, and chronologically earlier, study in the same program at Iowa State, Krenz developed a multiple-stage model to select optimal crop combinations and to analyze the machinery costs (including timeliness cost effects) for different sized farms (18). This model employed parametric linear programming and budgetary cost curve construction, and assessed the results according to game theory criteria. Though pre-dating them, this study represents an advance over all the above-mentioned studies in that it assesses the variability inherent in farm machinery investment decisions, in terms of a range of criteria and not just one specific (and perhaps less realistic) criterion.

Some similar work has been done in Canada by MacHardy and his directees at the University of Alberta (29, 30). This work has involved the use of a composite systems analysis approach, employing different optimizing tools to handle various parts of the over-all decision problem. Linear programming was used to select optimum crop combinations, and to assess the opportunity cost effects of competing operations associated with other activities or enterprises. The Lagrangian multiplier extension of calculus was used in combining the alternative components into optimum machinery systems, and Monte Carlo techniques were applied to assess the impact of variable weather effects on field operations. In an extension of this approach, Rutledge has sought to relate weather effects to soil conditions and thus to the operating time of machines in tillage operations (36), and the results of this work have been used in this study.

Another approach to this problem has been outlined by Donaldson (10, 11). This employed Monte Carlo simulation techniques in assessing harvest machinery cost in England. This study differs from the others in that each of the major categories of component variables is regarded as stochastic. Thus machine performance, biological tolerances and weather effects are each introduced as probabilistic, with a known frequency distribution. Some account is also taken of variations in operating decisions made during the harvest, and the results are expressed in the form of a range of possible outcomes at successive acreage levels. The study described in this report represents an extension of this approach, to the extent that the categories of variables are broken down into their component parts so that each of several variables is introduced as probabilistic. This permits a more thorough assessment of the variability of outcomes for alternative systems over a range of acreages.

System Simulation

A systems approach, as employed in this study, can be defined briefly as the identification and study of interacting functional units and the mechanisms between them. These may include biological, mechanical, behavioural, information and other elements, all integrated in a particular environment and destined to yield a range of possible outcomes or effects. Many familiar entities or processes might be studied as systems -- including production sequences, distribution networks, administrative programs, whole farms and national economies. All such systems are characterized by the independence and interaction of their elements. Thus *systems analysis* usually refers to the study of the working relationships of such systems.

One means of studying these effects is by the use of models, particularly computerized versions, of the type known as *system simulation* models. A simulation, as the name implies, is fundamentally a means of working with selected aspects of reality. Thus a simulation model is an abstraction from a real situation upon which trials or experiments may be conducted. In a spectrum of scientific methods -- from mathematical description on the one hand to experimentation with the actual system on the other -- the term "simulation" may be applied to most of the methods in between.

The simulation models used here are of the kind that use symbolic schemes to represent the component variables of a system in which the behaviour of the relevant entities is either known or assumed to be known, and is consequently reduced to data form. Further, though some of the variables are handled deterministically as single values, the major components are regarded as being stochastic and are introduced into the model as discrete probability distributions.

The technique used in the "simulation of stochastic processes" is widely recognized by the synonym "Monte Carlo method". Basically, the procedure allows the evaluation of a probability distribution when only a sample from it is available. This is achieved by selecting values at random and then constraining them according to the dimensions of the sample distribution. In this case, this was achieved for the large number of observations required by using a computer routine which generated pseudo-random numbers.

In the simulation sequences discussed here, each model contains certain identifiable elements known respectively as variables and functional relationships. The variables are of three types: exogenous, status and endogenous. *Exogenous variables* are the independent, external input factors in the model. They act upon the system and are not influenced by the system. Some are controlled, such as the location of the field operation and the days worked, but most are uncontrolled as is the time lost during operation, the yield and time of ripening of the crop, and the numerous weather effects including the spring thaw, the number of rain-free days, the level of precipitation, and so forth.

Status variables are those that describe the state of the system or one of its components at some stage of a time period. Thus the location specified, the size of the machinery system being considered, the loss in yield due to seeding either side of the optimal date, and the shelling loss for each period subsequent to the crop reaching harvest ripeness, are all status variables.

The *endogenous variables* are the dependent or output variables of the system that are derived from the interaction of the exogenous and status variables. The endogenous variables in each of the following models are the rate of work attained, and the stage of the operation achieved in each period, in terms of the number and sequence of effective operating days.

The way in which these variables interact in the models is specified by the functional relationships of each system. These are of two types, known as identities and operating characteristics respectively. *Identities* are statements about components of the model. For instance, the average total cost of the field operation is identified according to a specified formula in each case.

The *operating characteristics*, on the other hand, are statements or hypotheses relating the exogenous and status variables to the endogenous variables of the system. For example, the forward speed of each combine is specified in relation to the crop yield obtained; the grain moisture content is determined by the level and incidence of precipitation; and the level of precipitation affects the "tractability" of a field, according to specified operating characteristics.

The accuracy of the results of the simulations depends on the reliability of the estimates for the parameters of each of these elements, as will be discussed later. In addition, the way in which they are specified determines the nature of the simulation model. As previously mentioned, the models presented in the next two chapters have both deterministic and stochastic elements. That is to say, some variables and relationships have single values and others, probabilities or frequency distributions.

But models may also be categorized as static or dynamic, according to the way in which sequential activities and time lags are handled. Since risk effects imply a range of values for a variable occuring over time, all stochastic variables introduce a dynamic aspect. In addition, however, certain variables are included in the models used here as dynamic sequential variables for which the values are dependent on previous parameters for other variables. For instance, the number of harvest operating days in a week, in Model 1, is dependent on the number of rainy days and the level of precipitation in the previous week. Accordingly, these system simulation models can be said to include both static and dynamic elements. The ways in which the numerous variables and functional relationships are combined to simulate mechanized field operations on the Prairies are set out in the following chapters.

2. CEREAL-HARVEST SIMULATION

The objective of this study is to assess the operating capabilities and costs of alternative machinery systems used in harvesting and seeding cereals on the Prairies. This assessment is made using simulation models based on the interacting variables which characterize the operations. Since the variables are probabilities rather than single values, the models are based on the selection of single values from their ranges and combining them to simulate the possible outcomes in any one season. By repeating this process a large number of times for each of the alternative machine systems, locations and acreages considered, a range of outcomes is obtained from the model. From the means and distributions of these outcomes a series of capacity cost relationships is built up and interpreted in economic terms.

In constructing a simulation model of the cereal harvest on the Prairies it was necessary to quantify the relevant variables, and to specify the relationships between them. For this purpose, data were assembled from a variety of sources and analyzed to provide input parameters and operating characteristics. In order to facilitate this, however, it was first necessary to identify the major components of concern in the harvest process and to establish those status variables that would characterize the analysis. These include the machinery systems to be used, the location of their use, and the areas over which they should operate.

Harvest Model Components

Location -- For comparative purposes, and in order to examine a range of field working conditions, four locations were chosen --

Swift Current, Outlook, Saskatoon and Melfort -- in the Province of Saskatchewan. These four sites are roughly equidistant in a 500-mile arc, from southwest to northeast, through the centre of the great cereal-growing area of the Canadian Prairies.

The four locations cover a range of soil and climatic zones, characteristic of much of the cereal-growing region. Location 1 (Swift Current) is the southernmost and warmest, situated on the brown soils of the open prairie in the arid southwestern section of the province. Location 2 (Outlook) is on the borderline of the brown and dark-brown soils to the north of Location 1. Although relatively close to the latter, this site is included in the series because it is in a zone with some weather effects quite different from those of Location 1, as is demonstrated later.

Location 3 (Saskatoon) is situated on the next most extensive soil type, the dark-brown soils of the prairie. These are less arid than the brown soils, and the area is subject to less severe rainfall variations. Location 4 (Melfort) is the northernmost site, and is located in the zone of transition (black-grey) soils of the parkland-forest belt. The area is characterized by good moisture conditions and high crop yields. Thus the four locations provide a gradation from the relatively light soils and dry summers of the southwest to the relatively heavy soils and moister summers of the northeast.

Apart from providing a fairly representative range of farm operating conditions, these particular locations were selected because of data availability. Weather data for each location were readily available in computerized records, covering a period in excess of 30 years. At three of the sites there is either a federal or provincial government research station (at all except Outlook) from which biological data were obtained. In addition, the locations are all adjacent to areas in which the Saskatchewan Agricultural Machinery Administration undertook field trials with combines and a variety of other field machinery. Thus these locations satisfied the two requirements of (i) being representative of the area of interest, and (ii) having most of the types of data required relatively available.

Machine Systems -- In order that a comparative assessment could be made of alternative sized farm machinery, a range of six harvesting systems was selected for evaluation. A harvesting system is considered to include a combine and a grain dryer. It is assumed that auxiliary equipment is available to permit full exploitation of the capability of these main units. This assumption is necessary to maintain the generality of the model, because of the great variety of different items of equipment that might be combined into a harvesting system. The range of variation is such that the full range of component machines employed may not be the same for any two farms.

The variety of combines used, while still considerable, is less extensive than the range of auxiliary equipment. In order to reduce the alternatives to a controllable number, only those produced by the major manufacturers were selected. The combines in the range produced by each maker were classified into four size categories, according to their physical production characteristics. After rejecting from each group any model that was not fully comparable within a 10 per cent range about the mean for the major physical specifications, measurements of the operating characteristics and prices for the remaining examples were averaged and these used as "representative" parameters for the combine range. Thus the data used do not refer to any particular make, but are representative of the models sold by the major combine producers in the year 1968.

A summary of the production characteristics of the machines considered is shown in Appendix A. The range contains self-propelled machines only, and the specifications are for machines with gasoline engines only. The range of four combines covers the full range of all major manufacturers at the time the study was executed.

By comparison with combines, many fewer grain dryers are marketed in Canada. Consequently the parameters used were those for a leading U.S.-made machine of the continuous-flow type. A range of sizes was considered that was matched in capacity with the range of combine sizes.

In addition to combines and dryers, another machine variable is included in the model to provide some flexibility in the combine capacity available. In practice the combine capacity on a farm can fairly readily be extended by one or more actions. The existing combine may be used at a faster rate of work or in unfavourable working conditions, thus providing extra capacity at the cost of higher grain losses in the process. Alternatively, another machine may be purchased, rented or borrowed, an old and derelict machine may be pressed back into service, or a custom operator (perhaps a neighbour with surplus capacity) may be employed. All of these alternatives involve an extra cost. In order to simulate this flexibility in the system, additional combine capacity is provided in the model in order to handle any crop not harvested in the available time. This is charged at a penalty rate equal to the average custom rate -- but it does not imply that only custom combining may be used.

Acres Harvested -- To permit an assessment of the operating capacity of the different-sized machines when used in Canadian conditions, it was necessary to consider a range of crop acres similar to those found on farms in the cereal-growing acres. In practice, because of a wide range in farm size, and since other crop or livestock enterprises may replace cereals on some farms, the pattern of crop acreage to be harvested per farm varies enormously. In view of this, and in order to assess the full extent of a machinery system's capacity, the analysis was made for successive 25-acre intervals from 25 to a limit that varied from 1,000 to 2,500 acres.

Grain-Drying -- Despite the fact that artificial grain-drying is known to be technically feasible, and is widely used in many temperate farm production regions throughout the world, it is far from being an established practice in Canada. Consequently, one of the main questions to be answered by this study is whether or not artificial grain-drying is an economic proposition. To do this, it was necessary to consider the harvest operation with and without the aid of a grain dryer. The inclusion of a dryer in the harvest process so altered the sequence of operations, however, that it was necessary to build two separate simulation models -- Model 1, based on harvesting without a dryer, and Model 2, on harvesting with the full use of a grain dryer. Though two models were run in the computer, they contained common basic routines, and most of the variables are used in both. Because some additional variables are included in Model 2, the identities and operating relationships differ from one to the other. Thus the variables described below should be regarded as relevant to both models, except when they are specified as being otherwise.

Field Operating Variables

The externally determined or exogenous variables, and certain minor status variables, can be conveniently discussed in the categories of biological tolerances, weather constraints, and machine operating characteristics. The nature of the several variables in each of these categories and the ways in which they are quantified are set out below.

Biological Tolerances -- The variables in this category include (i) the time of ripening of the crop, (ii) the yield, (iii) the rate of shelling loss from the mature crop, and (iv) the grade loss associated with weather damage to the standing crop.

The *time of ripening* of the crop affects the harvest in two ways. First, the date of ripening determines the date on which harvesting can begin. In specifying this date it is assumed that a swather is used, enabling an earlier start than would otherwise be possible. When a grain dryer is used, an even earlier starting time is considered possible, relative to the maturity of the crop.

The harvest starting date is regarded as being location-dependent and was quantified using summarized data collected by the field representatives of the Saskatchewan Department of Agriculture. The first harvesting day has been recorded in each area since 1941, so that the starting date can be regarded as a stochastic variable (determined by weather previous to the harvest period), based on some 25 years' observations. The actual starting dates ranged from August 9 to September 5 at Location 1, and from August 19 to September 15 at Location 4. For each location any particular date within the range was given a probability based on its recorded frequency.

Second, the date of ripening of successive crops or fields on any one farm determines, *inter alia*, the length of time for which the crop remains standing once it is harvest-ripe. This in turn influences the shelling loss and the grade loss that occurs in the standing crop. This effect was introduced into the model by adjusting the proportion of the crop that was subject to shelling and grade losses as harvest progressed.

The number of days' lag between successive crops on a farm reaching harvest ripeness were based on the mean rate of seeding achieved in the tillage and seeding model described in the next chapter. Allowance was made for the telescoping effect that is observable in practice by assuming that the acreage seeded in successive three-day periods reached maturity on successive days. In other words, a spread of three weeks in seeding is assumed to result in a spread of only one week in reaching maturity. This relationship was assumed to hold for all four locations, though seeding progress was, of course, slightly different for each location.

The *cereal crop yield* similarly affects the harvest in two ways. First, it directly affects the rate of work achieved by the combine, as is shown in the discussion of machine operation. Second, it determines, in combination with the time of ripening and the prevailing weather effects, the amount of lost revenue due to shelling and grade loss. Consequently, crop yield is a parameter that appears in several identities within the model.

The yield obtained is regarded as location-dependent, and in order to simplify the assessment it is assumed that the crop to be harvested is all wheat. Employing this assumption, the range of yield for each area was based on the average yields recorded over time for each location. Yield data are also compiled annually by the Economics and Statistics Branch of the Saskatchewan Department of Agriculture, and are readily available for a 25-year period (38). The yields recorded vary from 2.5 to 25.0 bushels per acre at Location 1, from 5.0 to 27.5 bushels at Location 2, from 5.0 to 30.0 bushels at Location 3, and from 15.0 to 35.0 bushels at Location 4.

Since yield is a stochastic variable (again dependent largely on weather prior to harvest), each of the yield levels within the range at all locations can be given a probability based on the recorded observations. It should be noted that the recorded data are (i) based on yields obtained subsequent to harvest losses, and (ii) average yields for each location. Accordingly, the losses calculated for each location may be underestimated, and the degree of variability allowed may be less than is actually encountered on any one farm.

The *shelling losses* that occur in the standing crop are obviously affected by many factors. Clearly these will include the yield, but the proportional loss is also influenced by (i) the crop variety, since some varieties hold the grain more tightly (and are consequently considered harder to thresh), (ii) the prevailing weather, particularly wind, (iii) whether or not the crop is swathed, since losses in the swath are expected to be less than in the standing crop (7), and (iv) the length of time the crop is standing after harvest ripeness is reached.

Unfortunately, the measurements necessary to quantify this variable are not readily available for all locations, though some detailed measurements have been made at Swift Current Research Station, and some less specific observations made at the Melfort Research Station (6). A thorough evaluation of shelling losses has been made, however, in Sweden -- for a number of wheat varieties over a 15-year period (14). Using these data, an average grain loss over successive days was estimated. This was validated by comparison with the more limited Canadian data and found to be closely similar.

It was also determined that the Swedish varieties contained much of the same genetic material that Canadian varieties are based on, so that the crops are likely to be fairly comparable in genotype. Further, the climatic conditions at time of harvest are remarkably similar in Sweden and Canada. This is reflected in the fact that these are the only countries in the world where swathing is general practice. Thus an adjusted array of figures based on the Swedish data was used on the basis that it was the best estimate available.

The daily losses are relatively small, ranging from 0.03 to 0.07 per cent of the crop yield according to the time the crop has been standing. In cumulative terms the effect is greater, being about 3.0 per cent at 10 days, 4.5 at 20, 7.5 at 30, and up to 18.0 per cent by the time the crop has been standing for 60 days. Losses of this order have been frequently observed in experimental trials. To allow for the effect of swathing it is assumed that the first one-third of the crop is swathed, and that shelling losses in that part of the crop are reduced by one-third. Thus the actual figures used in the model are less than those specified above.

The grain quality effects, or *grade losses*, that arise in the unharvested crop due to weather damage are assumed to relate directly to rainfall. The dockage allowed is based on subjective estimates suggested by the grading specialists of the Board of

Grain Commissioners. Three grade dockages, of equal value, are allowed in the model, subsequent to specified levels of rainfall during the harvest. The losses were calculated on the unharvested crop after two, four, and six inches of rain, respectively. The dockage was 4 cents per bushel of the crop yield from the unharvested acres in each case.

Weather Constraints -- The weather variables considered in the models include (i) the occurrence of rain-free days, (ii) the level of precipitation on rainy days, (iii) the relative humidity and time available for combining on rain-free days, and (iv) the rate of drying of the wet grain.

It is assumed that harvesting can proceed only on *rain-free days*. In order to permit the widest possible variation in the time and duration of harvest, rainfall data were collected for the period July 1 to November 30. The daily rainfall for this period at the four locations was obtained from historical weather records covering 35 years from 1931 to 1966. A sequence of this duration is considered to be sufficiently long to contain any short-run cycles that may occur in the weather pattern (39). Days on which there was less than 0.01 inches of rain recorded are considered rain-free and regarded as potential operating days. Days when rainfall exceeding 0.01 inches was recorded are regarded as rainy days on which combining is not possible. This criterion is based on the reality that even very small amounts of surface moisture on the straw can effectively prevent combining. It is assumed that days when some combining is possible before rain falls are offset by rain-free days when early combining is prevented because of rain falling the night before.

The *level of precipitation* recorded in the form of rain was used to adjust the number of available days in order to allow for a drying-out period subsequent to rain. To do this, information was obtained from farmers' (or their wives'!) diaries as to the days on which combining took place. These were compared with the rainfall data in order to assess how long a delay occurred before combining continued. A number of different lags were tried, using "the experimental method", in order to simulate the actual delay that occurred. The scale of days lost, in relation to precipitation, used in the model was to lose one day for each 0.10 inches up to 0.30 inches, and subsequently one day for each additional 0.50 inches.

The estimated number of working days, based on this formula, was compared with the actual number of working days recorded on farms at the four locations. On the basis of Chi-squared tests, the relationship was found to be significant at the 95 per cent level for three locations -- and at the 90 per cent level for Location 1. Thus, although the actual time lost is likely to depend in practice on both the amount and the intensity of rainfall, on the subsequent weather including temperature and wind effects, and on soil types and terrain, this approximate measure is assumed to define the relationship adequately.

Within the rain-free operating days the time available for combining is further restricted by the grain moisture content and surface moisture on the straw, both of which are related to the *relative humidity*. Each day, a mature crop passes through a cycle of moisture content in concert with the ambient humidity. At certain temperatures this results in the accumulation of moisture on the straw, in the form of dew, which makes combining virtually impossible. Consequently, the amount of time available for combining in any one day varies from place to place.

Using the same farm records mentioned above, together with data from weather records for each location, an estimate was made of the average *daily hours available* for combining at each site. These ranged from 12 hours per day at Location 1, 11 hours at Locations 2 and 3, to 9 hours at Location 4. Again, these are approximate figures, since the actual hours available will vary from the beginning of harvest to the end, as the season progresses. To a large extent the shorter hours at Location 4 reflect the later harvest starting date as much as a difference in climate.

Finally, weather conditions affect the *grain moisture content* of the crop and therefore the amount of drying that may need to be done. Thus, in order to assess the need for drying, the relationship between grain moisture content and the prevailing weather effects needs to be established. In fact, the wetting and drying curves for grain have been much explored, but have been defined only for artificially high temperatures (as in a grain dryer) and not for field conditions. Such a relationship has been explored under English conditions, however, and data from that assessment are used as an approximation for those in a Canadian situation (2, 10).

The original data, recorded at the National Institute of Agricultural Engineering, consisted of detailed hourly readings of grain and air moisture content, recorded 24 hours a day over four consecutive harvests. By selecting periods with various proportions of rain-free days from the years recorded, it is possible to build up a pattern of grain moisture content that can be assumed to represent the pattern existing in any period with a similar proportion of rain-free days. Since this is the only information available, it is assumed that this relationship holds sufficiently widely to be indicative of that pertaining to a Canadian situation. The pattern of grain moisture content thus obtained is shown in Appendix B, Table B.4, in the form of percentage time at successive moisture levels -- the form in which such data are most useful in the simulation procedure.

Machine Performance -- The third group of variables simulated in the models are those relating to the field operating characteristics of the machines. These include (i) the rate of work achieved in operation, and (ii) the amount of time lost during an operating day. Both of these variables were quantified on the basis of measurements and information obtained from field test records kept by the Saskatchewan Agricultural Machinery Administration (AMA).

The *rates of work* expected for combines were estimated, using a combination of two methods (for details see Appendix A). The first involved analysis of the rates achieved by machines under field test conditions. To do this, the acreage harvested each day was divided by the time the machine was operated -- both of which were ascertained from the AMA records. The time for which the machine was operated was recorded mechanically on circular charts. On these were registered, by vibration, the exact duration of each run, and the length of each stoppage. Used in conjunction with these data, the daily record sheet showed the acres harvested, together with the yield, and identified the cause of the major stoppages. Using these data a rate of work was calculated for each each day worked. This was then assessed in relation to yield using regression analysis. The linear equation obtained was $R = 9.54 - 0.12X$, with a coefficient of determination of 0.80, significant at the 0.95 level. This implies that a basic rate of 9.5 acres per hour (with no yield) is reduced by 1.2 acres per hour for each additional 10 bushels yield.

Since sufficient data were not available for all machines, a further set of expected rates of work were determined, using the relationship:

$$R = 3[(W/192) + (B.L^{1.5}/38,600) + (S/7,400)]$$

where R = rate of work, tons per hour
W = cylinder width in inches
B = body width in inches
L = straw walker length in inches
S = combined chaffer and sieve area in square inches.

This value, based on the work of MacHardy (28), was related to a range of yields to give rates of work per acre. When compared with the rates obtained by regression analysis of the test data, this formula was found to over-estimate the rates expected for low yields and to under-estimate those for high yields. By comparison of the rates obtained by both methods (for the "medium-size" combine only), a correction factor was developed to adjust the rates obtained using the formula. This was applied to the expected rates calculated from the formula for the other sized combines. The adjusted rates are used in the simulation as deterministic values, related to the crop yield in each case.

For each five-day period considered, however, the acres harvested per day are also affected by the *lost time* due to stoppages for breakdowns, maintenance, adjustments and operator relief periods. Using the AMA records, the frequency and duration of lost time were estimated as a frequency distribution. The order of these values is also shown in Appendix A. These estimates of lost time were compiled from all combines tested by AMA and used in relation to all sized machines considered in the simulation, using the assumption that service requirements and reliability in operation should be similar for machines of all sizes. The time-loss factor is introduced in the simulation models as a probabilistic variable with a known distribution based on AMA field experience.

Harvest Model Specifications

In application, the simulation models used here take the form of quantitative computational sequences or routines, which represent in abstract a man-machine system working in a changeable environment. The variables relating to the system are either known or assumed to be known, and are consequently reduced to data form. Once this is achieved, the purpose of each model is to combine the variables so that they interact in such a way as to represent reality.

This is achieved here using the Monte Carlo procedure. Basically, this allows the evaluation of stochastic effects by using a large number of trials, each employing values that are selected at random from the range for each distribution and then constrained according to the dimensions of the specified distribution frequency. The computerized routines used to achieve this are outlined briefly below.

Outline of Model 1 -- This model is capable of simulating six harvesting systems over any four locations. The variables (or degrees of freedom) included are:

Biological tolerances
- variable yield
- variable ripening date
- grade losses
- shelling losses

Weather constraints
- harvest time limit
- variable wet days
- variable precipitation
- lost days

Machine performance
- variable rate of work
- operating hours per day
- variable lost machine time.

The program first reads the input data, which includes the following tables:

(1) Location-independent
  (a) fixed cost for each system
  (b) variable cost for each system
  (c) cost of custom combining (penalty charge)
  (d) cost of grade loss and cumulative precipitation that causes a grade loss
  (e) average hours available per operating day at each location
  (f) distribution of operating time, expressed in percentage of hours available

(g) correlation of rates of work with yield

(h) list of shelling losses for successive elapsed days; and

(2) Location-dependent

(a) distribution of number of wet days in each five-day period

(b) distribution of precipitation in each five-day period

(c) distribution of harvest starting date

(d) distribution of yield per acre.

For each location, each machine system is run over a specified 1,000 trials or "iterations" at each successive 25-acre level. For each iteration, or year, the harvest starting date and the yield per acre are selected from their respective distributions. The rate of work for the system is then found in correlation with yield.

Having established the yearly variables, harvests are simulated over successive 25-acre intervals up to a specified limit that is varied according to the size of the machine system. Each harvest is based on a series of consecutive five-day periods as independent quanta of the total time taken to complete the harvest. The days and five-day periods number from July 1. The starting date determines the starting period, which is always regarded as a full quantum even if the starting date does not occur on the first day of that period.

For each five-day period, the proportion of available hours per day actually worked (this simulates time lost due to breakdown and machine maintenance), the number of wet days during which no work is done, and the level of precipitation, are selected at random from their respective distributions. The actual number of working days in a five-day period depends upon the number of wet days, the precipitation, and the number of non-working days carried over from the previous period.

Wet days are automatically lost days, and if the number of wet days exceeds two, and extra lost day is added on that account. Lost days are also caused by excess precipitation in the period. One additional lost day is added for each 0.10 inches after the first 0.10 up to 0.30 inches. A further day is lost for each 0.50 inches after that, up to a maximum of five days. If the number of days lost on all accounts exceeds five days in a five-day period, no work is done in that period, and the excess is carried over to the next period as lost days.

When combining is possible, work done is calculated from the number of working days, hours available, proportion of available hours actually worked, and the rate of work of the system in that year. The remaining unharvested acres are found, and the cost of shelling and grade losses are calculated on that acreage. Subsequent periods are considered until the harvest is completed or until all available time has elapsed. If harvest has not been completed after a certain number of periods, custom combining is employed to augment the owned system so that in subsequent five-day periods the rate of work is effectively doubled, and a penalty charge is incurred equal to the custom rate. If, at the end of the maximum time allowable, the harvest is still not complete, the remaining acres are assumed to be harvested at a penalty rate equal to the cost of custom combining.

A grade loss occurs when the cumulative precipitation exceeds a given amount, and the cost incurred is equal to the remaining amount of grain multiplied by the grade dockage factor. A maximum of three grade losses is allowed for each harvest.

Shelling losses are calculated on a day-to-day basis, when the cost incurred is equal to the remaining amount of grain multiplied by the shelling loss factor for each elapsed day. It is assumed, for the purpose of calculating shelling losses, that the amount of grain decreases linearly within a five-day period.

When the harvest has been completed, the cost of the harvest is formed from the cumulative sum of the fixed and variable costs of the system, the cost of custom combining, and the grain loss penalties. The total cost is then computed for successive 25-acre levels, and accumulated over the number of trials, according to the identity:

$$TCai = Fc + Vc(N - Nc) + Cc(Nc) + Ls + Lg$$

where

- TCai = total cost at acreage "a" for machine system "i"
- N = acreage harvested
- Nc = acreage harvested by custom services
- Fc = fixed costs of combining

Vc = variable costs of combining
Cc = custom combining charge
Ls = cumulative value of shelling loss
Lg = cumulative value of grade loss.

From this, the average total cost per acre and the average marginal cost (averaged over the 25-acre increment) are computed, in the form:

$$ATCa = TCai/N$$

$$AMCa = TCai - (TCai - 25)/25$$

and for each identity the standard deviation is calculated, and the variance distribution over the total number of trials is determined. After cycling over the requisite number of five-day periods, all levels of crop acres, and the full complement of harvests (trials), machine systems, and locations, the sequence stops and the output is printed.

Outline of Model 2 -- This model is a variation of Model 1 in that it uses all the same routines but provides for grain-drying in addition to the combining process. For this purpose, it contains one additional variable -- the grain moisture content in relation to rainfall -- with certain changes in other variables.

The grain moisture content is location-independent and is specified in a pseudo-three-dimensional table showing the proportion of time at different grain moisture levels for given proportions of rain-free days.

The model is run in the same way as Model 1, but when the harvest starting date is selected, the first combining day is taken as the beginning of that five-day period prior to the one in which the selected day lies, since the dryer allows an earlier start than is possible otherwise. Subsequently, the number of wet days in the next 10 five-day periods is summed, and used to calculate a proportion of rain-free days for the purpose of selecting the grain moisture content characteristics. Using the proportion of wet days, the particular array of grain moisture contents is identified. From this, five grain moisture content observations are drawn at random, as if from a frequency distribution, using the proportion of time at various moisture contents as a weighting. In each five-day period used, one-fifth of the acreage harvested is considered to be combined at these five moisture contents.

As the sequence proceeds, wet days are automatically lost days, but no additional days are lost for a series of wet days because the drying facility allows combining to continue as soon as the straw surface is dry. Similarly, no additional days are lost due to the level of precipitation until 0.50 inches is recorded, and one additional day is lost for each successive 0.50 inches in a five-day period. This particular lag effect is assumed to represent the soil moisture restraint, which can prevent combining even if the grain is dry.

No harvesting is considered possible if the grain moisture content exceeds 22 per cent of the dry weight of the grain, and no drying is considered necessary until the grain moisture content exceeds 16 per cent. Once grain has to be dried, it is assumed necessary to reduce it to 14 per cent moisture. All other variables are calculated in the same way.

When the harvest has been completed, the cost of the harvest is formed from the cumulative sum of the fixed and variable costs of the combine, the fixed and variable costs and the heating costs of the dryer, the cost of the custom combining, and the cost of the grain loss penalties. The total cost is computed in the same way, according to the identity:

$$TCa = Fc + Vc(N - Nc) + Fd + Vd(Nd) + [Hd \,.\, Nd(M.14)] + Cc(Nc) + Ls + Lg.$$

where
- Fd = fixed cost of dryer
- Vd = variable cost of dryer
- Nd = number of acres of crop dried
- Hd = cost of heat for drying
- M = grain moisture content before drying

Average and marginal costs at each successive acreage level are then derived as before.

Model Output -- The output from each model comprises a range of average and marginal costs for successive 25-acre increments in the acreage harvested. This is the mean for 1,000 trials at each level. The marginal cost is also averaged over the 25 acres in each increment. At each successive acreage level, the standard deviation is indicated for both average and marginal costs. In addition, the frequency with which custom combining is used is shown for each acreage level.

Separately, there is printed a pseudo-three-dimensional table, showing the frequency of occurrence of each cost level at each successive 25-acre level. This is used to show the variance about the mean average and marginal costs presented previously.

Additional output was obtained by running the models with different data and assumptions. Experiments conducted in this way include the use of (i) different cost values to simulate the holding of a combine for a longer period before resale, (ii) different costs to simulate the use of a second-hand machine, (iii) different cost and rate-of-work parameters to simulate the introduction of a prototype machine, (iv) restrictions on the starting and finishing dates to simulate competing activities, and (v) different weather constraints, such as shorter delays after rain. The results of these experiments are detailed in Chapter 4.

3. CEREAL-SEEDING SIMULATION

The purpose of this model was to evaluate, using the same general type of procedure as before, the cost of spring tillage and seeding operations using alternative machinery systems, taking into account seasonal variations affecting these operations and associated biological tolerances. Just as in the harvest simulation, the exact form of the model was finally determined by the nature of the variables and the way in which they could be quantified. Consequently, the first stage in building the model was to identify the major components, quantify the variables, and then specify the relationships between them.

Seeding Model Components

Location -- Only two locations were considered, using this model -- Swift Current (Location 1) in the southwest and Melfort (Location 4) in the northeast. One reason for restricting the number of locations was the paucity of input data, of the type required, at the other stations. A second reason was that the output from the harvesting model showed less significant differences between Locations 1, 2 and 3 than between each of them and Location 4. Though it does not necessarily follow that the differential will be similar for seeding operations, it seemed that consideration of these two locations would adequately demonstrate the importance of location differences. Thus, for these reasons, the simulation model was built to encompass only Locations 1 and 4.

Machine Systems -- A wide variety of different cultural practices are followed in cereal-growing, even within a small district. Consequently, the range of field equipment that might constitute a tillage and seeding system is extensive and the number of possible systems, almost limitless. However, within this range there is, at most points in time, a modal system that is most popular and widely accepted. On this basis, a single combination of equipment items was chosen as representative of the whole. This included a tractor, disker, cultivator and harrow, with the assumption that these three implements would be used in a sequence of tillage and seeding operations.

A size range of five alternative systems was considered, based on the horsepower range of the tractor models marketed by the major manufacturers in 1968. The sizes used were chosen by classifying the tractors according to their production characteristics and then taking the mean of the relevant parameters for the five most populous categories. The tractor sizes considered were 38.4, 56.0, 68.2, 96.4 and 123.3 PTO horsepower, respectively. Using estimated draft requirements for the three implements, and assuming the effective drawbar horsepower to be 65 per cent of maximum PTO horsepower (9), a set of optimum sized implements was calculated for each tractor. The optimum sizes were then adjusted to coincide with the nearest size available on the market. The relevant data are summarized in Table 3.1, and described in more detail in Appendix D.

TABLE 3.1

COMPOSITION OF TILLAGE AND SEEDING MACHINERY SYSTEMS

	I	II	III	IV	V
Tractor (PTO HP)	38.4	56.0	68.2	96.4	123.3
Disker (ft.)	8	12	16	21	28
Cultivator (ft.)	10	13	16	23	29
Harrow (ft.)	36	52	64	92	120

Acreage Seeded -- The acreage range over which the machine systems were used was determined, as with Models 1 and 2, by the need to assess the full extent of each system's capacity at all locations. In addition, it was considered desirable to evaluate systems that would be compatible with the harvesting systems available. Thus the same acreages were considered as for the cereal harvest models; *viz.*, successive 25-acre increments up to a variable maximum, which in most cases was 2,000 acres.

Soil Types -- In this model it is assumed that the major determinant of field operating capacity for any machine system is the condition or "tractability" of the soil. This is determined largely by soil moisture content and is thus susceptible to weather effects. However, tractability is also significantly influenced by physical soil conditions. In the study of tractability, upon which this model is based, a significant difference in the relevant characteristics was found between the different soil types that occur in the cereal-growing areas. In order to assess the effect of this variable, therefore, two soil types were considered. These are identified as a "sandy soil" and a "medium-to-heavy soil", respectively. The characteristics of these soil types are described more fully in Appendix E.

Field Operating Variables

Biological Tolerances -- The biological variables included in the model are (i) the starting date of spring tilling, (ii) the yield effects associated with seeding progressively later than the starting date, and (iii) the final seeding date. It is recognized that each of these is influenced by weather effects, but these are regarded as being outside the scope of the model.

The date on which farmers first begin seeding, along with many other husbandry dating practices, has been recorded by the field staff of the Saskatchewan Department of Agriculture at all major locations for the past 30 years. Using this information, in conjunction with weather records for each location, it was estimated that tilling could commence about seven days prior to the earliest seeding date. Thus it is assumed in the model that the *spring tillage starting date* was seven days earlier than first seeding at each location.

After modifying the recorded dates to allow for this assumption, a distribution of the occurrence of the starting dates was produced to serve as a basis for selecting a starting date in the model. The adjusted dates ranged from April 10 to April 30 at Location 1, and April 16 to May 12 at Location 4. More detail is shown in Appendix E. Although the starting date for spring tillage has been adjusted, no seeding is permitted in the simulation until the successive seven days have elapsed.

It has long been postulated that there is a narrow optimum time range for seeding cereals, and that seeding outside that range will result in lower yields. It is accepted by cerealists that each variety of wheat has a genetic yield potential which, because of less than ideal growing conditions, is generally never realized. Low yields are usually blamed on low rainfall, but it has been suggested that the variations that have occurred in the past "may conceivably be a reflection, not so much of moisture limitation, but of low fertility, adverse soil structure, undue loss of water by run-off and evaporation, outbreaks of disease or rust, and of insects such as grasshoppers, poor seed-bed preparation, weed infestations, and so on" (5). Since many of these factors are weather-related, and weather varies as each season progresses, it is also conceivable that these factors manifest themselves as a *yield penalty for untimely seeding*.

Using existing data from the research stations at Swift Current and Melfort, together with experimental results from stations in North Dakota and Montana, the effect of seeding time on yield was investigated. Some of the information obtained is detailed in Appendix F. On the basis of these data a schedule of yield loss factors was derived, showing the expected variation in yield from the expected maximum. In the model this was expressed in the form of positive and negative additions to yield, over successive days.

Apart from the yield penalties associated with seeding time, an additional charge is made as a *harvest timeliness penalty*. The time of seeding affects the time of harvest. The later the harvest period, the worse the weather encountered. The extra cost involved was calculated by running Model 1 with the harvest starting date fixed at two dates -- first August 15, then September 14. The difference in the cost per acre was then divided by 30 days and this figure was applied as a penalty charge. Since the spread in seeding dates is at least halved by the time the crop is ready to harvest, the loss factor was applied to every third day after the "optimum" seeding date.

Since the yield penalty increases progressively, once it begins, it is reasonable to suppose that there will be a *last* *seeding date* after which seeding will be unprofitable, due either to yield penalty or the risk of a frozen crop. It is assumed, therefore, that all seeding stops on June 15 at both locations.

In establishing *crop yields* upon which to base the penalties, it seemed appropriate to use something higher than the average yield obtained in each area, since this figure would reflect the losses we are trying to estimate, as well as the variation in husbandry from one farm to another. The average yield at Location 1, over the period 1938-67, was 15.4 bushels per acre. At Swift Current Research Station the average yield of wheat on fallow, over the period 1941-58, was 22.7 bushels per acre. Potential wheat yields for the area are estimated by de Jong and Rennie (5) to be 32 bushels per acre on fallow and 26 bushels per acre on stubble. Taking these into account it is assumed in the model that the yield for Location 1 is 25 bushels per acre.

The average yield around Location 4, during the period 1938-67, was 25 bushels per acre. No research station yields from large areas are available, but the de Jong and Rennie projections are 58 bushels per acre on fallow and 47 bushels per acre on stubble. Assuming the same relationship exists between the district average and the projections at both locations, an assumed yield of 37 bushels per acre would be comparable to that made for Location 1.

Weather Constraints -- The weather effects applied in the model were determined, using a method developed by Rutledge and MacHardy (37). This employs daily minimum and maximum temperature and precipitation, and monthly averages of wind velocity, dew point, sunshine hours and day length. Using these data, soil moisture content is computed, using the budgeting formula developed by Baier and Robertson (4). The Rutledge and MacHardy study related moisture content in the top three zones of a medium soil or the top two zones of a sandy soil to *effective tractability*, using conventional tractors. They were able to establish critical moisture levels in these respective soil zones, above which cultivation was expected to be impossible. By examining the weather for the period 1931-60, using this relationship, the probability of a day being unsuitable for cultivation was calculated for each day from April 1 to June 15 (the assumed last day of seeding). The probabilities, which were computed for both sandy and medium-heavy soils at both locations, are summarized in Appendix F. These values were then used in the simulation with the assumption that a non-working day in terms of cultivation is a non-working day for all similar operations.

Machine Performance -- The operating performance of the alternative sized machinery systems is assumed to be adequately described by (i) estimated rates of work, related to the width of the respective implements and the speed at which they are pulled, (ii) a time loss factor, representing turning and adjustment losses, and maintenance and repair time, and (iii) a constraint on the hours operated per day, depending on the number of operations employed.

The rate of work was calculated for all five sizes of the three types of implement, using the formula:

$$C = \frac{R.W.e}{8.5}$$

where C = capability in acres per hour
R = forward speed in miles per hour
W = width of cut in feet
e = efficiency factor to allow for turning and other time losses, including removel of blockages and filling seed and fertilizer boxes.

For the *cultivator*, the size was adjusted to suit the different tractor sizes, assuming a draft requirement of 250 pounds per foot of width, with the drawbar horsepower of the tractor being 65 per cent of the PTO horsepower at a forward speed of four miles per hour. It is also assumed that an efficiency factor of 82.5 per cent is applicable.

The size of the disker used in each case was similarly chosen on the basis of a draft of 250 pounds and a forward speed of four miles per hour. The efficiency factor applied in this case was 60 per cent.

The same approach was used for *drag harrows*, assuming a draft of 50 pounds per foot and a forward speed of five miles per hour. The efficiency factor applied was again 82.5 per cent. The implement width and assumed rate of work, based on the above data, are summarized in Table 3.2, and further details are shown in Appendix D.

Fixed and Variable Costs -- These costs were estimated for each machine in all systems, using data from a variety of sources. The costs used in the model are summarized in Table 3.3 and their derivation is explained in Appendix D.

Seeding Model Specifications

This simulation model is in every way similar to those described in the previous chapter. In fact, this constitutes Model 3 of a suite of programs, and employs many routines common to Models 1 and 2. Though the actual situations that are simulated are very different, in abstract they are surprisingly alike. The computational sequence is charted in Figure 3.1 and is outlined briefly below.

Outline of Model 3 -- This model is constructed to simulate five alternative tilling and seeding systems over any acreage range in any two locations. The variables considered are:

Biological tolerances	- crop yield
	- variable starting date
	- yield effects
	- harvest timeliness penalty
Weather constraints	- seeding time limit
	- variable soil tractability (related to weather)
	- soil types
Machine performance	- rates of work

The program first reads the input data, which in this case includes the following tables:

(1) Location-independent

(a) fixed cost for each system

(b) variable cost for each system

(c) rates of work for all implements of each system; and

(2) Location-dependent

(a) value of yield gain or loss for successive days from start of seeding

(b) cost of harvest delay for successive days after best seeding day

(c) distribution of tillage starting dates

(d) probabilities of successive days being working days (for both soil types).

For each location every machine system is used over 1,000 trials, each representing a single season. At the beginning of each trial a starting date is selected from the specified distribution. The three implements are used over the same acreage in sequence. The whole area is cultivated first at the given rate for each system, operating 10 hours per day. Once cultivation is completed the area is seeded, using the disker; seeding for four successive working days then stopping to harrow that area. The seeding and harrowing sequence is repeated until the job is complete.

If the selected starting date is later than a specified date, then the first cultivation is omitted and a penalty charge is incurred, related to the estimated loss of yield resulting, and no variable costs are incurred for cultivation. If the seeding operation is not completed by a second specified date, then the rate of work is doubled, to simulate the working of a double shift, and an additional variable cost of $2 per hour is incurred, representing the opportunity cost of the extra labour. If seeding is not completed by a third specified date, then all operations stop and a cost is incurred equal to net revenue from the unseeded acres.

The tilling and seeding sequence is simulated over successive 25-acre intervals up to a specified limit. Each spring operating period is based on a series of individual days which together comprise the total available days. The probability of being able to work on any one day (based on soil tractability as determined by the soil moisture budget) is determined, using random numbers as for selecting rain-free days in Models 1 and 2.

Over consecutive days, beginning on the starting date, the cost of the yield timeliness effects is accumulated from the array of positive and negative yield effects. In addition, the cost of the harvest timeliness effects is accumulated, using the estimated daily additional cost derived from Model 1.

When tilling and seeding have come to an end, the cost of the operation is formed from the cumulative sum of the fixed and variable machine costs, and the cost of the yield and harvest penalties. The total cost is then computed for successive 25-acre levels, and accumulated for the number of trials, according to the identity:

$$TCai = Fs + (Vk \cdot Nk) + (Vw \cdot N) + (Vh \cdot N) + Ly + Lh$$

where TCai = total cost at acreage "a" for machine system "i"
Fs = fixed cost of system
Vk = variable cost of cultivating
Vw = variable cost of wide-levelling (disking)
Vh = variable cost of harrowing
N = acreage seeded
Nk = acreage cultivated
Ly = cost of yield-time effects
Lh = cost of harvest-time effects

From this, the average and marginal costs per acre are calculated, as in Model 1. The standard deviation of these values is computed for each 25-acre level and all values, together with the range and frequency of the average cost, are printed.

Model Output -- The printed output for this model is of the same form as that for the previous models. Additional output is provided to cover the different soil types considered at the two locations. The nature of the output is shown graphically in Chapter 4.

Experiments were conducted on this model by varying the rates of work to allow for differences in efficiency between the different-sized systems. Since the rate of work is a very significant variable in these models, in that it is multiplied by very large numbers (acreages), the deterministic values employed must be considered inadequate to characterize the various systems. Some of the disadvantages associated with using these figures are overcome by experimenting with adjusted figures. The results of these experiments are also detailed in Chapter 4.

4. CAPACITY-COST RELATIONSHIPS

Production Cost Concepts

In economic terms a production process can be represented as a functional relationship between inputs and outputs. The inputs involve costs, and the outputs generate revenue. When such a process is considered over the short run, some inputs are regarded as fixed and others, variable. Thus the capital costs of a machine are fixed costs and those for the fuel to run it are variable. Over the long run, all inputs are considered variable, and decisions on their level of use are necessary so that profitable production may continue.

To the extent that the inputs into the production process are controllable, their level of use may be assessed in terms of the "additional" or marginal principles which lead to the identification of minimum-cost and maximum-profit combinations. But many inputs involved in production processes may -- particularly in agriculture -- be uncontrollable. These may be variable according to some pattern in the long run, but in the short run are usually random in nature -- such as are weather inputs.

The contribution of such inputs as weather may be positive or negative. In some cases an input, such as moderate rainfall in the growing season, may yield a positive marginal product at no cost. But if this input becomes excessive or falls outside the growing season, such as during the cereal harvest, it may have a negative marginal product with an associated loss of revenue. It may also involve a cost to cover some remedial measure, such as grain-drying.

Although such uncontrolled inputs may have a great variety of effects on production processes, their impact can still be assessed -- providing it can be measured -- in the standard cost and revenue terms. In this study the random inputs are introduced into the analysis in order to assess their effects, by using simulation models of the production processes being examined -- that is, of farm machinery field operations.

In these models the uncontrolled inputs that are assumed to be significantly affecting the process are quantified in terms of the best available data. In addition, the cost and revenue functions associated with the random effects are identified, again in terms of the best available estimates. Thus, within the limits of the random input effects, the best amounts of the controlled inputs to use can be determined.

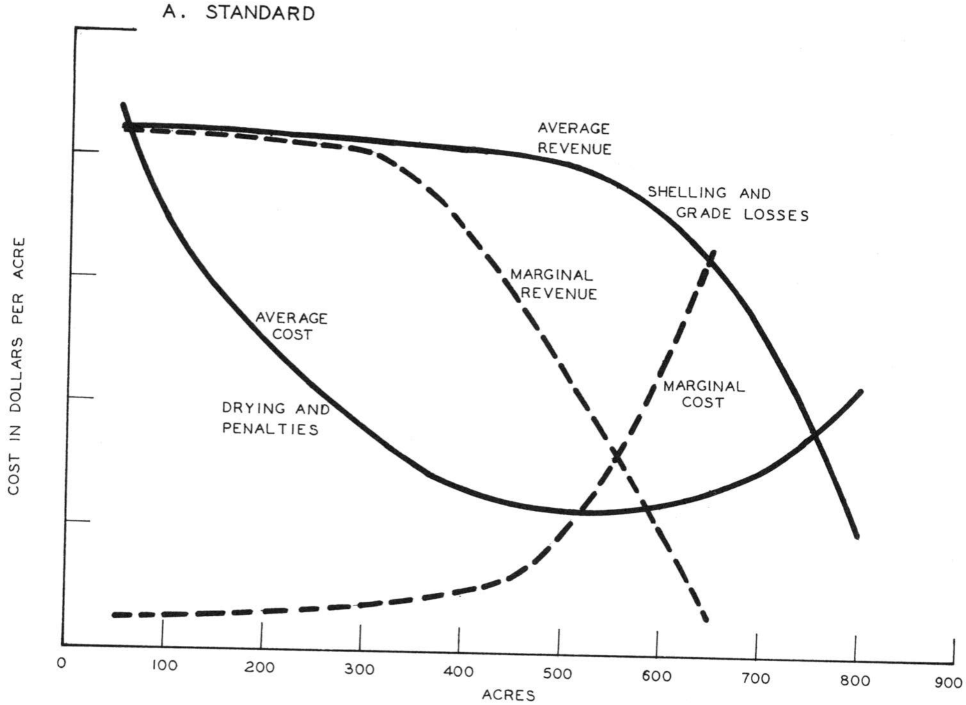
As indicated in the previous chapters, the random variables considered have both positive and negative revenue effects, such as an increased yield due to timely seeding, on the one hand, or yield losses due to shelling and grain damage in the unharvested crop, on the other. They may also have positive cost effects, such as those for grain-drying and the employment of additional machines. The nature of such cost and revenue effects in relation to varying levels of production is shown in Figure 4.1A.

Standard Cost and Revenue Curves -- The generalized curves shown in Figure 4.1A represent the average cost and average revenue per acre for the use of a particular machinery system for different levels of production, in terms of crop acres handled. The average revenue curve declines as the cumulative effects of weather on the standing crop reduce the yield and quality of grain. The average total cost declines at first, as the fixed costs are spread over larger acreages, and then increases as additional variable costs are encountered, such as for custom services or grain-drying. The marginal revenue and marginal cost curves must respectively fall and rise more steeply than the average values, since they represent the incremental effects at each level. The difference between the average revenue and average cost curves represents the "profit" per acre from the field process, and this is at a maximum where the difference is greatest. On the other hand, total profit is at a maximum where the marginal revenue and marginal cost curves intersect.

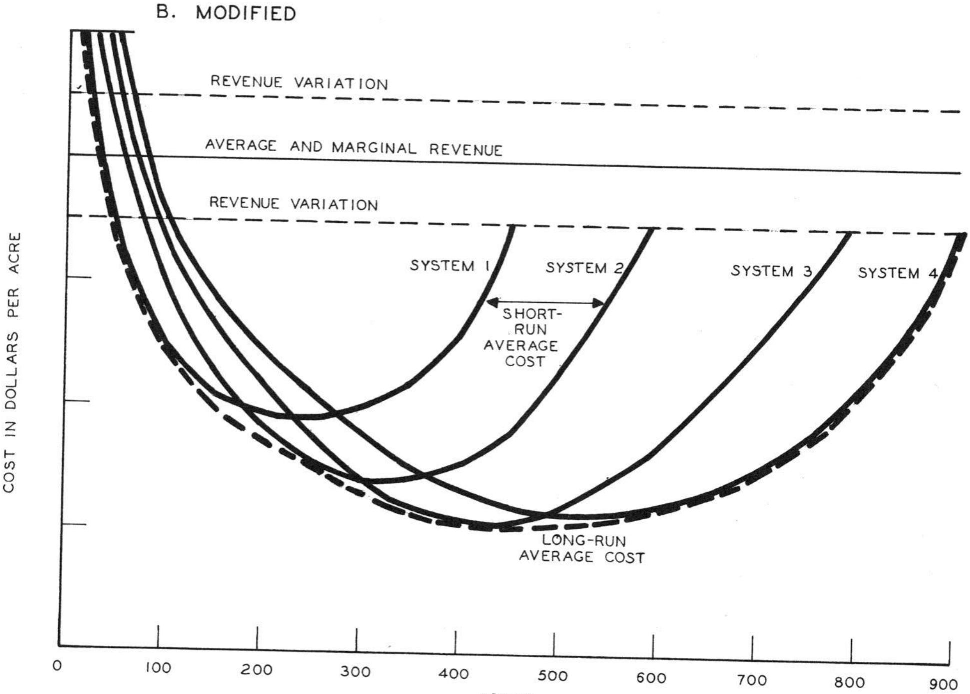
Since it is these cost effects that are evaluated, using the simulation models, the results could be presented in this form.

FIGURE 4.1—COST AND REVENUE CURVES

A. STANDARD



B. MODIFIED



However, as the analysis refers in each case to only a part of the full production sequence, the actual revenue is difficult to assess. Moreover, the revenue effects taken into account may be considered as *opportunity costs* associated with the use of a particular system. The nature of these effects is such that they will be different for each system. Thus it is convenient, in order to facilitate a comparison of the alternative machinery systems, to assess the revenue losses as additional costs associated with the various systems, and to offset revenue gains against the costs of each system.

Modified Cost and Revenue Curves -- In this way, most of the revenue variability is removed (for any given level of production) and the average revenue curve takes the form of a straight line shown in Figure 4.1B. In this case average revenue will equal marginal revenue in any one season. However, since there is some residual variation in yield associated with random variables that are not taken into account in the simulation model, the level of the average revenue will vary from year to year within a range determined by the various physical constraints on production. This range is represented by the broken lines on each side of the average revenue line in Figure 4.1B.

Since the average revenue per acre is thus constant for all machinery systems, its level can be disregarded and the costs for the alternative systems can be compared directly. Figure 4.1B shows hypothetical, overlapping, average cost curves for four machinery systems. The intersections of these curves define the acreage range over which each successive system provides the minimum cost alternative. This is subsequently referred to here as the "least cost range" for each system. Each of these average cost curves is of the same type as shown in Figure 4.1A.

But the consideration of one curve is useful only for a short-run decision, such as choosing a level of production, given the availability of the one system. In practice, since the system is fixed only for the short run, the farmer usually wishes to consider the long-run decision so as to select the machinery system to best suit his production level (crop acreage). This in turn is usually determined by other constraints, such as the size of the farm, types of enterprises, and pattern of cropping. Thus *the costs that are of interest to the decision-maker* are represented in the long-run cost curve delineated by the least cost range of the successive short-run curves. This is not the same as the theoretical long-run cost curve which is the lower boundary line enveloping the family of short-run curves, as is indicated in Figure 4.1B.

When variables are considered as probabilities, however, the average costs shown are not only averaged over the acreage level considered, but are also the mean of 1,000 trials. Since the variables considered in the model vary from season to season as well as from one part of the season to another, the cost at any given acreage level will vary from year to year (or trial to trial). Thus the position of the average cost curve will differ from year to year within a range determined by the coincidence of the extreme effects of the interacting variables. Given a large number of trials the position of the average cost within this range can be defined as a frequency distribution. The nature of the cost curves, and their variability, relating to the alternative machinery systems evaluated in the simulation models, are outlined below.

Harvest Costs

Cost Characteristics -- Estimated costs for cereal-harvesting on the Canadian Prairies, as computed from the simulation Model 1, are presented in Figures 4.2 to 4.9. In each case the form of the cost curves approximates the stylized version shown in Figure 4.1 though there are observable departures from the hypothetical format.

The average and marginal costs for the four basic (one combine) harvesting systems are shown for Location 1 in Figure 4.2, and for Location 2 in Figure 4.3. In every case there is a characteristic decline in average cost as the level of use is extended. After a point, it then increases as the variable and opportunity costs begin to increase. Though the four systems provide a family of curves, there is a tendency for them to group -- showing some affinity between Systems 1 and 2 and Systems 3 and 4, respectively.

As the curves overlap they delineate at their point of intersection, the least cost alternative for each acreage.

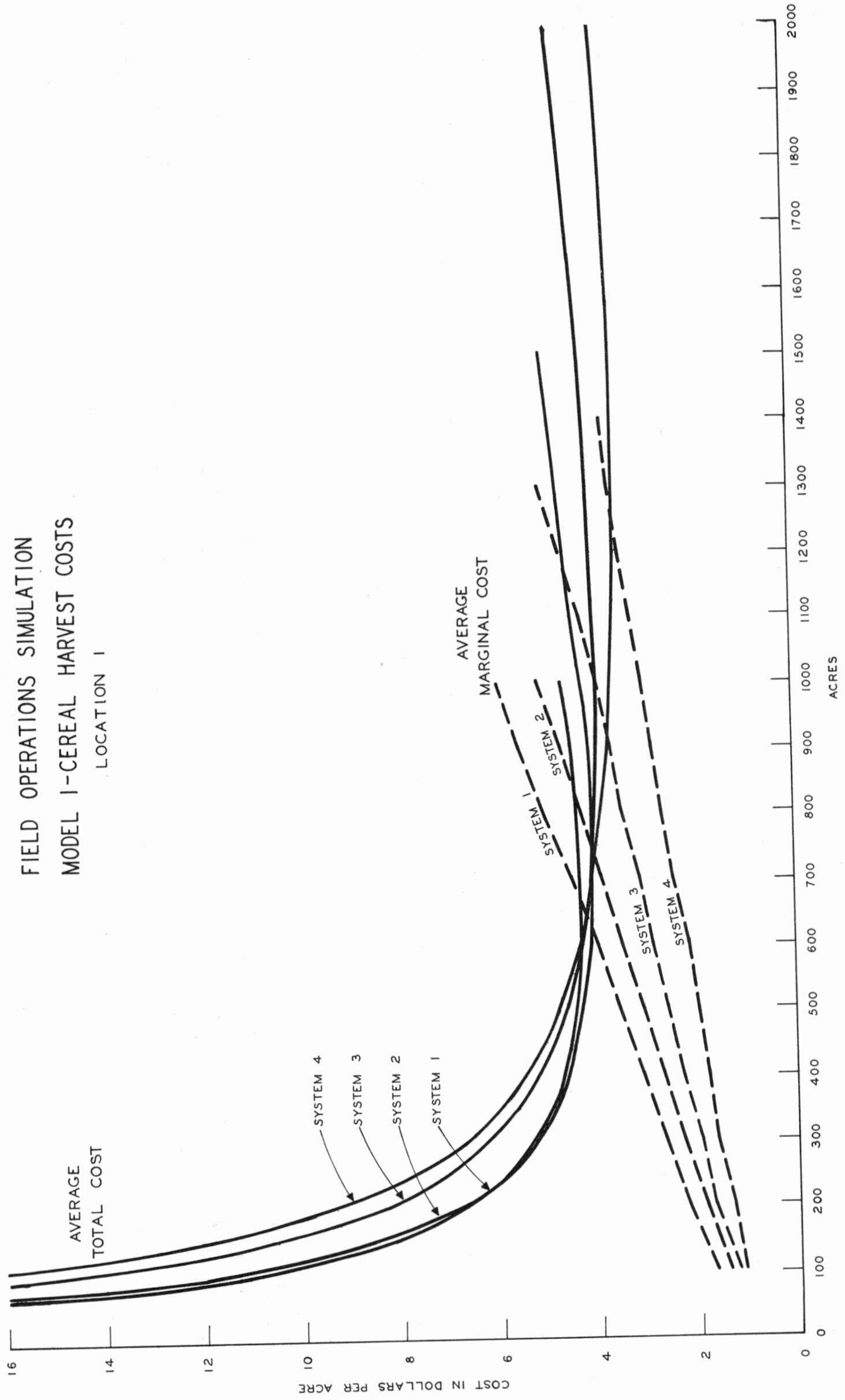


FIGURE 4.2
FIELD OPERATIONS SIMULATION
MODEL I-CEREAL HARVEST COSTS
LOCATION I
AVERAGE TOTAL COST
AVERAGE MARGINAL COST
SYSTEM 1
SYSTEM 2
SYSTEM 3
SYSTEM 4
COST IN DOLLARS PER ACRE
ACRES
0
2
4
6
8
10
12
14
16
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

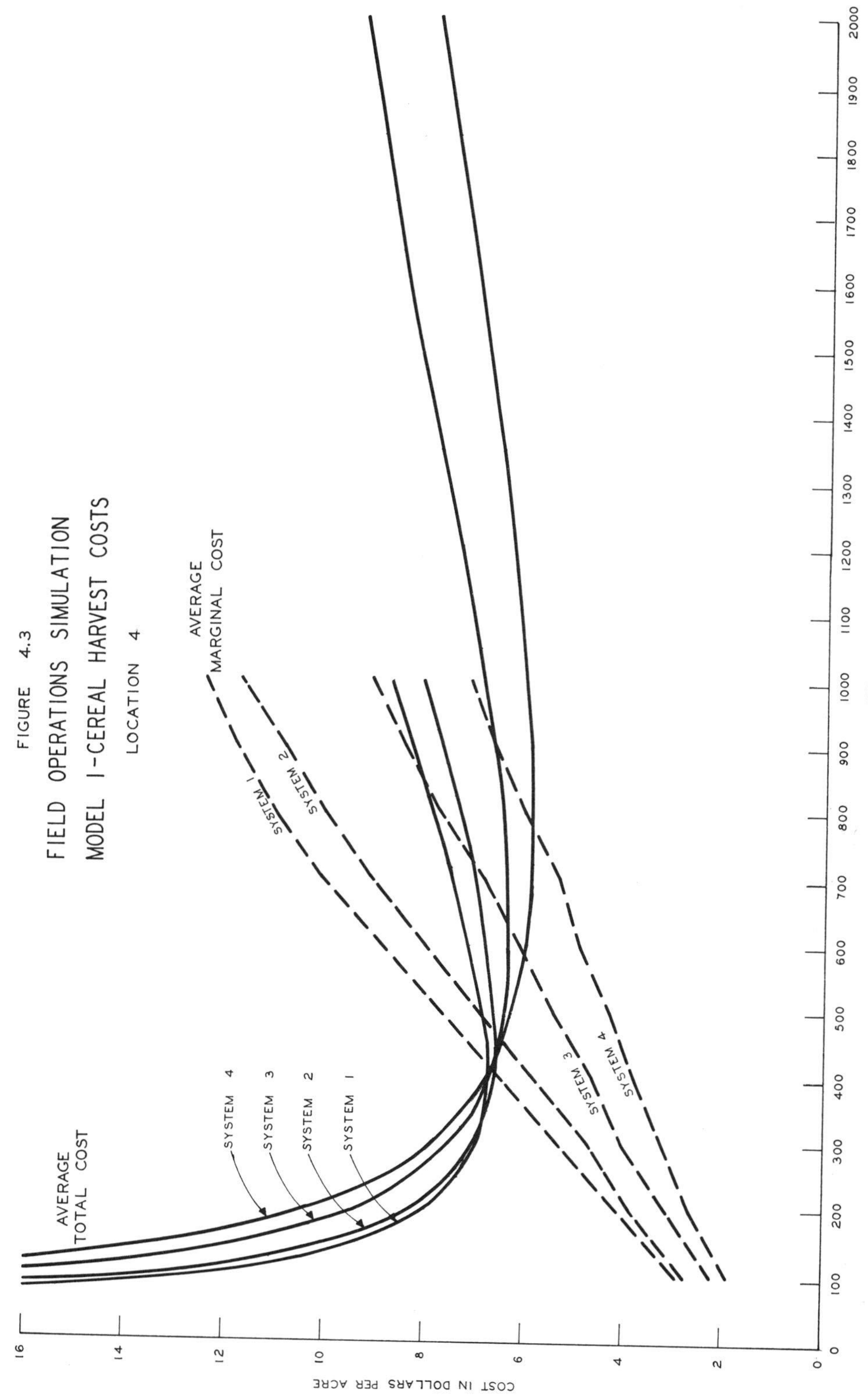


FIGURE 4.3
FIELD OPERATIONS SIMULATION
MODEL I-CEREAL HARVEST COSTS
LOCATION 4

The ranges so defined are not even. At Location 1 (Figure 4.2) the smallest system is the least cost alternative up to the 200-acre level, but gives a very high cost. This suggests that for a farm growing less than 200 acres of cereals, a larger second-hand machine may be a cheaper alternative. System 2 provides the least cost alternative from 200 to 700 acres; above 700 acres, System 4 is the cheapest. At no stage does System 3 become the least cost alternative.

At Location 4 (Figure 4.3) the smallest machinery complement, System 1, is the least cost choice over a wider range (up to about 300 acres), and at a more competitive cost level. Again, however, System 3 fails to become the least cost alternative.

The marginal cost curve for each system slopes upwards from the origin from the outset. This reflects the fact that some of the variable or opportunity cost effects begin to influence the harvest process even at the 25-acre level. The juxtaposition of the marginal cost curves suggests again the affinity between System 1 and 2, and 3 and 4, respectively. The fact that the marginal cost curves appear not to cut the average cost curves at the lowest point is an artifact caused by the marginal cost value plotted at each successive 25-acre level, being the average of the marginal cost over the last 25 acres -- it is thus an *average* marginal cost for the preceding 25 acres.

The level of incline of the marginal cost curve gives some indication of the flexibility of the machinery systems. At Location 1 all four systems could be extended to cover additional acres without a very large increase in total cost. At Location 4 the curves are steeper; thus, extending a system will result in a more rapid increase in total cost. This suggests that the constraints on the harvest operation are more acute at Location 4 than they are further south.

Modified Systems -- Apart from a choice between the four systems based on the four available combines, a farmer may also opt for a system with more than one combine. Systems 5 and 6 in Figures 4.4 and 4.5 include two of the combines considered in Systems 3 and 4, respectively. The average cost curves for the two multiple combine systems have a slightly different shape because of the higher fixed cost ingredient with no change in the operating costs per acre. The fact that the variable costs are not doubled, and that some of the opportunity costs can be saved

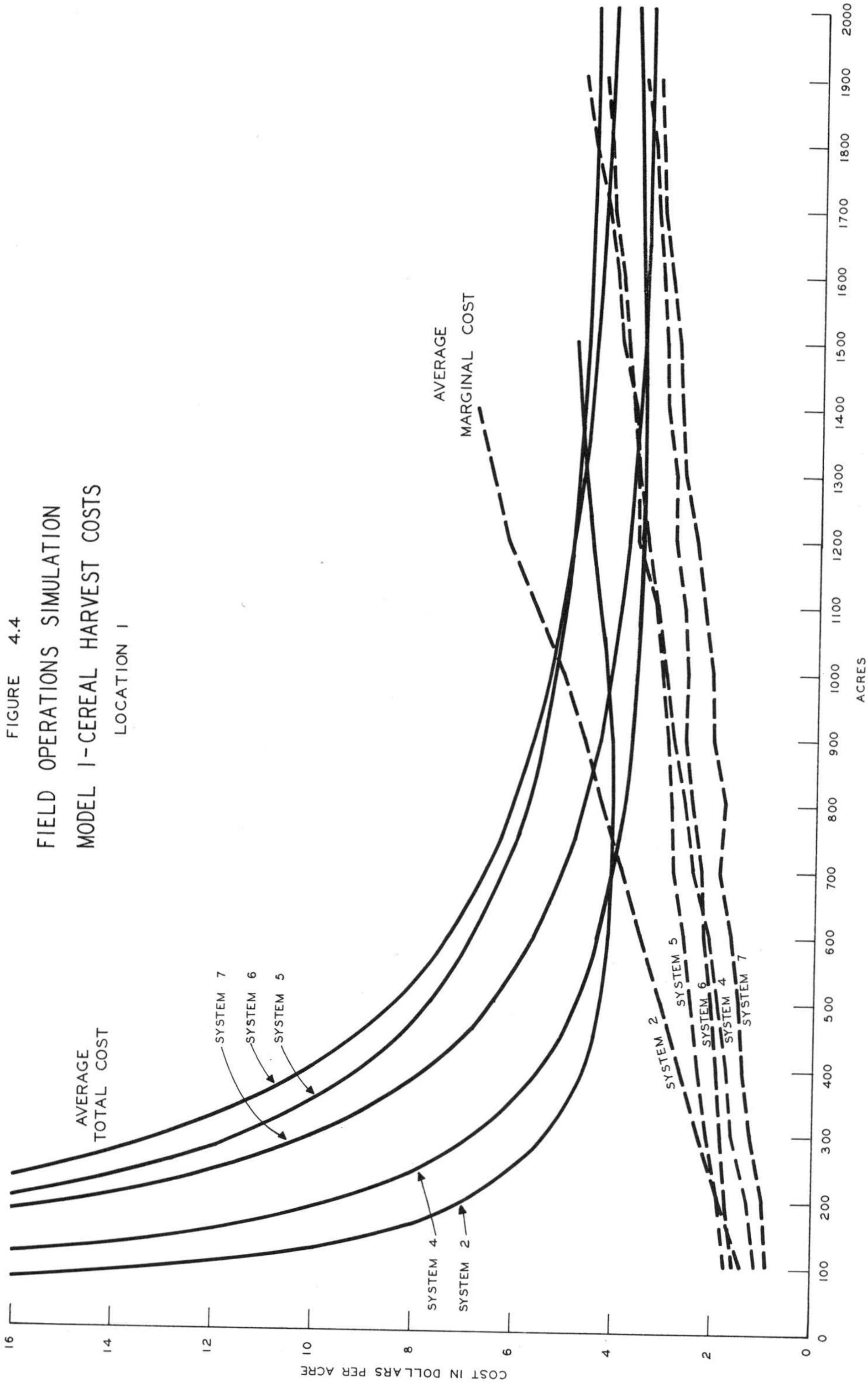


FIGURE 4.4
FIELD OPERATIONS SIMULATION
MODEL I-CEREAL HARVEST COSTS
LOCATION I

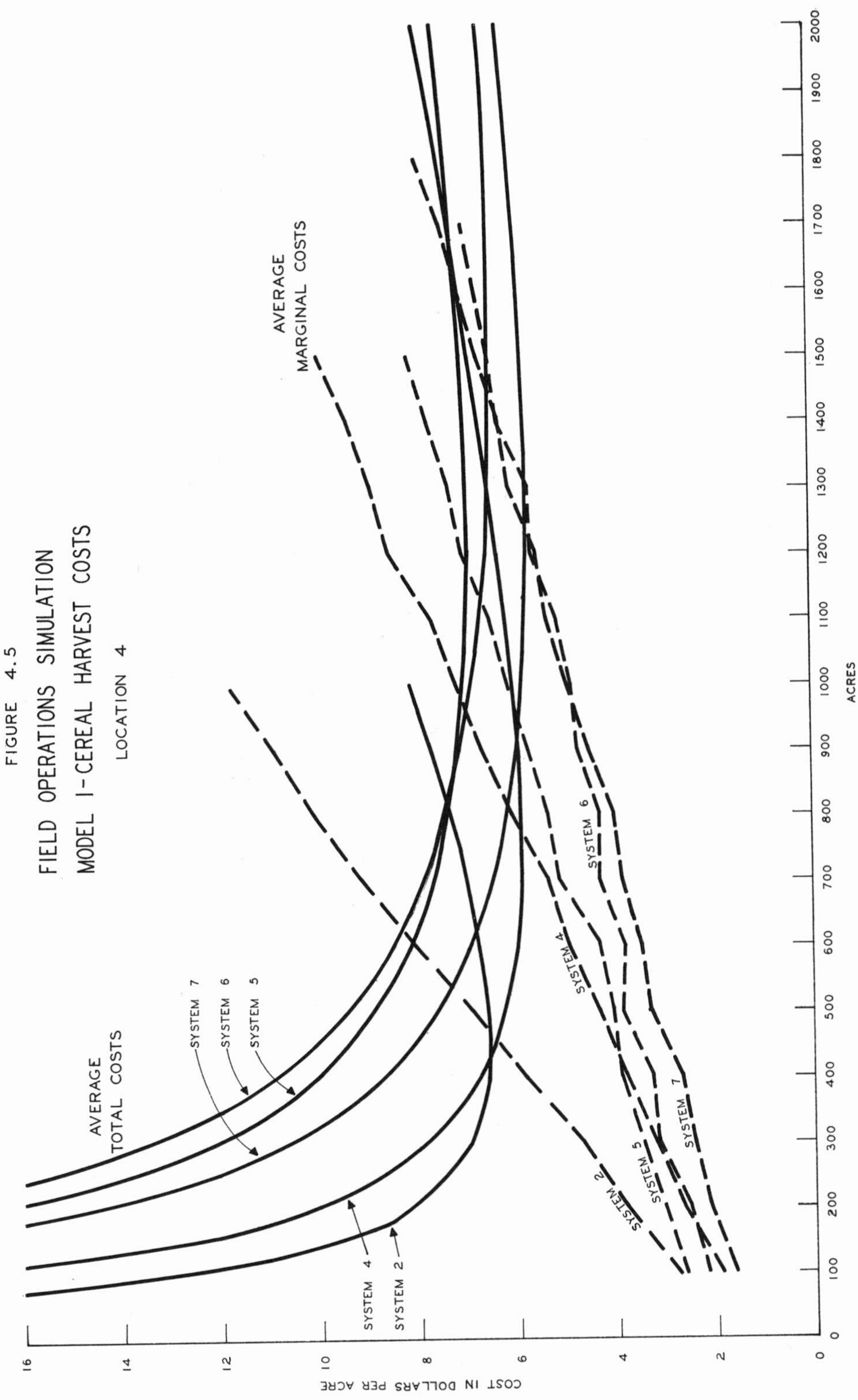


FIGURE 4.5
FIELD OPERATIONS SIMULATION
MODEL I-CEREAL HARVEST COSTS
LOCATION 4
AVERAGE TOTAL COSTS
AVERAGE MARGINAL COSTS
SYSTEM 7
SYSTEM 6
SYSTEM 5
SYSTEM 4
SYSTEM 2
COST IN DOLLARS PER ACRE
ACRES
0
2
4
6
8
10
12
14
16
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

by employing two machines, is reflected in the position of the marginal cost curves. For instance, although higher for lower acreages, System 6 has a marginal cost lower than System 4 even though it contains two combines of the same size as that in System 4. The "two-combine" systems become least cost alternatives only at very high acreage levels.

Also shown in Figures 4.4 and 4.5 are the cost curves for System 7. The combine considered in this system was a new larger model which had not been released on the market at the time this analysis was built. Forecasts of its performance and price were made on limited information, it being assumed that in physical terms it would provide a rate of work 50 per cent higher than the combine in System 4, and that it would cost proportionally more. The aim of this exercise was to indicate that once the operating characteristics of a family of combines was understood, the performance of a new member could be forecast. Unfortunately, insufficient information is available to verify the adequacy of this assessment.

Adjusted Cost Assumptions -- In order to assess the effect of alternative cost assumptions, three different fixed cost estimates were used. The effect is illustrated in Figure 4.6. Farm survey data suggest that combines are kept on farms for about eight years (35). However, in order to avoid high repair and maintenance costs or the reduced reliability of an older machine, some farmers keep their combines for a shorter time. The cost effect of doing this was evaluated by using five years' depreciation and interest, instead of eight.

The effect can be seen from Figure 4.6. Depending on the level of use, the shorter machine life could increase unit costs by as much as $1 per acre, or as little as 20 cents. The differences were similar for the two locations. The larger the acreage harvested per year, the lower the cost of early replacement. The model does not allow for the decline in reliability that may occur as the machine gets older, thus the opportunity cost of holding the machine for the extra three seasons is not assessed. At higher levels of use, however, the risk reduction achieved through more rapid replacement would not need to be great to justify so doing.

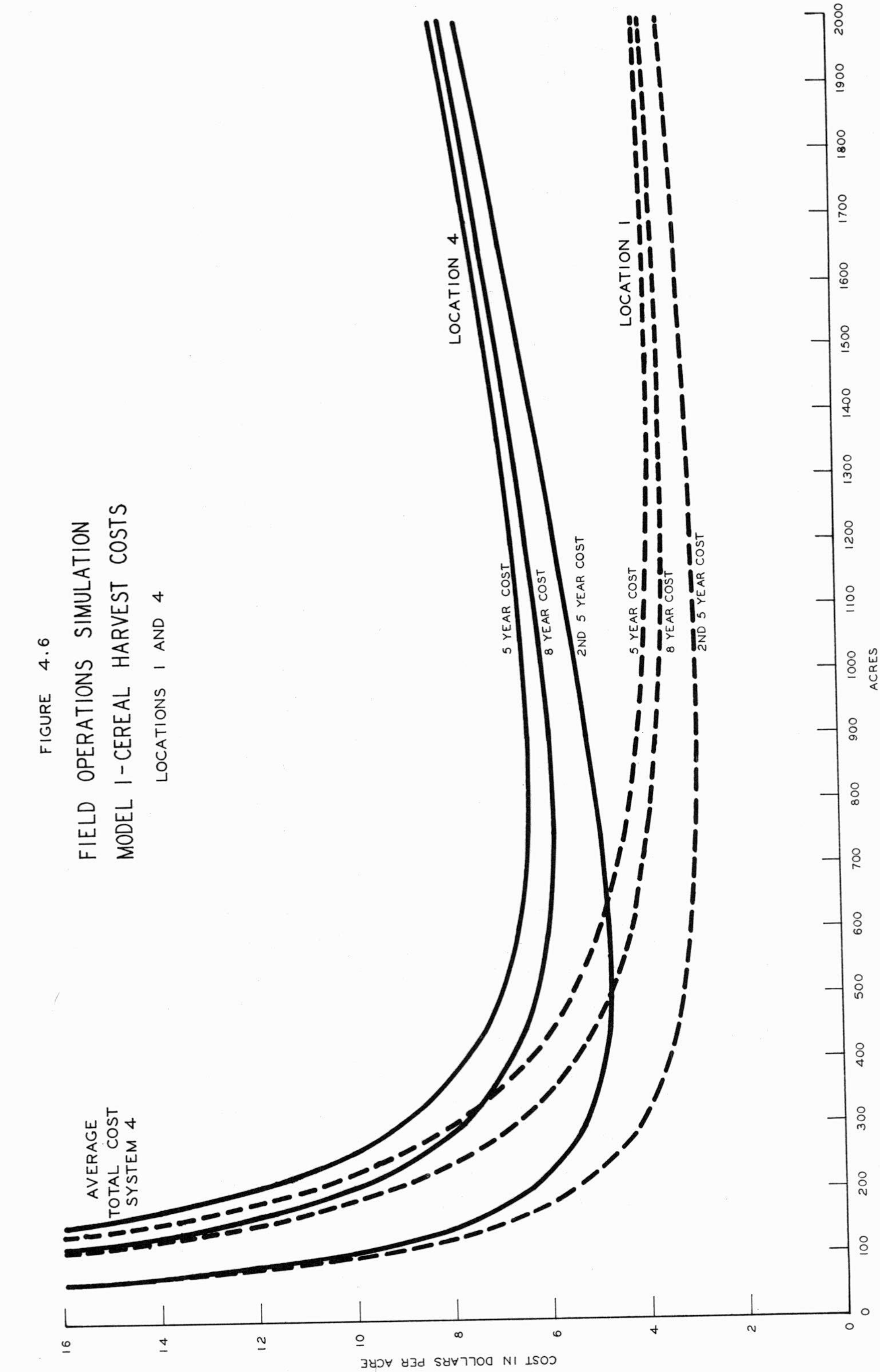


FIGURE 4.6
FIELD OPERATIONS SIMULATION
MODEL I-CEREAL HARVEST COSTS
LOCATIONS 1 AND 4
AVERAGE
TOTAL COST
SYSTEM 4
LOCATION 4
LOCATION 1
5 YEAR COST
8 YEAR COST
2ND 5 YEAR COST
5 YEAR COST
8 YEAR COST
2ND 5 YEAR COST
COST IN DOLLARS PER ACRE
0
2
4
6
8
10
12
14
16
ACRES
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000

The harvest model was also used to assess the effect of employing a used or second-hand machine. For this purpose a machine was assumed to be purchased following a full mechanical overhaul after the end of its fifth year of service at its depreciated value plus 10 per cent. A slightly higher variable cost was assumed to cover higher repair and maintenance charges. The cost curve based on these assumptions is also shown in Figure 4.6. Here it can be seen that the average cost curve is moved downward and towards the origin, giving a much larger reduction in cost at lower acreages than at higher levels of use. It is largely this effect that makes used machines desirable on farms with small crop acreages, and which leads to an effective demand for used equipment.

Location Differences -- As stated in Chapter 2, four locations were considered using Model 1. It was expected that the costs of harvest might be different for all four, but with approximately equal differences between each. The very different results obtained are shown in Figure 4.7.

As the average cost curves for the four locations show, the interacting variables cause a very large difference between Location 4 and the others, but little difference between the other three. Location 1 has the driest climate and the lowest yields, and might therefore be expected to have the lowest costs. However, it seems that this area is subject to irregular storms during the harvest period, and that these cause (in the model, if not in reality) sufficient delays to increase the unit cost of harvesting. That the average cost at Location 3 should be above that for Location 2 is rather more expected, since the rainfall and yield are both higher at Location 3 than at Location 2.

The markedly higher cost at Location 4 is explained by higher yields, hence slower rates of work and higher shelling losses; higher harvest rainfall, thus longer delays and more grade losses; and by the shorter operating hours per day due to the later harvest starting date and moister climate. Because the results showed this major difference between Location 4 and the others, the costs for Locations 1 and 4 only are discussed in the foregoing and following sections.

Cost Variability -- The costs discussed so far have been the mean of those occurring in each of 1,000 trials or "years".

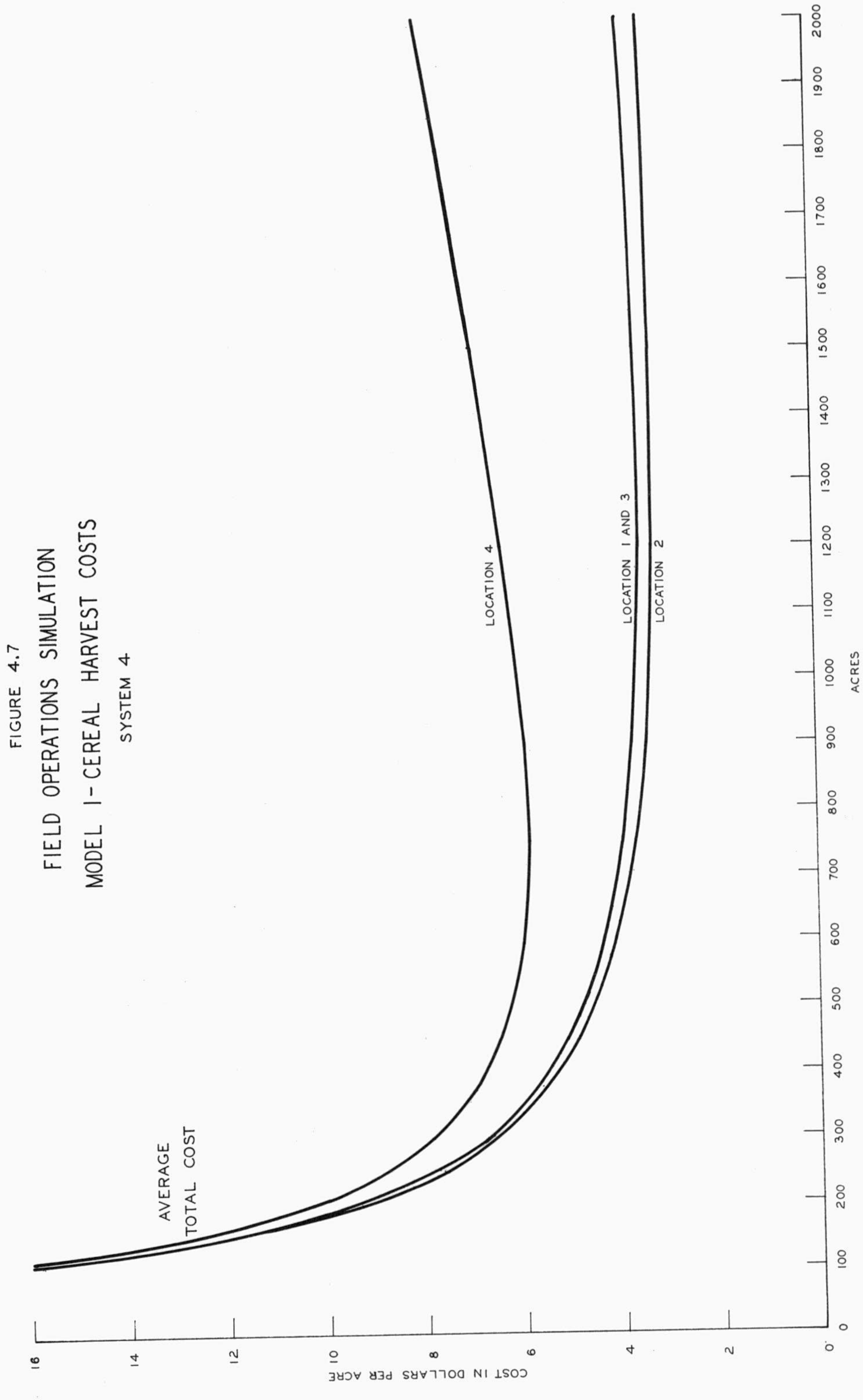


FIGURE 4.7
FIELD OPERATIONS SIMULATION
MODEL I-CEREAL HARVEST COSTS
SYSTEM 4

Because the production variables, particularly weather or those related to weather, change and interact in different combinations from one year to another it is not surprising that the costs incurred will vary. The extent of this variability is shown in Figures 4.8 and 4.9.

As can be seen from the average cost for any system, the degree of variability increases as the capacity of the system is extended. This reflects the nature of the exogenous variables and the fact that their impact is cumulative over any one season. A comparison of Figures 4.8 and 4.9 will verify that the degree of variability also increases for the more northerly locations. Although not shown, it is significant to note that although Location 1 does not have the lowest cost curve, it does have the lowest level of variability. The range of variability of Locations 2 and 3 is in keeping with their position in the sequence.

The shape of the distributions, showing a negative skew in all cases, is attributable to the effect of the fixed cost element in the average cost calculation. The variation can only be upward, since there must always be a minimum average cost equal to the fixed cost plus a minimum variable cost. The lower end of the distribution effectively delineates this level. The extent of the skewness is much greater than shown, though the long tail that has been cut off contains less than 5 per cent of cases.

The level of variability is known to be important in decision-making. Rather than select the minimum cost alternative based on projected long-run experience, a farmer may prefer to choose on the basis of minimum cost variation in anticipation of possible adverse outcomes in the short run. In every case a bigger system will give less cost variation than will the system that is the least cost alternative for the acreage being considered. But the selection of a larger system to avoid the possible incidence of very high costs in some years will necessitate the incurring of somewhat higher costs in all years. The price to be paid varies from place to place, with costs and variability in general both increasing as the harvest moves further north.

The frequency distributions shown in Figures 4.8 and 4.9 are noticeably irregular. This variation is caused by the uneven values that occur in the data for some variables, and by the

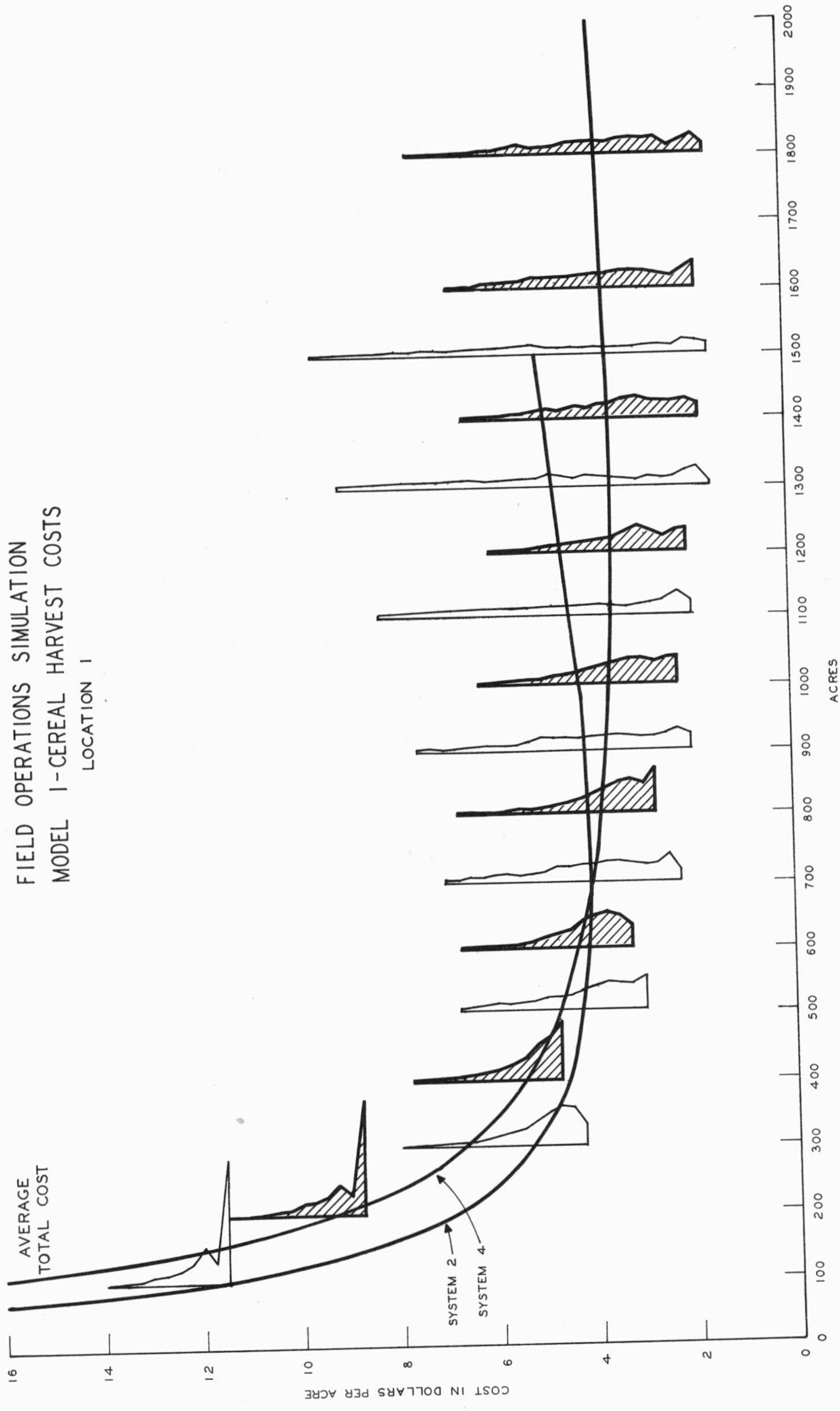


FIGURE 4.8
FIELD OPERATIONS SIMULATION
MODEL I-CEREAL HARVEST COSTS
LOCATION I

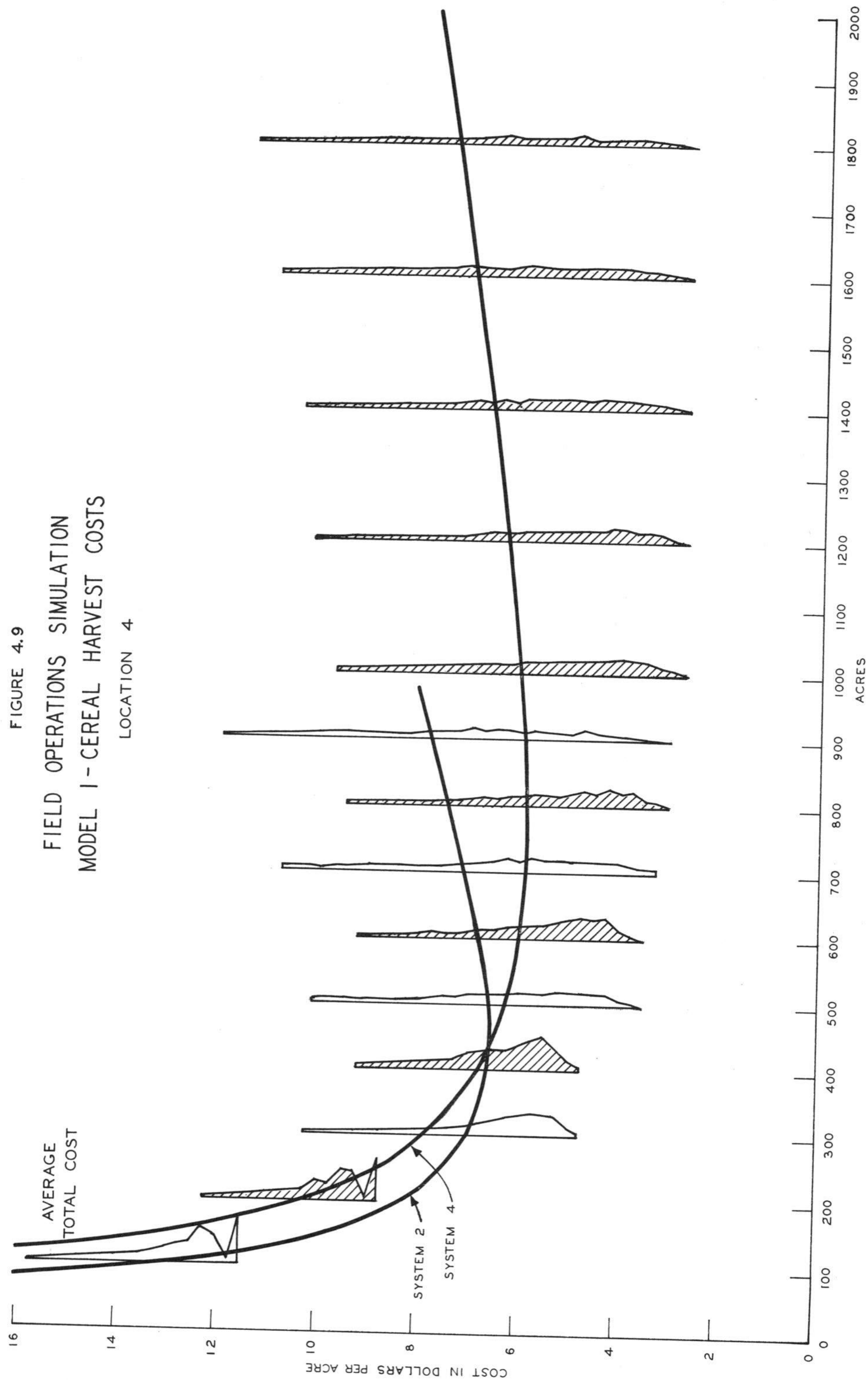


FIGURE 4.9

FIELD OPERATIONS SIMULATION

MODEL I-CEREAL HARVEST COSTS

LOCATION 4

"trip" variables that enter the model at certain stages. These "trip" variables, such as grade loss and the use of custom services, cause sudden jumps in costs which partly account for the irregularity shown.

The effect of such jumps in data and "trip" variables is reflected in the marginal cost too. The variation about the mean marginal cost is much greater than that about the average cost. The standard deviation of the average and marginal costs are similar at very low acreage levels, but that for marginal costs increases rapidly as the acreage is increased. At the point where the two curves intersect the standard deviation of the marginal cost is in most cases about double that for the average cost. This is explained by the numerical relationship between the two cost measures. The marginal cost reflects all of the changes that occur between any given acreage level, and the one before it. The average cost obscures this effect since it is added to all of the previous costs and divided by the given acreage.

Harvest Costs Including Grain-Drying

Combine-Dryer Costs -- The cost estimates obtained from Model 2, which includes grain-drying and its related husbandry adjustments, are shown in Figures 4.10 to 4.15. The costs presented are computed in the same way as those for Model 1, and a comparison is made between those obtained from that model, in order to enable an assessment to be made of the economic advantages of drying.

The basic cost estimates provided by the second simulation model are shown in Figures 4.10 and 4.11, together with the cost curves, with several modified assumptions. Comparison of the curves labeled "All Restraints" and "With Shelling" indicates the cost effect of including a dryer in the system. At Location 1 the dryer results in a higher average cost, particularly in the acreage range over which the machine system without the dryer is the least cost alternative. The system with the dryer becomes lower in cost only at a very large acreage, about 2,000 acres. At Location 4, however, the system with the dryer does provide a lower cost alternative within the least cost range of System 2 without the dryer.

Adjusted Husbandry Assumptions -- A more realistic assessment of the effects of incorporating a grain dryer into the system

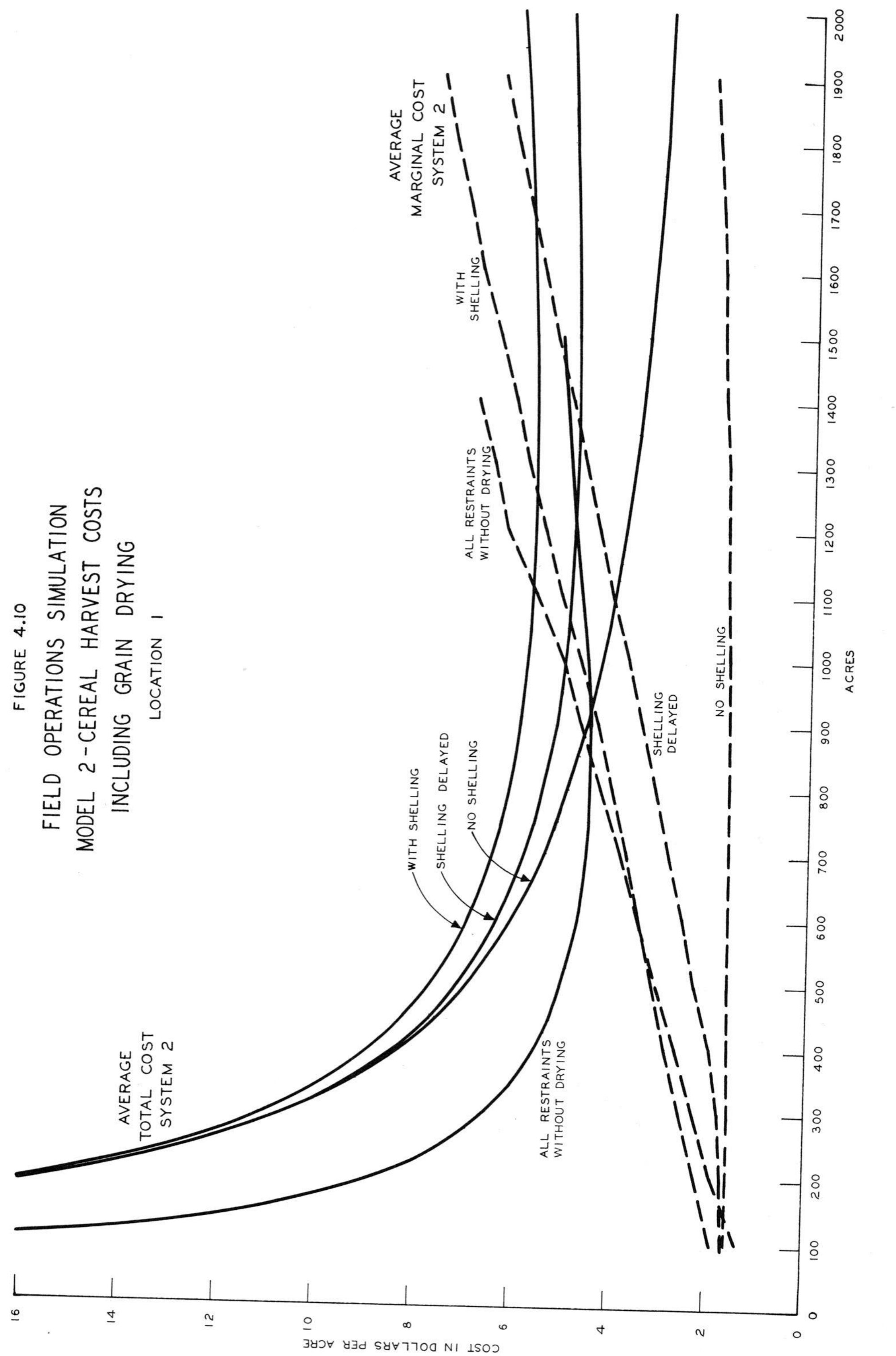


FIGURE 4.10
FIELD OPERATIONS SIMULATION
MODEL 2-CEREAL HARVEST COSTS
INCLUDING GRAIN DRYING
LOCATION I

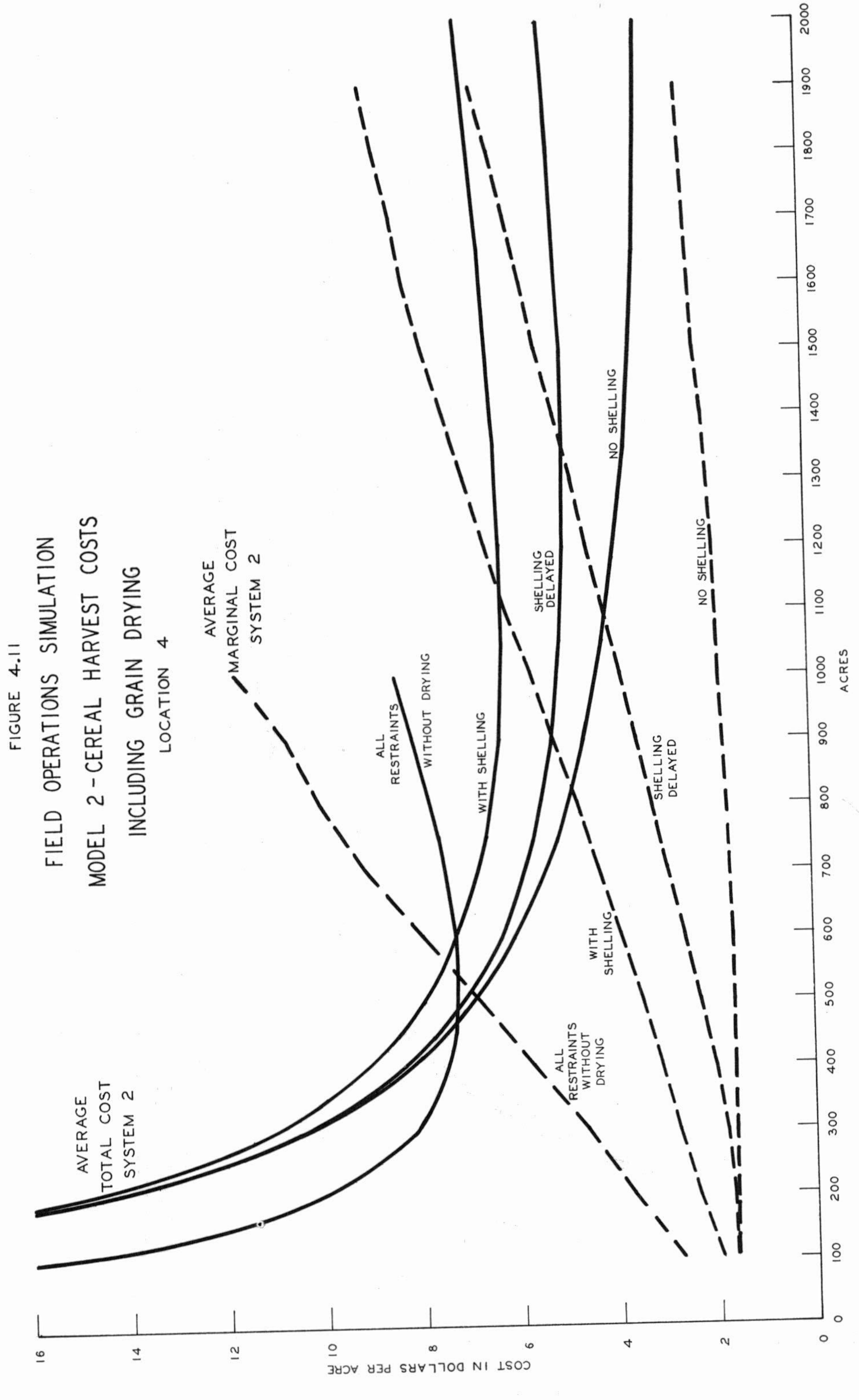


FIGURE 4.11
FIELD OPERATIONS SIMULATION
MODEL 2 - CEREAL HARVEST COSTS
INCLUDING GRAIN DRYING
LOCATION 4

might be obtained by varying the husbandry assumptions to allow harvesting to begin at an earlier stage. This modification depends on acceptance of the work which shows that grain in the ear is mature several days before it reaches "harvest ripeness" -- that is, the grain moisture content at which it can be harvested (8). This means that harvest can begin up to seven days earlier if a dryer is available. This involves swathing at a moisture content as high as 35 per cent of the dry weight of the grain, and combining at about 20 per cent.

Using this assumption, the cost curve labeled "Shelling Delayed" is obtained (so called since the earlier start effectively delays the onset of shelling). On this basis, the "with dryer" system becomes cheaper than the "no dryer" system, at a much lower acreage at Location 1 (about 1,200 acres), though it is still outside the least-cost range for the system in each case. At Location 4 the cost advantage also starts at a significantly lower acreage, though the effect is not so great as for Location 1. For larger acreages, however, the introduction of a dryer at Location 4 reduces costs greatly -- to the extent that the "Shelling Delayed" curves for Location 1 and 2 are almost identical -- a feature which might hold important implications for northern cereal growing areas where large area farms are currently the exception rather than the rule.

For experimental purposes, the model was also run without the shelling loss variable. The resulting cost curve is labeled "No Shelling", and a comparison of this with the other two curves for the "with dryer" system indicates that the use of a dryer with an earlier starting date reduces a large proportion of the total shelling loss. The early start assumption not only provides some operating days without shelling, but, by using the dryer weather earlier in the harvest period, it permits combining with fewer lost (wet) days. The relatively flat marginal cost curve for the "No Shelling" run reflects the fact that shelling loss is the predominant time-cost effect in the model, as it seems to be in reality.

Combine-Dryer Substitution -- Because of the cost reducing effect of a dryer in the harvesting system, the question arises as to whether a dryer may be an effective substitute for either an additional or a larger combine. To examine this question a comparison is made in Figure 4.12 of the average costs for System 2 with a dryer and System 4 without. As can be seen from the diagram, the "with dryer" system does not appear likely to become the cheaper alternative for Location 1. On the other hand, at Location 4 it seems that a dryer might effectively substitute for combine capacity in some systems. The systems compared in Figure 4.12 were based on an annual capital cost of $2,038 for System 4 and of $2,652 for System 2, including the dryer. It is possible, however, that alternative combinations of different sized combines and dryers might provide even greater benefits, on an average cost basis, than the fixed combinations compared in this study.

Cost Variability -- In order to fully assess the cost effect of introducing a grain dryer into the harvesting system, it is necessary to consider the change that occurs in the year-to-year variation in harvest costs. These are shown, in comparison with a "no dryer" system in Figures 4.13 and 4.14.

The effect of employing the grain dryer is to provide a spectacular reduction in the range of variability of costs -- at all acreage levels. While the advantages are most significant at the northern Location 4, the reduction is sufficient to make the use of a dryer worth considering even at Location 1.

Although the risk reduction effect is shown here for System 4 only, the tabular results show that the same advantage is obtained for all six systems. If the simulation is realistic, the potential benefits to cereal growers from using grain dryers seem very considerable indeed.

Tillage and Seeding Costs

Cost Characteristics -- As for the harvesting models, the computed average and marginal costs obtained from Model 3 can be presented as overlapping and intersecting cost curves. The nature of the results obtained are shown in Figures 4.15 to 4.19, and are described below.

The average and marginal cost curves for the five alternative systems, each consisting of a tractor and three appropriate sized implements, are depicted for Locations 1 and 4 in Figures 4.15 and 4.16, respectively. The successive intersections of the average cost curves define a series of minimum cost ranges that is much

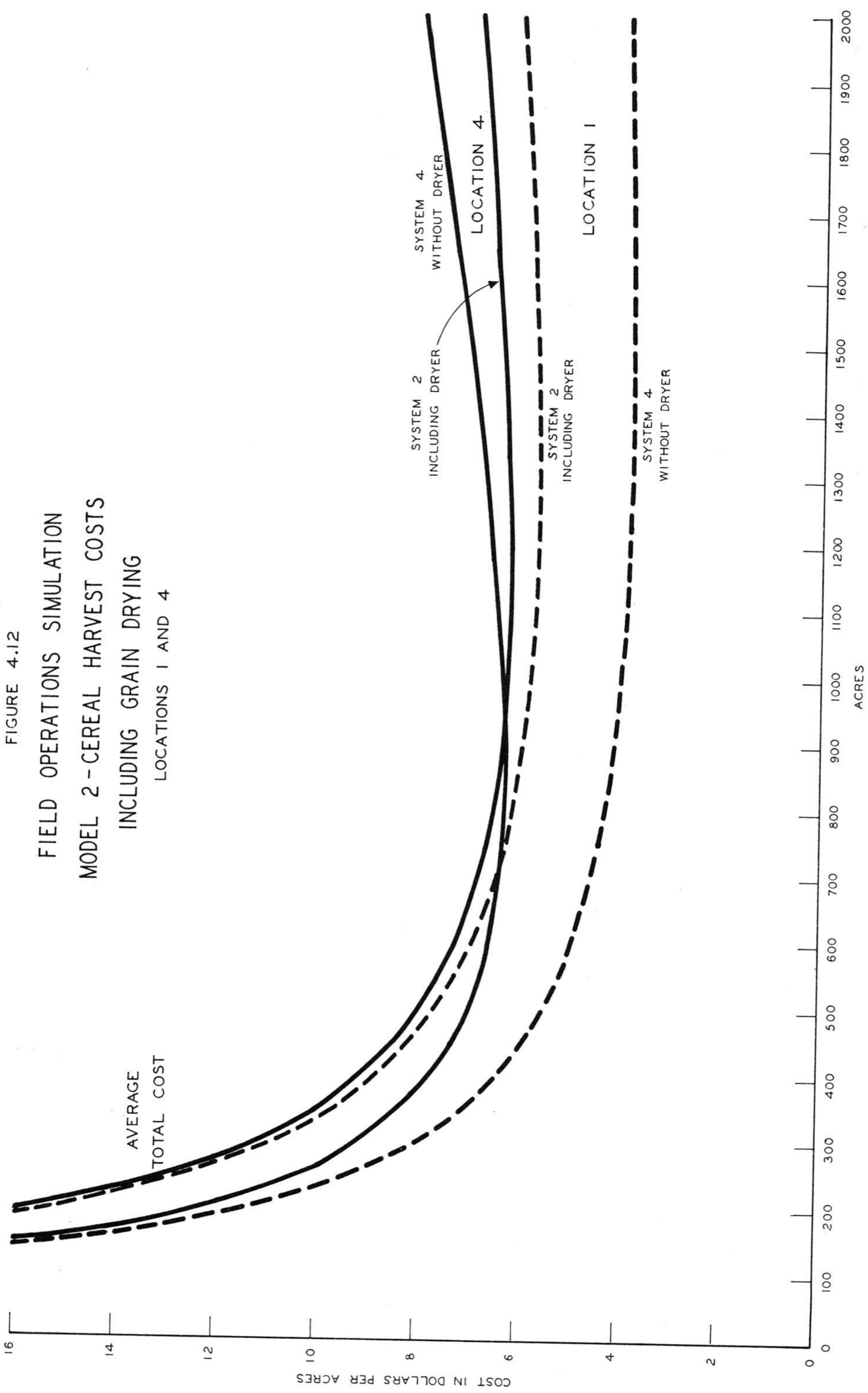


FIGURE 4.12
FIELD OPERATIONS SIMULATION
MODEL 2-CEREAL HARVEST COSTS
INCLUDING GRAIN DRYING
LOCATIONS 1 AND 4

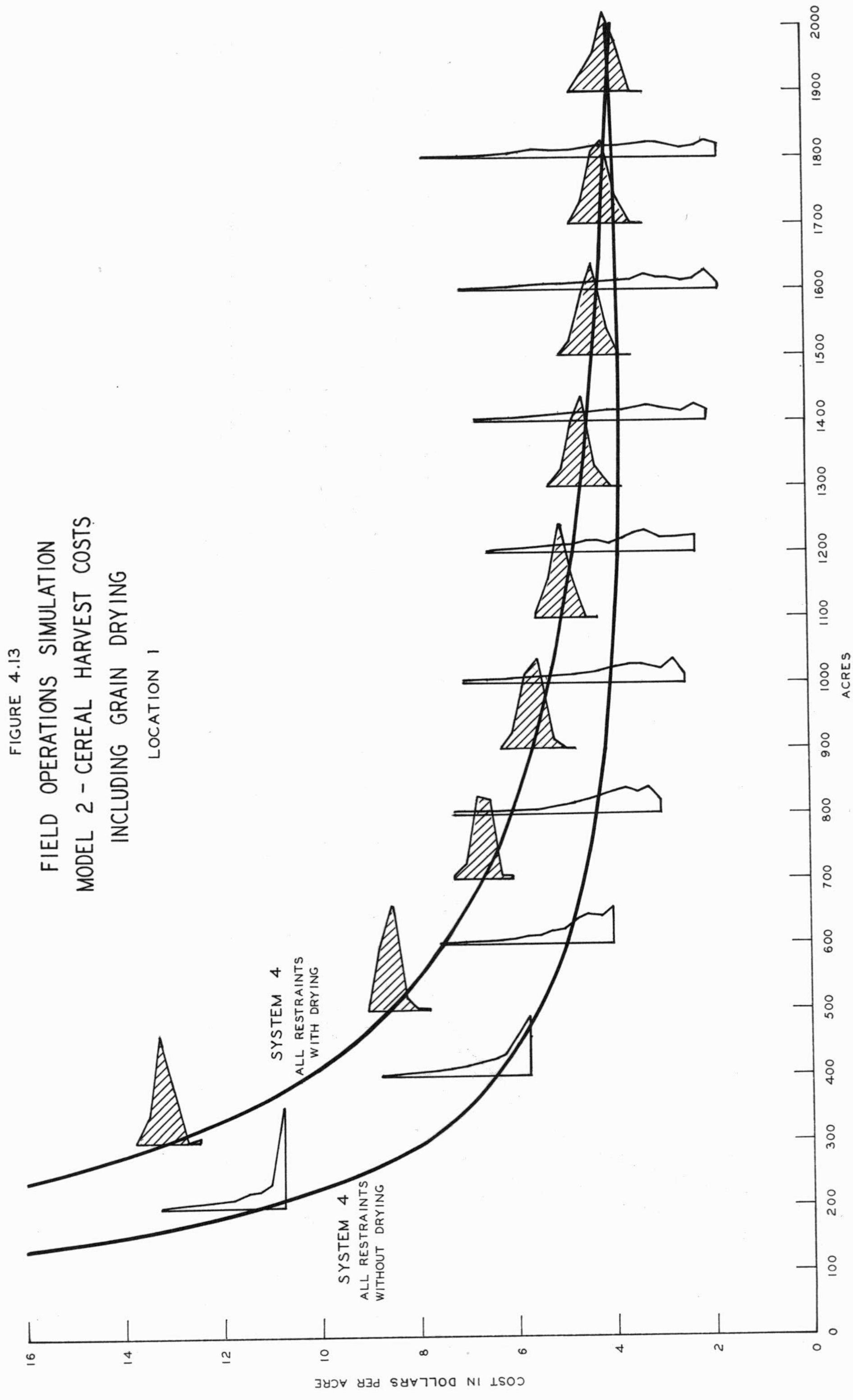


FIGURE 4.13
FIELD OPERATIONS SIMULATION
MODEL 2 - CEREAL HARVEST COSTS
INCLUDING GRAIN DRYING
LOCATION 1

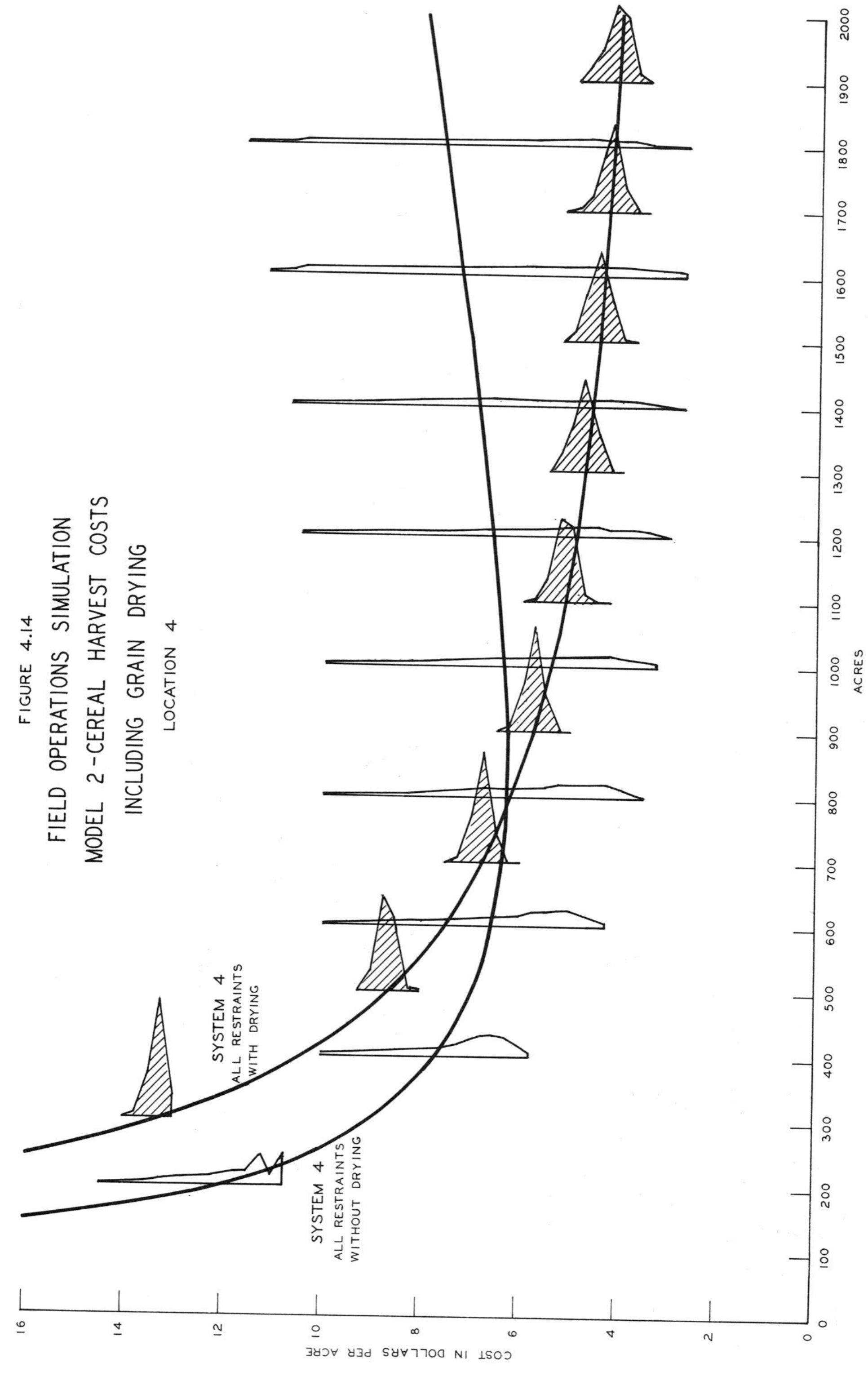


FIGURE 4.14
FIELD OPERATIONS SIMULATION
MODEL 2-CEREAL HARVEST COSTS
INCLUDING GRAIN DRYING
LOCATION 4

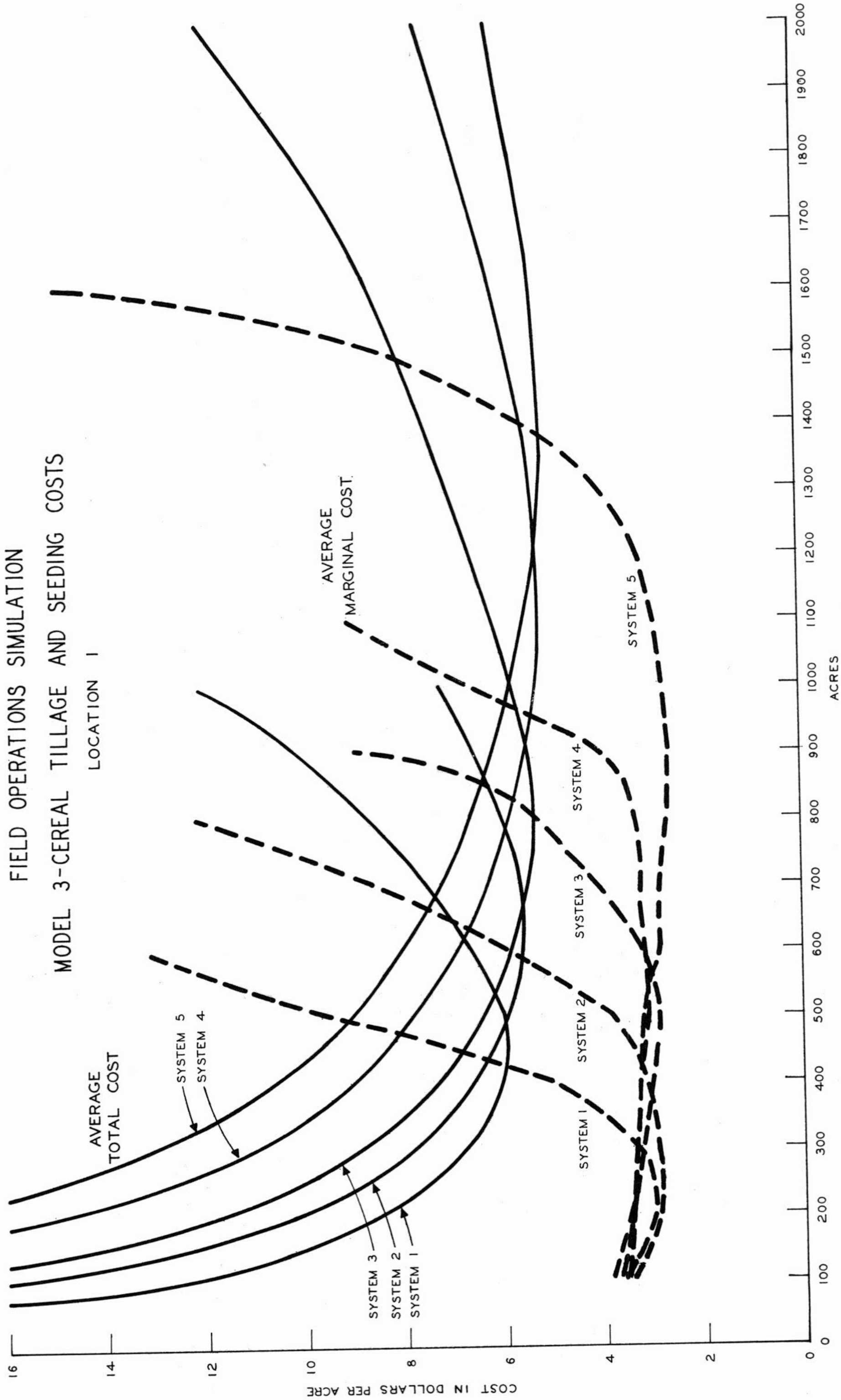


FIGURE 4.15

FIELD OPERATIONS SIMULATION

MODEL 3-CEREAL TILLAGE AND SEEDING COSTS

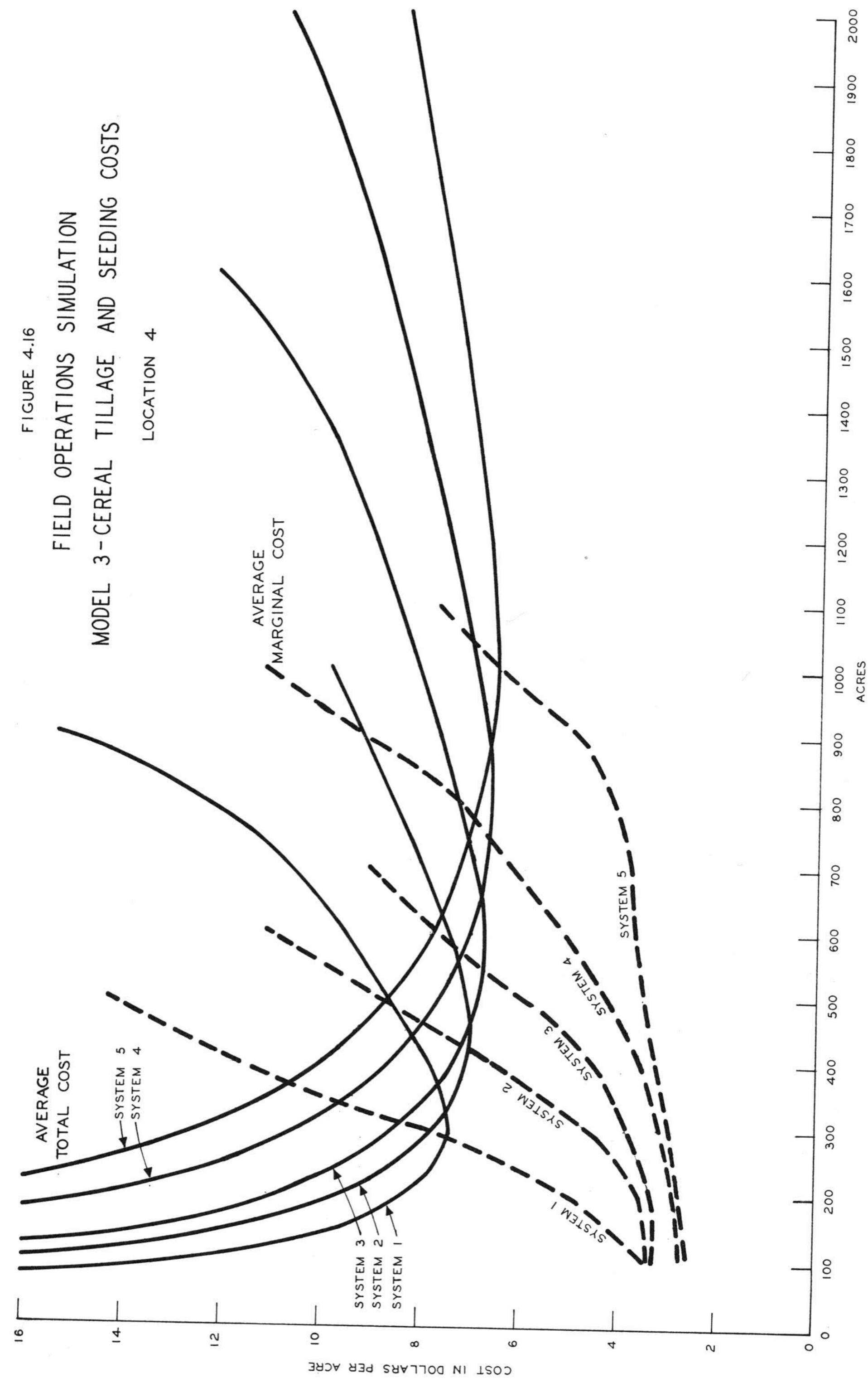
LOCATION 1

FIGURE 4.16

FIELD OPERATIONS SIMULATION

MODEL 3-CEREAL TILLAGE AND SEEDING COSTS

LOCATION 4



more even than that obtained for the harvesting systems. Each system is a least cost alternative for an acreage range of some 200 or more acres. Similarly, the distances between the curves are relatively even, with the exception of a slightly wider jump separating Systems 3 and 4.

The average or unit costs per acre are similar in pattern at both locations considered, but as for the harvest costs, the curves are higher and their upturn steeper at Location 4 than at Location 1. This reflects both the higher yields and the more restrictive constraints on field operations at the more northern location. The five machinery systems each become a least cost alternative over certain acreages at Location 4, but for a lower and narrower acreage range for each system than at Location 1.

The evenness of the average cost curves is partly explained by the fact that the rate of work used was a deterministic one, and that it was proportionately higher for each successive system size. The rate of work is a key variable in all three simulation models used in this study since it is multiplied by such large numbers -- that is, the acreages handled. Since this is so, the use of a single value for a highly irregular variable represents an inadequacy in terms of the reality of the model. This particular limitation applies only to Model 3.

The marginal cost curves cut the average cost curves from below, as is theoretically expected. They are, however, not as smooth as the average cost curves -- in fact, the curves plotted have been smoothed by omitting some intermediate points. The relatively greater variability in marginal costs follows from its relationship to the average costs. In absolute terms the variability is caused by the several "trip variables" that are built into the model. Each time a fixed constraint is used to "trip" the model into introducing another variable, the marginal cost changes abruptly. For instance, if seeding is not completed by a certain date, the model introduces a second shift, doubles the rate of work, and adds on a penalty labour charge. When this is combined with a deterministic rate of work, the jump in costs tends to occur at approximately the same acreage in each trial, and the marginal cost curve is irregular as a result.

The marginal cost curves also intersect with the average cost curves at a very steep angle. This steepness is approximately equal for both locations. Because of this, it might be expected that the flexibility of the systems will be limited, since a slight change in the acreage seeded, using any system, will result in a large increase in total cost. Since these marginal cost curves are much steeper than those described above for harvesting systems, it follows that there is greater flexibility in the harvesting operation than in seeding.

Soil Type Differences -- In the specification of Model 3 specific account is taken of differences in soil type and their effect on tractability. In their earlier work, Rutledge and MacHardy found significant differences in physical operating constraints for "sandy" and "medium-heavy" soils, respectively (37). The effect of this restraint upon operating days, as it influences costs, is shown in Figure 4.17.

The average cost curves show a distinct difference in capacity-cost effects between the two soil types at both locations. They also suggest that the effect of the heavier soil is greater at the northern location where the climate is moister, and the cost of delays in terms of lost yield, greater. These effects demonstrate quite clearly that taking account of climatic factors alone is not sufficient in any attempt to evaluate the field operating capacity of farm machinery -- at least for tillage operations. On the other hand, the effects also demonstrate the potential advantage in taking soil type into account in such assessments.

Cost Variability -- As for Models 1 and 2, the cost curves presented are based on the mean of 1,000 trials at each acreage level. Thus, at any one acreage level, given that the simulation variables are stochastic, there will be a distribution of costs representing the range and frequency of their occurrence. This distribution is shown in Figures 4.18 and 4.19. As for the harvesting models, the range of variation increases as the acreage covered is extended, suggesting an increase in risk as the capacity of a machinery system is extended.

There are, however, two other effects manifest in these graphs which are anomalous. The first is the relatively small range of costs, by comparison with those shown for the harvesting models (see Figures 4.8 and 4.9). The relatively lower variation is perhaps due as much to the use of single values for certain probabilistic variables, such as the machine rates of work, as to the range of variability inherent in the operations.

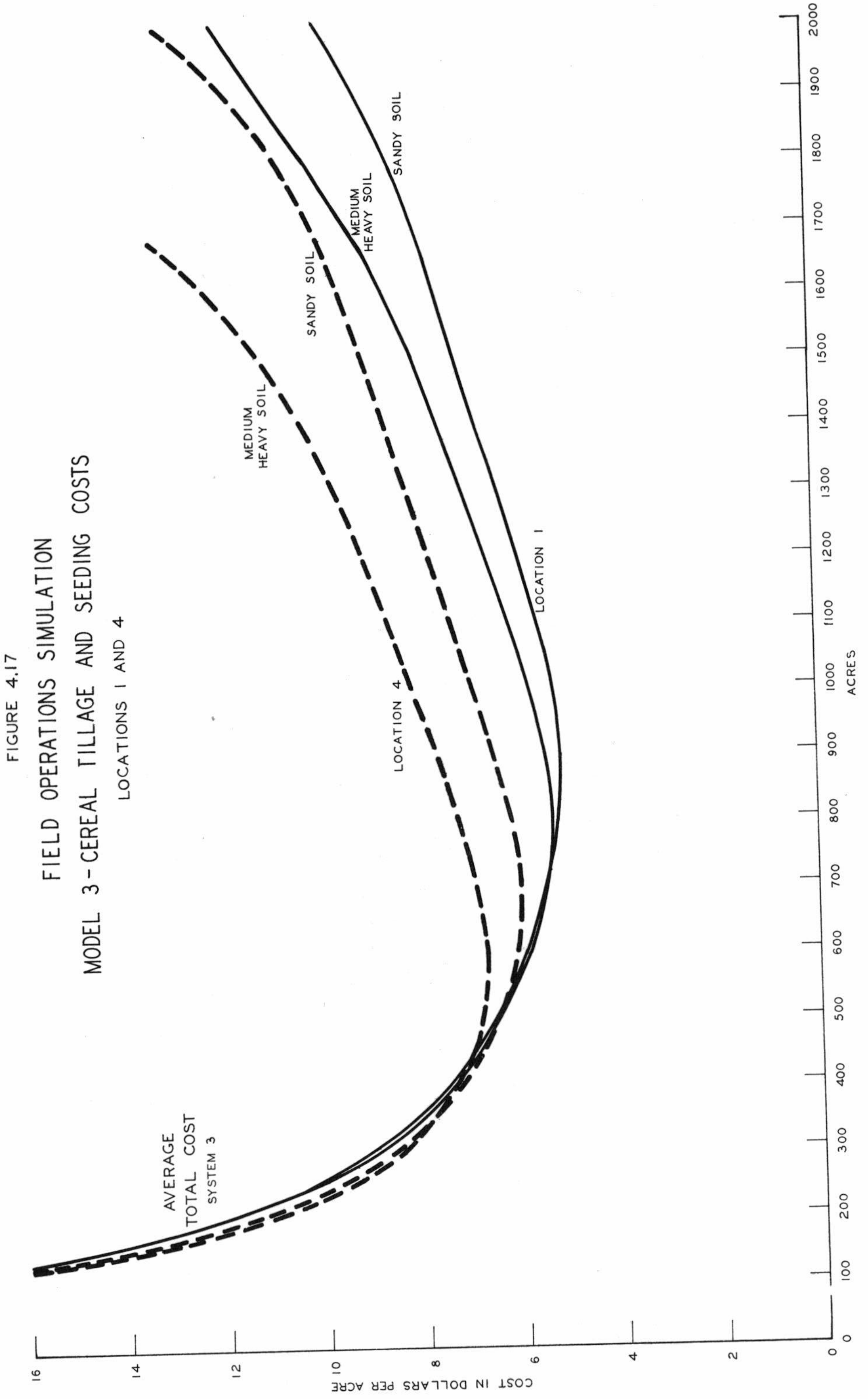


FIGURE 4.17

FIELD OPERATIONS SIMULATION

MODEL 3 - CEREAL TILLAGE AND SEEDING COSTS

LOCATIONS 1 AND 4

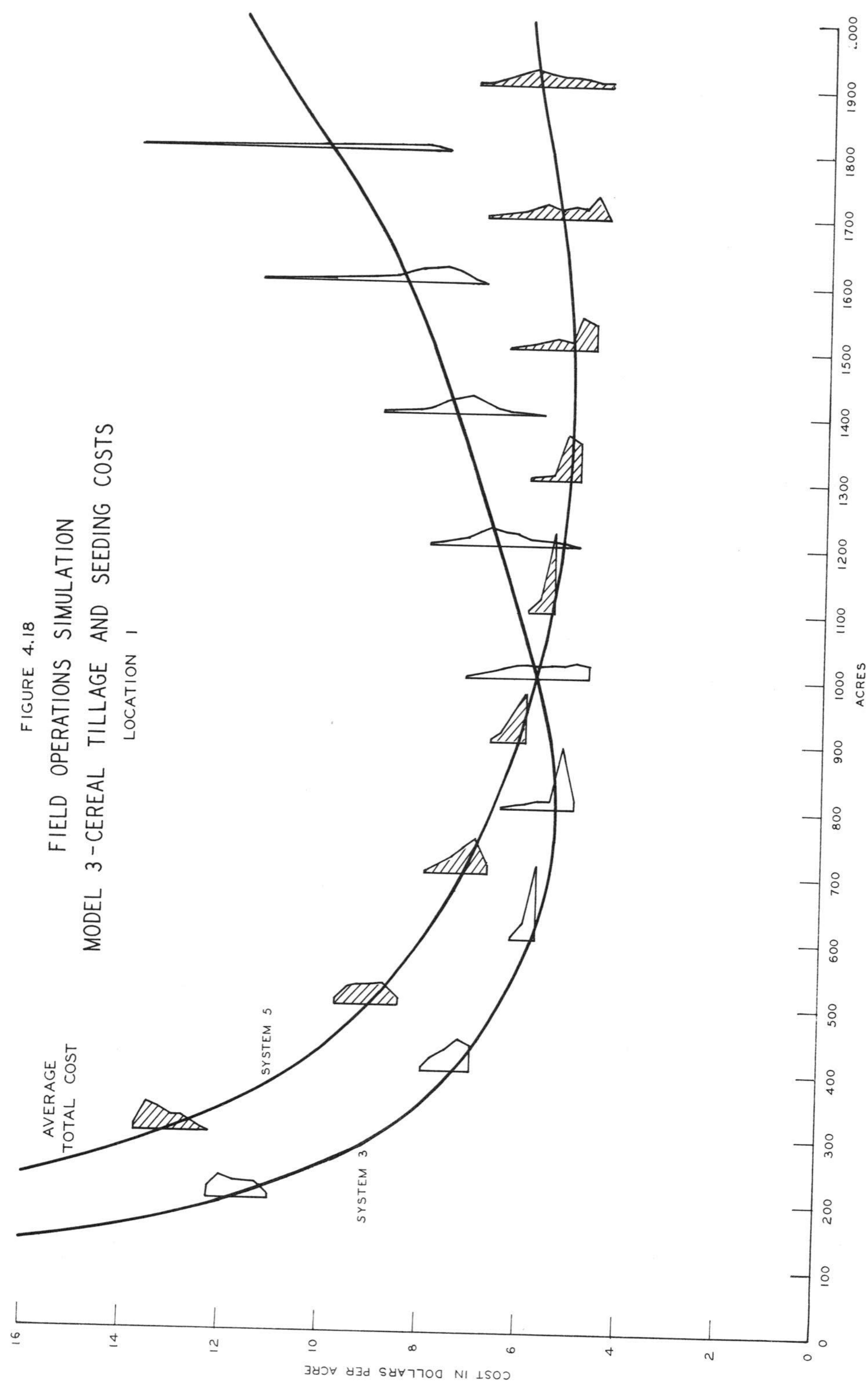


FIGURE 4.18
FIELD OPERATIONS SIMULATION
MODEL 3-CEREAL TILLAGE AND SEEDING COSTS
LOCATION 1

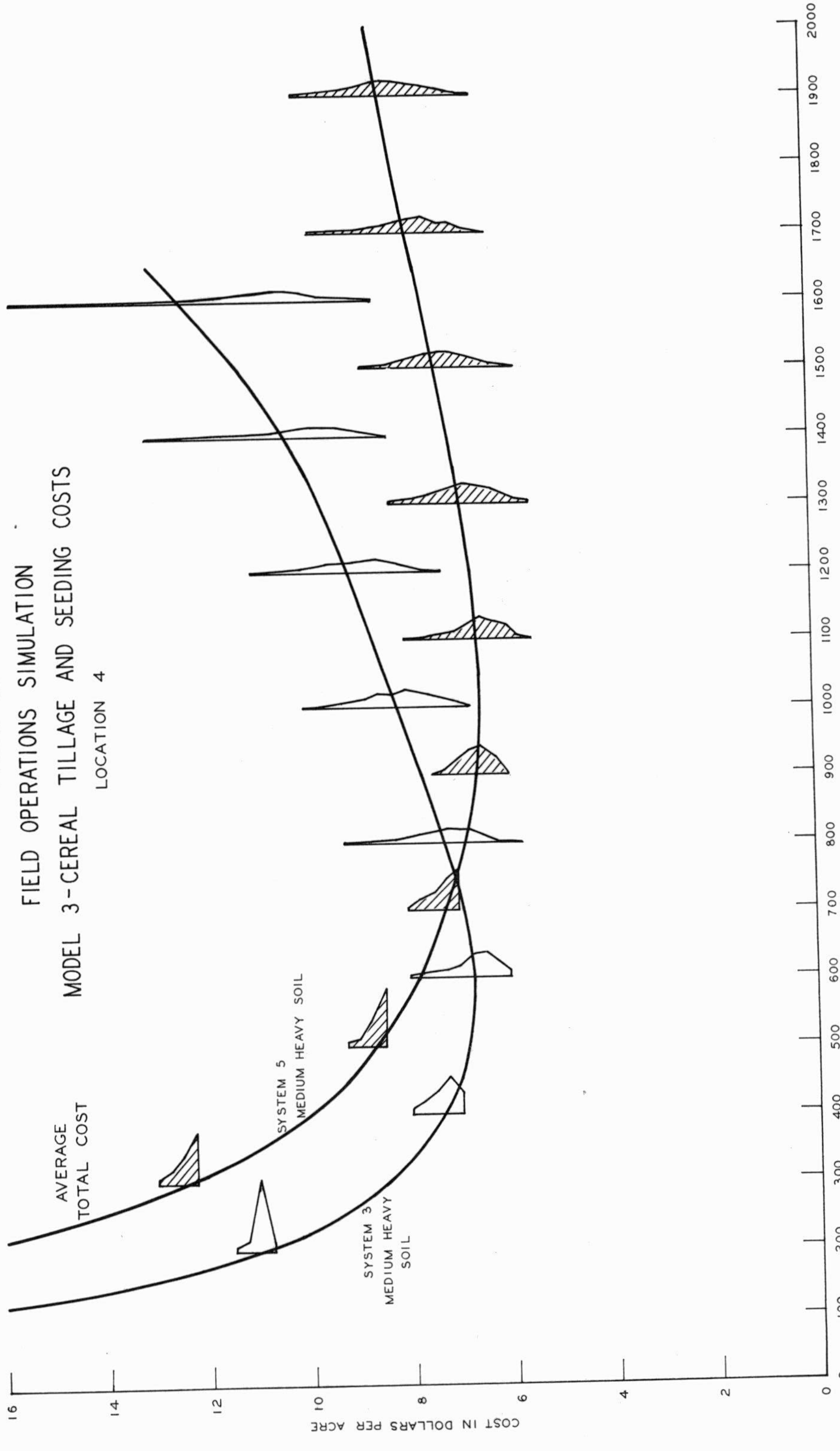


FIGURE 4.19
FIELD OPERATIONS SIMULATION
MODEL 3-CEREAL TILLAGE AND SEEDING COSTS
LOCATION 4

The second is the relatively high level of variation at low acreages, which is reduced as the acreage is extended. This effect is created by the assumption that the same starting date will apply regardless of the acreage to be sown. In practice this is unlikely, as a farmer with a small acreage, whose system will not be stretched, will see no need to start as early as one with a larger acreage, who fears he will not get all of his crop sown within the available time. At higher levels of use, the single starting time assumption will not create the same distortion.

The variability in costs estimated is higher at Location 4 than at Location 1. Again, this reflects the fact that the yields and yield penalties are higher at the northern location, and that the variable constraints -- particularly weather -- are more severe.

This difference in the tautness of the restraints results, too, in the minimum risk system alternative occurring at a lower acreage at Location 4 than at Location 1. Overall, a farmer at Location 4 would, on a minimum cost basis, require a machine system one size larger for his acreage than would a farmer with the same acreage at Location 1. On a minimum risk basis the farmer at Location 4 would need a system two sizes larger than a farmer with the same acreage at Location 1. Thus the differences in costs and in capital stock associated with machinery field operations are significant from one location to another.

Conclusion

Model Validation -- Before making any inferences from the results obtained, using these models, it is necessary to assess their adequacy as a representation of reality. The models are each an abstraction from reality, and have been constructed, using only the main variables relating to the real situation. Since the value of such models depends on the accuracy with which they represent actuality, the validation process begins at the outset of the model-building procedure.

The variables to be included in the models were chosen after many discussions with research station scientists, farm economists, extension personnel, and farmers. Just as the scientist searches for *a priori* postulates that are acceptable, so the model-builder seeks to incorporate those aspects of reality that are intuitively recognized to be significant in the system. Since these variables and their quantification are spelled out in some detail in the foregoing chapters and in the appendices, the reader can decide to what extent they are acceptable to him.

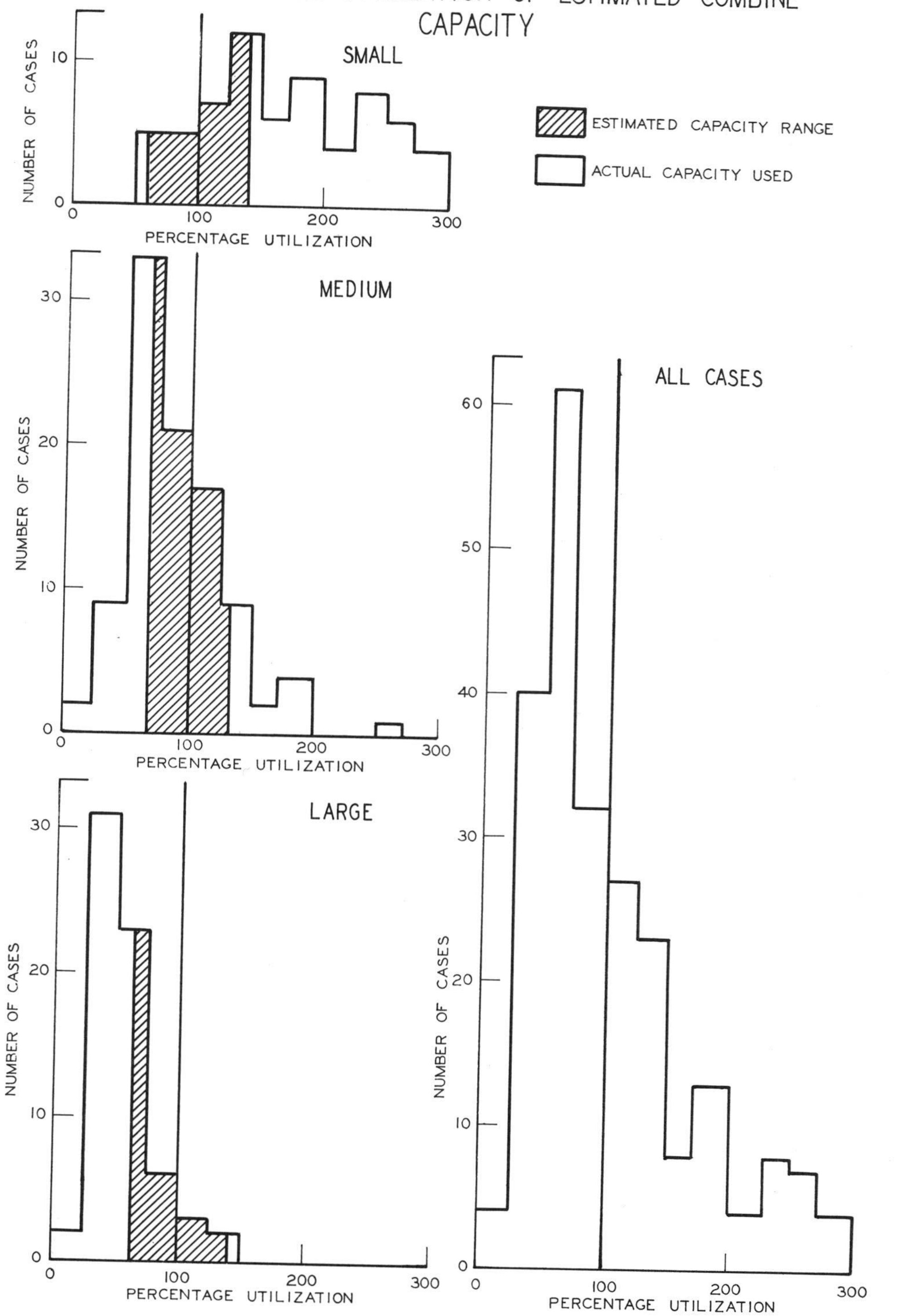
In the subsequent stage of quantifying the variables, every effort was made to check the accuracy of observations contained in the data obtained. Where possible, an attempt was made to identify the relationships involved, by applying statistical tests (see, for instance, Appendix A) and by reference to other studies where such tests have been used. By empiricist scientific standards, the extent of statistical testing is inadequate, but the form in which the variables considered are introduced into the model helps to overcome this inadequacy. The distributions used are regarded as discrete, and are based on unmodified historical data and not on fitted mathematical expressions. Where operating relationships had been little explored, an experimental approach was used in reaching values that fitted reality (see, for example, the weather-lag effects in Appendix C).

Once the models had been built and the first results obtained, an *ex post* validation was made. To do this, information on the size of combine owned, and the acreage of cereals harvested on farms, was obtained from farm survey records. The combines were classified into sizes approximating three of those considered in Model 1. The farms chosen were from several areas, but all in the region of Locations 1, 2 or 3 -- for which costs were very similar. Using the minimum cost ranges from the study, a comparison was made between the optimal acreage range (on a minimum cost basis) and the acreage harvested. The results of this comparison are shown in Figure 4.20.

Certain assumptions made in the course of this comparison may, to some extent, explain some of the observable differences. For instance, the combines in the model were all self-propelled, whereas many in the sample -- particularly in the small category -- were tractor-drawn, and so their operating capacity might be different. Similarly, it is assumed that the acreage harvested in the year of the survey (which covered different farms in five different years) is the acreage for which the machine was purchased. This may not be so, since some may be planning expansion and others cutting back on their cereal acreage. Again, it is assumed that the combines in the survey can be accurately represented by cost estimates relevant to new machines in 1968. In view of these assumptions, the coincidence of the projected range and the actual acreages harvested, as shown in Figure 4.20, might be regarded

FIGURE 4.20

PERCENTAGE UTILIZATION OF ESTIMATED COMBINE CAPACITY



as a happy coincidence. It nevertheless gives some support to the validity of Model 1.

It must be recognized that Model 1 is by far the most adequate of the three. Model 2 is suspect because the grain moisture content data may in fact bear only a passing resemblance to the real parameters in a Canadian summer. On the other hand, if the moisture content is a function of fairly rigid physical relationships involving water movement across a membrane, as seems likely, the general form of the data may have fairly universal relevance.

Of the three models the most inadequate is Model 3. Although the soil water budget and tractability relationships seem well identified and reliable, the enforced use of deterministic rates of work greatly reduces the value of the model.

Accordingly, the results presented above should be regarded with circumspection, and might best be considered as little better than the output from a pilot study. On the other hand, some additional information of a general kind can be obtained from the models, and some comparative evidence is valid if, again, only in general terms. In particular, the results may lead to some useful hypotheses and pave the way for a more thorough analysis. There is also provided some insight into the potential value of such assessments in investment decisions.

Information Provision -- Farmers are confronted with many choices in the process of mechanizing their operations and, as indicated in Chapter 1, not the least significant of these are investment decisions. These are becoming larger (in terms of the magnitude of the sums involved), more frequent, and vastly more complex. Yet the farmer has to make such decisions as the choice of a combine or a tractor, which on the foregoing evidence are none too simple, with little information save the minimum provided by the manufacturer, relating to the production characteristics of each machine, and that gleaned from the experience of neighbours (12).

In spite of the problems confronting them in machinery selection decisions, farmers are often accused of irrational purchasing behaviour concerning their machinery, and particularly of maintaining "excess capacity". On the basis of the evidence presented in Figure 4.20, it could be argued that as many farms are likely to have inadequate capacity as will have excess. What is apparent from the range of acres harvested with each combine size is that farmers have difficulty in selecting the machine system (and hence the level of investment) that best suits their acreage.

It is because this difficulty exists that the type of assessment attempted in this study may be useful. On the basis of the results from the models, providing they are adequate and valid abstractions, a decision might be made according to a range of economic criteria with full allowance for the farmer's subjective attitude to the risk involved, and recognition of the opportunity cost of hedging against it -- or of not hedging, as the case may be.

Consideration of the most obvious decision criteria based on the cost curves demonstrates both the versatility of the analysis, and the effects that lead observers to the conclusion that farmers maintain excess machinery capacity. The first criterion might be *maximum profit.* In terms of the charts above, the average revenue curve is horizontal, and average and marginal revenue are equal. The maximum profit point occurs where the marginal cost curve and the marginal revenue curves intersect. This point will usually be to the right of -- that is, at a higher acreage than -- the minimum cost point. Thus the system selected on maximum profit criteria would be a high risk system.

The next criterion might be *minimum average cost.* The system chosen on this basis should minimize expenditure in the long run, but may also be a high risk alternative in the short run, as the distributions about the average cost curves will show.

Alternatively, a third possible criterion might be *minimum risk*, or some combination of risk and cost minimization. On this basis, a larger and more expensive system will be selected for any given location and acreage than would be chosen on the other criteria. If farmers do use this type of criterion (as seems likely) this may explain some of the supposed "excess capacity" observed on farms.

Although this type of analysis may never provide an exact prescription for any particular situation, it would provide useful guidelines and a great deal of insight into the determinants of operating capacity in each situation, if it were undertaken on an organized basis. Once developed, such models should also be capable of use in assessing new models before they reach the purchaser -- provided field trial data are available for a sufficiently wide range of field conditions. Such an assessment would be as useful to manufacturers in assessing sales potential as to farmers in assessing adequate capacity.

Such an approach may be imperfect, but it may not need to be too perfect to be better than that used at present. On the other hand, the use of this type of assessment will not drive out the intuitive evaluations and experience that practical decision-makers use at present, unless over time this approach proves superior. In this context, such analysis is useful for the additional insight and information it provides, not as an alternative for existing knowledge and information.

Machinery Systems -- Although the results from the models need to be considered with circumspection, they do give rise to several questions about the adequacy of some machines, and help to explain the characteristics of some others. Some of these questions are discussed below:

1. Adequacy of Range -- The existing range of combines appears to provide no reasonable cost alternative for low acreages. Is this spectrum of the market adequately served by second-hand machines? Do small systems which will never be extended by the operating constraints need to be built to the same quality specifications as larger systems where the rate of work may be higher and the working conditions less satisfactory? Given that System 3 in Model 1 did not become a minimum cost alternative for any acreage at any location, (though it may provide a minimum risk alternative), could it be omitted from the range? Given the affinity of the cost relationships of Systems 1 and 2, and 3 and 4, respectively, would two (instead of four) harvesting systems with larger production runs, and possibly lower prices as a result, be feasible? Since combines are built for a widely dispersed market, to what extent do these relationships hold for other areas in North America and elsewhere?

2. Differences in Flexibility -- The differences in the slope of the marginal cost curves suggests greater flexibility for harvesting systems than for tillage systems. Does this help to explain why there are four main alternatives in combine size, but eight or more alternative tractor sizes? Is the major constraint on the acreage of cereals grown per man, or per farm in Canada, the seeding operation, and not, as is widely believed, the harvest operation? Should more research be done, therefore, on seeding equipment or on the agronomic characteristics of crops that are related to time of seeding?

3. Economies of Scale -- The long-run cost curve, defined by the least cost range of the series of system cost curves, does show some economy-of-scale effects. But is this sufficient to justify the claims made for extensive economies associated with mechanization? Given that the best-bet decision policy might be a combination of minimum risk and cost -- suggesting optimal capacity ranges to the left of the least cost ranges -- are there any machinery scale economies at all?

4. Appropriateness of Technology -- Since the mechanization of agriculture has been a piecemeal, rather than a scientific, process -- witness the simple substitution of tractor power for horses -- it is possible that new technology may have great advantages. Given the great benefits from grain-drying suggested by Model 2, why has grain-drying not been more widely used in Canada? Why has most of the development work on the introduction of grain-drying been left to one or two energetic and innovative farmers (17)? Why has the Board of Grain Commissioners not facilitated the delivery of artificially dried grain? Why has there been no extension program to impress on growers the care needed in drying in order to maintain quality? Grain-drying has been a standard practice in many countries with higher fuel costs than Canada, for several decades (34). Are agricultural

> administrators and applied scientists so oriented to developments elsewhere that they have failed to see the relevance of practice in Sweden, Denmark, France or Britain? Even if the benefits from artificial drying are half, or a quarter of the magnitude suggested by this assessment, they are still so significant that it is difficult to understand why they have been overlooked. Is this assessment so inaccurate as to be entirely false?

Whatever the answer to these questions, and in spite of the limited validity of the analysis, the fact that it brings them clearly into focus at least suggests the value of the approach.

APPENDIX A

HARVESTING MACHINERY CHARACTERISTICS

COMBINE COSTS

Combine costs have two components -- fixed or overhead costs, and variable or operating costs. Overhead costs comprise depreciation, interest on capital invested, shelter and insurance charges; operating costs include fuel, maintenance, repairs and labour. These costs have been estimated on the basis of three possible ownership patterns: five-year and eight-year ownerships, when purchased new, and five-year ownership when purchased five years old.

The available combine models have been grouped into four size categories on the basis of comparable physical specifications and price (see Table A.1). The purchase price used in the cost calculation is based on an intermediate price estimate that includes all the necessary options for effective operation, but does not include a diesel engine, or a straw chopper (see Table A.2).

TABLE A.1

COMBINE MODELS BY SIZE

Company	Smallest	Small	Medium	Large
		(model numbers)		
International Harvester	IH 105	IH 303	IH 403	IH 503
Massey-Ferguson	MF 205	MF 300	MF 410	MF 510
J. I. Case	Case 660	Case 960	Case 1060	Case 1660
John Deere	JD 45	JD 55	JD 95	JD 105

TABLE A.2

LIST PRICES, 1968, FOR DIFFERENT SIZES OF COMBINES

(Canadian dollars)

Company	Smallest	Small	Medium	Large
International Harvester	8,166	10,464	12,196	14,460
Massey-Ferguson	8,616	9,816	12,171	14,106
J. I. Case	9,293	10,543	12,163	14,512
John Deere	8,757	10,792	12,834	14,987
Average	8,708	10,404	12,341	14,516
Estimated price to farmer, 80% of list price	6,946	8,323	9,873	11,613

Fixed Costs

Depreciation -- Second-hand values were obtained from the *National Farm Tractor and Implement Blue Book*. Table A.3 gives second-hand combine prices for combines purchased during the first year in which they appear in the table.

TABLE A.3

SECOND-HAND COMBINE VALUES

(Canadian dollars)

Company & Model		1962	1963	1964	1965	1966	1967
International Harvester	203		6,772	4,368	4,242	3,767	3,249
	303	7,437	4,549	4,221	4,412	3,699	3,440
	403	8,948	5,499	5,151	5,197	4,484	4,182
	503	10,547	6,585	6,111	6,172	5,294	5,097
Massey-Ferguson	300		7,683	4,807	4,565	4,490	3,826
	410			9,970	6,412	6,141	5,684
	510			11,731	7,552	7,126	6,619
J. I. Case	600	6,332	3,783	3,329	3,473	2,982	2,846
	800	7,662	4,628	4,029	3,886	3,374	3,221
	1000	8,998	5,391	4,731	4,563	3,951	3,778
John Deere	45			6,885	4,391	4,133	3,770
	55			7,777	5,250	4,690	4,335
	95			9,294	6,295	5,615	5,150
	105			11,471	7,730	6,829	6,319
Allis-Chalmers	E	6,053	4,763	3,498	3,445	3,242	3,093
	A	7,804	3,798	4,145	3,959	3,484	3,223
	C	9,319	5,618	4,935	4,795	4,159	3,978

From the values in Table A.3 it would appear that depreciation is in the order of 35 per cent the first year and 7 to 8 per cent per annum thereafter. To obtain depreciation rates for the harvesting model, depreciation was assumed to be 35 per cent of the estimated price to the farmer the first year and 7.5 per cent per annum thereafter. Depreciation values on this basis are given in Table A.4.

TABLE A.4

ANNUAL DEPRECIATION FOR DIFFERENT SIZES OF COMBINES1/

(Canadian dollars)

	Smallest	Small	Medium	Large
First ownership				
5-year	722	866	1,027	1,208
8-year	538	645	765	900
Second ownership				
5-year	222	266	316	372

1/ See Table A.1.

Interest -- Interest charges were made on the basis of an 8 per cent interest rate on the average value of the machine. Interest charges are given in Table A.5.

TABLE A.5

ANNUAL INTEREST CHARGES FOR DIFFERENT SIZES OF COMBINES1/

	Smallest	Small	Medium	Large
First ownership				
5-year	411	493	584	688
8-year	382	458	543	639
Second ownership				
5-year	222	266	316	372

1/ See Table A.1.

Insurance -- Estimated cost of combine insurance was $1.50 per $100 value for "all risk" protection, based on insurance company quotations. Table A.6 is based on this rate.

TABLE A.6

ANNUAL COST OF INSURANCE FOR DIFFERENT SIZES OF COMBINES1/

(Canadian dollars)

	Smallest	Small	Medium	Large
First ownership				
5-year	77	92	110	129
8-year	72	86	102	120
Second ownership				
5-year	42	50	59	70

1/ See Table A.1.

Shelter -- The cost of shelter is dependent upon machine size rather than value. Given that buildings may be built for approximately $1 per square foot of floor area and may be expected to last 30 years, the cost of shelter is 3.3 cents per square foot of floor area required for storage. On this basis, shelter charges used are $10, $12, $14 and $15 for smallest to large combines, respectively.

TABLE A.7

SUMMARY OF OVERHEAD COSTS FOR DIFFERENT SIZES OF COMBINES1/

(Canadian dollars)

	Smallest	Small	Medium	Large	Extra Large2/
First ownership					
5-year	1,220	1,463	1,735	2,040	2,653
8-year	1,002	1,201	1,424	1,674	
Second ownership					
5-year	496	594	705	829	

1/ See Table A.1.

2/ Estimated cost of a combine 150 per cent as large as the large combine.

Operating Costs

Repair Costs -- Information concerning combine repair costs was obtained from two sources: the Swift Current Research Station and the Agricultural Machinery Administration Test Reports. Tables A.8 and A.9 contain the repair costs obtained from these two sources.

TABLE A.8

COMBINE REPAIR COSTS BASED ON AGRICULTURAL MACHINERY ADMINISTRATION DATA

Combine Record Reference	Hours Used	Repair Cost (dollars)	Cost/ Hour
1	286.00	92.23	0.32
2	307.00	480.20	1.51
3	324.50	145.37	0.22
4	347.00	98.77	0.28
5	348.75	431.00	1.24
6	363.00	107.07	0.34

TABLE A.9

COMBINE REPAIR COSTS BASED ON SWIFT CURRENT RESEARCH STATION DATA

Combine Record Reference	Hours Used	Repair Cost (Canadian dollars)	Cost/ Hour
1	167.3	131.90	0.79
2	217.3	102.47	0.47
3	298.0	569.21	1.91
4	348.0	420.02	1.22
5	711.0	148.60	0.21
6	737.0	404.69	0.55
7	752.0	238.14	0.32
8	754.0	379.61	0.50
9	934.0	627.41	0.67
10	1,012.0	269.14	0.27
11	1,171.0	708.53	0.60
12	1,329.0	670.54	0.50
13	1,344.0	548.70	0.41

After plotting this information on a graph it was decided to assume repair costs of 50 cents per hour for the five-year ownership, 75 cents per hour for the eight-year ownership, and $1 per hour for the second five-year ownership. Since repair costs are on an hourly basis, the repair cost per acre depends upon machine rates of work, which in this case are assumed to average 3.5, 4.5, 5.5 and 6.5 acres per hour respectively. Table A.10 indicates the repair costs per acre used in the model.

TABLE A.10

REPAIR COSTS PER ACRE FOR DIFFERENT SIZES OF COMBINES1/

(Canadian dollars)

	Small	Medium	Large	Extra Large
First ownership				
5-year	0.143	0.111	0.091	0.077
8-year	0.214	0.167	0.136	0.125
Second ownership				
5-year	0.286	0.222	0.182	0.154

1/ See Table A.1.

Fuel Cost -- Fuel consumption data were obtained from two sources: The Agricultural Machinery Administration (AMA) Test Reports (3) and the National Institute of Agricultural Engineering (NIAE) Test Reports (33). The data obtained have been included in Table A.11.

Larsen and Bowers (25) report that diesel tractors burn 73 per cent as much fuel as gasoline tractors. If this relationship is used to convert NIAE figures to gasoline, fuel consumption is approximately 1.1 gallon per acre, which is about the same as the values obtained by the AMA. If gasoline costs 21.3 cents per gallon, fuel costs are in the order of 23.5 cents per acre -- a value that was assumed, regardless of combine size.

TABLE A.11

COMBINE FUEL CONSUMPTION

Model	Brake Horsepower	Separating Area (sq. in.)	Fuel per Hour (gal.)	Fuel per Acre (gal.)
National Institute of Agricultural Engineering (Diesel Fuel)				
Massey-Ferguson 500-7	94	5,979	2.1	0.8
Ransomes 902	62.5	5,713	1.0	
Claas 106	50	5,507	1.6	
Claas Giant Matador	87	7,229	2.4	0.8
Bamford Claeys	80	6,480	2.2	0.8
Agricultural Machinery Administration (Gasoline)				
International Harvester 403		6,538	3.6	1.0
Massey-Ferguson 410		6,240	3.5	1.2
Cockshutt 431		5,510	3.4	0.74

Maintenance -- Maintenance expenses include the cost of grease and oil. Most companies recommended an oil change every 100 hours -- with a new filter every 200 hours. The cost of bulk oil is approximately $1.60 per gallon. A filter costs in the neighbourhood of $2. An oil change requires four quarts of oil, and an additional quart may be required between oil changes. Hence oil and filter costs are approximately $6 per 200 hours or 3 cents per hour.

Grease purchased in bulk costs 28.5 cents per pound (Alberta). Grease purchased in cartridges costs 33.6 cents per cartridge (Ontario). Since cartridges are cleaner and easier to handle, they are often preferred. One cartridge is required about every three days; hence grease costs approximately 1 cent per hour.

Maintenance costs are thus 4 cents per hour. On an acreage basis they are .011, .009, .007 and .006 cents per acre, respectively.

Labour -- Labour costs have been included at a flat rate of $1.50 per hour. Hence labour costs per acre depend on machine rates of work and are 42.9, 33.3, 27.3 and 23.1 cents per acre, respectively.

TABLE A.12

SUMMARY OF OPERATING COSTS PER ACRE FOR DIFFERENT SIZES OF COMBINES1/

(Canadian dollars)

	Smallest	Small	Medium	Large	Extra Large2/
First ownership					
5-year	0.82	0.69	0.61	0.55	
8-year	0.89	0.74	0.65	0.60	0.45
Second ownership					
5-year	0.96	0.80	0.70	0.63	

1/ See Table A.1.

2/ Estimated cost of a combine 150 per cent as large as the large combine.

Custom Rates -- A charge for custom combining was estimated on the basis of the operating costs likely to be incurred. Variable costs per acre have been estimated, based on a rate of work of 3.5, 4.5, 5.5 and 6.5 acres per hour for smallest, small, medium and large combines, respectively. They are as follows:

TABLE A.13

OPERATING COSTS PER ACRE FOR DIFFERENT SIZES OF COMBINES1/ ON A FIVE-YEAR BASIS

(Canadian dollars)

	Smallest	Small	Medium	Large
Fuel	0.235	0.235	0.235	0.235
Grease and oil	0.011	0.09	0.007	0.006
Repairs (50¢/hr.)	0.143	0.111	0.091	0.077
Labour ($1.50/hr.)	0.429	0.333	0.273	0.231
	0.82	0.69	0.61	0.55

1/ See Table A.1.

The inclusion of overhead costs raises these values considerably. Based on five-year ownership and 200 hours' annual operation, overhead costs per acre are as given below:

TABLE A.14

OVERHEAD COSTS PER ACRE FOR DIFFERENT SIZES OF COMBINES1/ ON A FIVE-YEAR BASIS

(Canadian dollars)

	Smallest	Small	Medium	Large
Depreciation	1.03	0.96	0.93	0.93
Interest	0.59	0.55	0.53	0.53
Insurance	0.11	0.10	0.10	0.10
Shelter	0.01	0.01	0.01	0.01
	1.74	1.62	1.57	1.57

1/ See Table A.1.

TABLE A.15

ESTIMATED COST OF CUSTOM OPERATION OF DIFFERENT SIZES OF COMBINES1/ ON A FIVE-YEAR BASIS

(Canadian dollars)

	Smallest	Small	Medium	Large
Cost per acre	2.56	2.31	2.18	2.12
Cost per hour	9.20	10.60	12.20	14.00

1/ See Table A.1.

COMBINE OPERATING CHARACTERISTICS

Rates of Work

Two alternative methods were used to estimate combine rates of work. The first method was based on observations supplied by the Agricultural Machinery Administration Test Reports; the second was based on an equation by MacHardy (28).

TABLE A.16

RATES OF WORK FOR DIFFERENT SIZES OF COMBINES1/ BASED ON AGRICULTURAL MACHINERY ADMINISTRATION DATA

Yield (bushels per acre)	Smallest	Small (acres per hour)	Medium
0-10	7.0		8.7
10-15	8.2		8.0
15-20		5.2	6.4
20-25	9.3	4.2	6.4
25-30	5.9	3.4	6.1
30-35	4.8	2.8	6.0
35-40	5.8	2.7	4.6
40-45	5.1	1.5	4.2
45-50	2.9		4.3

1/ See Table A.1.

Analyzing the AMA data one step further, a regression equation was developed to express the relationship between the rate of work, R, in acres per hour, and the yield, X, in bushels per acre. The medium size combine group had sufficient observations to permit a reliable analysis. The regression equation obtained is:

$$R = 9.54 - 0.12X$$

The correlation coefficient for this data was r = 0.80 with a standard error of estimate $S^2y.x = 0.73$ acres per hour. The estimated rates of work based on this equation are given in Table A.17.

TABLE A.17

RATES OF WORK FOR MEDIUM SIZED COMBINES1/ BASED ON REGRESSION EQUATION

Yield (bushels per acre)	Estimated Rate of Work (acres per hour)
5	8.9
10	8.3
15	7.7
20	7.1
25	6.5
30	5.9
35	5.3
40	4.7
45	4.1
50	3.5

1/ See Table A.1.

The alternative method used in estimating combine capacity was MacHardy's formula, which is as follows:

$$R = 3\left[\left(\frac{W}{192}\right) + \left(\frac{B^{3/2} \times L}{38,600}\right) + \left(\frac{S}{7,400}\right)\right]$$

where

R = rate of work, tons per hour

W = cylinder width in inches

B = body width in inches

L = straw walker length in inches

S = combined chaffer and sieve area in square inches

TABLE A.18

RATES OF WORK FOR DIFFERENT SIZES OF COMBINES1/ BASED ON MACHARDY'S FORMULA

Yield (bushels per acre)	Smallest	Small	Medium2/		Large
	(acres per hour)				
10	10.4	11.9	16.8	(8.3)	24.3
15	6.9	7.9	11.2	(7.7)	16.2
20	5.2	5.9	8.4	(7.1)	12.1
25	4.2	4.8	6.7	(6.5)	9.7
30	3.5	4.0	5.6	(5.9)	8.1
35	3.0	3.4	4.8	(5.3)	6.9
40	2.6	3.0	4.2	(4.7)	6.1
45	2.3	2.6	3.7	(4.1)	5.4
50	2.1	2.4	3.4	(3.5)	4.9

1/ See Table A.1.

2/ Numerals in brackets are the regression equation estimates for the same combine size.

The rates of work used in the simulation models are shown in Table A.19. The rates for the medium combine (System 3) were those derived from the regression equation. Those used for the large (System 4) and extra large (System 7) combines (where no field data were available) were the values estimated by MacHardy's formula, except for those in the 10- to 20-bushel range which were adjusted downwards. The rates of work used for the smallest (System 1) and small (System 2) combines were determined by adjusting the estimates obtained by MacHardy's formula in relation to the difference between those so calculated for the medium combine and the regression estimates for the same machine.

TABLE A.19

DISTRIBUTION OF RATES OF WORK FOR DIFFERENT SIZED COMBINES1/ USED IN MODELS 1 AND 2

Yield (bushels per acre)	Smallest	Small	Medium (acres per hour)	Large	Extra Large
10	5.2	6.0	8.3	12.1	19.4
15	4.9	5.6	7.7	11.5	18.4
20	4.5	5.2	7.1	10.1	16.2
25	4.2	4.8	6.5	9.7	15.5
30	3.9	4.4	5.9	8.1	12.9
35	3.6	4.1	5.3	6.9	11.0
40	3.2	3.7	4.7	6.1	9.8
45	2.9	3.3	4.1	5.4	8.6
50	2.1	2.4	3.5	4.9	7.8

1/ See Table A.1.

Operating Time Lost

The inter-year variation in combine performance is assumed to be taken into account in the yield-related rates of work. Within-year variation was similarly estimated on the basis of AMA data. The measurements used were mechanically recorded using service recorders whose charts showed the exact time during which the machine was in motion. These permitted an exact measurement of the amount of time for which the combine was not operating during the working period. Using the field diary, it was possible to isolate the weather-related lost time, so that the data in Table A.20 relates to expected and unexpected mechanically determined stoppages.

TABLE A.20

CUMULATIVE DISTRIBUTION OF OPERATING TIME LOST

Operating Time Worked %	Frequency of Observation	Cumulative Frequency	Operating Time Worked %	Frequency of Observation	Cumulative Frequency
		Mean = 73 per cent			
16	2	0.009	69	4	0.356
19	1	0.013	70	6	0.382
23	1	0.018	71	7	0.413
27	1	0.022	72	6	0.440
29	2	0.031	73	8	0.476
30	1	0.036	74	7	0.507
31	1	0.040	75	4	0.524
35	1	0.044	76	5	0.547
42	1	0.049	77	3	0.560
43	3	0.062	78	13	0.618
44	1	0.067	79	4	0.636
46	1	0.071	80	5	0.658
47	1	0.076	81	3	0.671
48	2	0.084	82	8	0.707
50	3	0.098	83	10	0.751
51	1	0.102	84	5	0.773
52	2	0.111	85	7	0.804
53	1	0.116	86	7	0.836
54	3	0.129	87	2	0.844
55	3	0.142	88	3	0.858
56	2	0.151	89	2	0.867
57	1	0.156	90	3	0.880
58	2	0.164	91	3	0.893
60	1	0.169	92	5	0.916
61	3	0.182	93	4	0.933
62	4	0.200	94	1	0.938
63	4	0.218	96	3	0.951
64	3	0.231	97	3	0.964
65	7	0.262	98	1	0.969
66	1	0.267	100	7	1.000
67	9	0.307			
68	7	0.338		225	

APPENDIX B

BIOLOGICAL TOLERANCES IN CEREAL-HARVESTING

Harvest Starting Dates and Cereal-Harvest Yields

The data used in the cereal-harvest simulation for the two variables -- *harvest starting dates*, and *cereal-harvest yields* -- were obtained from the records of the Economics and Statistics Branch of the Saskatchewan Department of Agriculture. For the purpose of the study, the harvest was considered to be all wheat. A summary of the data used is presented in Tables B.1 and B.2.

Shelling Losses in Wheat

In the normal sequence of events, once wheat is ripe the kernels start falling out of the head. This is necessary for species reproduction, but for agronomic purposes it represents an additional cost. The actual losses fall into two main groups, natural and mechanical, but in this case it is assumed that mechanical losses are unavoidable (6).

Work done in Sweden (14) indicates that the rate of shelling increases with time after ripeness. In order to place a value on shelling loss, the recorded loss of two Swedish varieties (Ring and Svenno), in the middle of the spectrum of varieties assessed, were averaged. These figures were then extrapolated in a straight line to obtain values for the last three-week period. That losses of this order occur in Saskatchewan is supported by observations at both Swift Current and Melfort Research Stations.[1/] The daily shelling loss used in the model is given in Table B.3 as a percentage of yield.

1/ Private communication with research staff.

TABLE B.1

FREQUENCY DISTRIBUTION OF HARVEST STARTING DATES IN SASKATCHEWAN, 1941-65

	Swift Current		Outlook-Saskatoon		Melfort	
	Frequency	Cumulative Frequency	Frequency	Cumulative Frequency	Frequency	Cumulative Frequency
August 9	1	.04				
August 10						
August 11			1	.04		
August 12						
August 13						
August 14	1	.08				
August 15	2	.16				
August 16	1	.20				
August 17	2	.28				
August 18			1	.08		
August 19			2	.16	1	.04
August 20	3	.40	2	.24	1	.08
August 21	1	.44	2	.32	1	.12
August 22			2	.40		
August 23						
August 24	2	.52	1	.44		
August 25			1	.48		
August 26			4	.64	1	.16
August 27	3	.64	2	.72		
August 28	2	.72	1	.76		
August 29			1	.80		
August 30	2	.80			4	.32
August 31			1	.84	1	.36

TABLE B.1 *(Concluded)*

September 1	2	.88			1	.40
September 2	1	.92			1	.44
September 3	1	.96			2	.52
September 4			1	.88	2	.60
September 5	1	1.0			1	.64
September 6					1	.68
September 7					2	.76
September 8			1	.92	1	.80
September 9						
September 10			2	1.0	1	.84
September 11					1	.88
September 12					1	.92
September 13						
September 14						
September 15					1	.96
September 16						
September 17						
September 18						
September 19						
September 20						
September 21						
September 22						
September 23						
September 24					1	1.0

TABLE B.2

SASKATCHEWAN ANNUAL AVERAGE WHEAT YIELDS, 1938-67

	Swift Current	Outlook	Saskatoon	Melfort
		(bushels per acre)		
1938	6.5	6	6	16
1939	19	19	23	35
1940	10	8	16	29
1941	1	3	7	17
1942	26	25	23	32
1943	8	12	9	26
1944	22	20	24	28
1945	6	8	7	27
1946	9	9	8	24
1947	8	5	6	14
1948	16	5	6	21
1949	3	8	8	30
1950	12	8	16	27
1951	17	21	21	31
1952	20	24	25	31
1953	22	19	15	32
1954	17	5	6	14
1955	22	23	21	23
1956	24	18	20	28
1957	20	11	9	22
1958	12	7	7	25
1959	17	15	12	32
1960	18	22	21	29
1961	7	6	8	15
1962	15	7	8	25
1963	22	23	24	32
1964	15	11	10	21
1965	24	20	20	26
1966	29	26	30	32
1967	14	11	19	20

Cumulative Relative Frequency, 1938-67

Yield Per Acre				
5 bushels or less	0.07	0.13	0.00	
5-10	0.30	0.43	0.47	
10-15	0.47	0.60	0.54	0.10
15-20	0.74	0.77	0.71	0.20
20-25	0.94	0.97	0.98	0.43
25-30	1.00	1.00	1.00	0.73
30-35				1.00
35-40 bushels				

TABLE B.3

PERCENTAGE OF SHELLING LOSSES IN WHEAT AFTER REACHING HARVEST RIPENESS

Day	Loss %	Day	Loss %	Day	Loss %	Day	Loss %	Day	Loss %
1	0.11	14	0.09	27	0.12	40	0.13	53	0.19
2	0.09	15	0.05	28	0.11	41	0.12	54	0.20
3	0.11	16	0.06	29	0.09	42	0.13	55	0.18
4	0.10	17	0.05	30	0.09	43	0.07	56	0.20
5	0.11	18	0.04	31	0.09	44	0.06	57	0.14
6	0.09	19	0.05	32	0.09	45	0.07	58	0.15
7	0.11	20	0.06	33	0.09	46	0.05	59	0.14
8	0.09	21	0.05	34	0.09	47	0.07	60	0.13
9	0.09	22	0.11	35	0.09	48	0.06	61	0.14
10	0.09	23	0.12	36	0.13	49	0.07	62	0.15
11	0.09	24	0.11	37	0.12	50	0.20	63	0.14
12	0.09	25	0.13	38	0.13	51	0.18	64	0.18
13	0.09	26	0.11	39	0.14	52	0.20	65	0.18

Grain Moisture Content

The grain in a standing crop passes through a daily cycle of moisture content in relation to the relative humidity of the air around it. The pattern of variation is influenced by the stage of maturity of the crop, and several other meteorological variables (8). Once a crop is harvest-ripe, the pattern of moisture content is cyclical within a steady range, except where rainfall causes it to increase.

This diurnal variation has been measured, under all weather conditions, by Arnold at the National Institute of Agricultural Engineering in England (2). The data used in this study were based on observations from the NIAE. The original data consisted of detailed hourly readings of grain and air moisture and temperature levels, recorded 24 hours a day over four consecutive harvests. By selecting periods with various proportions of rain-free days from the years recorded, a pattern of grain moisture contents was built up which is assumed to be representative of harvest with similar proportions of rain-free days.

The data used in Model 2 are presented in Table B.4.

TABLE B.4

PERCENTAGE OF TIME AT VARIOUS GRAIN MOISTURE CONTENTS (W.B.[1/])

Grain Moisture Content % \ Rain-Free Days %	30	40	50	60	70	80	90	100
12							1.0	6.5
13					.5	1.5	5.5	15.5
14				2.1	3.0	8.3	15.5	22.5
15	1.6	2.4	2.7	2.9	7.5	14.2	22.5	18.8
16	2.4	3.6	4.5	6.8	13.0	17.2	13.8	11.0
17	6.0	7.0	9.0	12.1	16.0	13.0	9.0	7.0
18	8.8	10.8	15.2	17.7	12.7	11.0	8.0	6.5
19	13.2	16.7	15.6	14.4	11.0	9.1	7.0	4.4
20	15.4	14.2	12.8	10.5	9.0	7.3	6.5	3.2
21	11.6	10.7	9.2	8.5	6.8	5.0	4.4	2.6
22	9.2	7.7	6.8	6.0	4.7	3.7	3.2	1.0
23	8.3	6.2	5.4	4.2	3.6	3.0	2.6	
24	6.7	5.2	4.6	3.3	2.7	2.2	1.0	
25	5.6	4.5	4.0	2.5	2.0	1.5		
26 and over	11.2	11.0	10.2	9.0	7.5	3.0		
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

1/ Wet basis

APPENDIX C

WEATHER CONSTRAINTS ON HARVESTING

The main weather restraints in the models are in the form of rain-free days. The general pattern of the data used for the four locations is shown in Table C.1. The relative frequency distribution of rainy days and precipitation levels for successive five-day periods during the harvest season are set out in Table C.2.

Weather restraints in Model 1 were applied at two levels of severity, referred to as "Part Lags" and "Full Lags", respectively. In the first level, a workday was lost if more than .01 inches of rain fell. If precipitation was greater than 3.0 inches or there were three or more rainy days in a five-day period, then an additional day was lost. If the precipitation in a five-day period exceeded 1.5 inches, a 4-cent grade loss penalty was imposed to a maximum of three grade losses in any one year.

At the second level of severity a workday was also lost if more than .01 inches of precipitation fell. However, an additional lost workday occurred for each .10 inches up to .30 inches of precipitation and an additional workday was lost for each .50 inches thereafter. A further workday was lost if rain fell for more than three days. A grade loss occurred for each two inches of rain accumulated over the season to a maximum of three grade losses.

Actual observations for combining days were obtained from at least one farmer in the vicinity of each of the four locations.

The number of combining days in each case was recorded from diaries kept by farmers or their wives. Where identification was possible, days that were rain-free, though not combining days (presumably due to breakdowns, rest days, and so on) within a series of rain-free days, were counted as combining days. A comparison between the two levels of weather restraints and the actual observations is given in Table C.3.

TABLE C.1

RAIN-FREE DAYS IN SASKATCHEWAN, AUGUST 15th TO OCTOBER 18th, 1930-66

No. of Days Rain-Free	Percentage of Period Rain-Free	Annual Occurrence of Rain-Free Days and Cumulative Frequency at Different Locations							
		Location 1 (Swift Current)		Location 2 (Outlook)		Location 3 (Saskatoon)		Location 4 (Melfort)	
		A	B	A	B	A	B	A	B
36	55.5	1	.03						
37	57								
38	58.5								
39	60					1	.03	1	.03
40	61.5	1	.06			1	.06	3	.11
41	63					1	.08		
42	64.5							2	.17
43	66	1	.08						
44	67.5			2	.06			2	.22
45	69	2	.14	1	.08	1	.11	1	.25
46	71					1	.14	2	.31
47	72	2	.19	1	.11	4	.25	2	.36
48	74	1	.22	1	.14	1	.28	4	.47
49	75.5			1	.17	2	.33	1	.50
50	77	2	.28	1	.19	3	.42	3	.58
51	78.5	8	.50	2	.25	6	.58	3	.67
52	80	4	.61			3	.67	3	.75
53	81.5	3	.69	4	.36	4	.78	3	.83
54	83	2	.75	3	.44	4	.89	2	.89
55	84.5	2	.81	7	.64	1	.92	2	.94
56	86	2	.86	1	.67	1	.94	1	.97
57	88	1	.89	3	.75	1	.97	1	1.00
58	89	1	.92	2	.81				
59	91			3	.89	1	1.00		
60	92.5	1	.94	1	.92				
61	94	1	.97						
62	95.5	1	1.00	2	.97				
63	97								
64	98.5								
65	100.0			1	1.00				

A - Frequency
B - Cumulative Frequency

TABLE C.2

CUMULATIVE FREQUENCY DISTRIBUTIONS FOR RAINFALL BY SUCCESSIVE FIVE-DAY PERIODS, 1931-66

	Location 1 (Swift Current)											
	August						September					
	5-9	10-14	15-19	20-24	25-29	30-3	4-8	9-13	14-18	19-23	24-28	29-3
Rainy days												
0	.42	.42	.36	.33	.36	.39	.39	.36	.53	.25	.42	.50
0-1	.61	.75	.67	.58	.64	.61	.69	.61	.67	.61	.72	.83
0-2	.78	.92	.89	.83	.78	.80	.94	.92	.83	.78	.94	.97
0-3	.92	1.0	.97	.92	.92	.97	1.0	1.0	.89	.92	1.0	1.0
0-4	1.0		1.0	.97	1.0	1.0			.97	.97		
0-5				1.0					1.0	1.0		
Precipitation (inches)												
0-0.25	.43	.57	.74	.46	.61	.45	.59	.56	.41	.59	.76	.78
0-0.50	.71	.76	.87	.71	.65	.64	.77	.87	.53	.81	.95	1.0
0-0.75	.81	.90		.79	.70	.82	.91	.91	.70	.85		
0-1.0	.86		.91	.83	.74		1.0		.76		1.0	
0-1.25	.90	.95	1.0	.88	.78				.82	.92		
0-1.50		1.0		.96	.83			.96	.94			
0-1.75	.95				.91	.95		1.0				
0-2.0	1.0			1.0						1.0		
0-2.25					.96	1.0			1.0			
0-2.50												
0-3.0					1.0							
0-5.0												

TABLE C.2 *(Continued)*

	October						November					
	4-8	9-13	14-18	19-23	24-28	29-2	3-7	8-12	13-17	18-22	23-27	28-30
Rainy days												
0	.42	.58	.61	.47	.58	.53	.39	.47	.33	.22	.42	.67
0-1	.75	.80	.89	.64	.72	.75	.67	.78	.64	.56	.61	.92
0-2	.94	.94	.94	.80	.92	.94	.89	.86	.83	.75	.89	1.0
0-3	1.0	.97	.97	.94	1.0	.97	1.0	.92	.94	.94	.97	
0-4		1.0	1.0	.97		1.0		1.0	1.0	1.0	1.0	
0-5				1.0								
Precipitation (inches)												
0-0.25	.67	.73	.71	.42	.73	.70	.82	.58	.62	.89	.76	1.0
0-0.50	.90	.87	.93	.68	.80	.88	1.0	.95	.92	.96	.95	
0-0.75	.95	.93		.84	.93				.96		1.0	
0-1.0	1.0	1.0	1.0	.89	1.0	1.0		1.0	1.0			
0-1.25				.95								
0-1.50										1.0		
0-1.75				1.0								
0-2.0												
0-2.25												
0-2.50												
0-3.0												
0-5.0												

TABLE C.2 *(Continued)*

	Location 2 (Outlook)											
	August						September					
	5-9	10-14	15-19	20-24	25-29	30-3	4-8	9-13	14-18	19-23	24-28	29-3
Rainy days												
0	.36	.53	.50	.30	.33	.47	.44	.42	.44	.42	.56	.56
0-1	.75	.75	.75	.61	.69	.69	.75	.72	.64	.69	.89	.92
0-2	.92	.94	.97	.86	.89	.89	.94	1.0	.86	.86	.92	1.0
0-3	1.0	1.0		.94	.94	.97	1.0		.94	1.0	.94	
0-4			1.0	1.0	1.0	1.0			.97		1.0	
0-5									1.0			
Precipitation (inches)												
0-0.25	.61	.76	.56	.52	.56	.47	.65	.62	.50	.48	.56	.94
0-0.50	.91	.94	.83	.72	.65	.79	.75	.71	.80	.81	.94	1.0
0-0.75	.96		.94	.76	.78	.84	.85	.76	.90			
0-1.0	1.0	1.0	1.0	.92	.83	.95		.86	1.0			
0-1.25				.96	.87	1.0	.90	.95		.86		
0-1.50				1.0	.91		.95	1.0		.95		
0-1.75										1.0		
0-2.0					.96		1.0				1.0	
0-2.25					1.0							
0-2.50												
0-3.0												
0-5.0												

TABLE C.2 *(Continued)*

	October						November					
	4-8	9-13	14-18	19-23	24-28	29-2	3-7	8-12	13-17	18-22	23-27	28-30
Rainy days												
0	.61	.64	.75	.61	.53	.64	.67	.61	.39	.61	.64	.89
0-1	.83	.92	.94	.86	.80	.97	.97	.94	.83	.89	.86	.94
0-2	.94	.97	1.0	.94	.94		1.0	1.0	.97	.97	1.0	1.0
0-3	1.0	1.0		1.0	1.0	1.0			1.0	1.0		
0-4												
0-5												
Precipitation (inches)												
0-0.25	.78	.92	.78	.64	.65	.92	.83	.93	.68	.78	.62	1.0
0-0.50	.92	1.0	.89	.86	.82		1.0	1.0	.91	.93	1.0	
0-0.75			1.0	.93	.94				1.0	1.0		
0-1.0	1.0					1.0						
0-2.0					1.0							
0-2.25												
0-2.50				1.0								
0-3.0												
0-5.0												

TABLE C.2 *(Continued)*

	Location 3 (Saskatoon)											
	August						September					
	5-9	10-14	15-19	20-24	25-29	30-3	4-8	9-13	14-18	19-23	24-28	29-3
Rainy days												
0	.30	.28	.28	.22	.25	.39	.22	.28	.28	.36	.50	.33
0-1	.64	.61	.67	.61	.58	.69	.58	.61	.53	.53	.72	.80
0-2	.89	.92	.94	.67	.80	.86	.89	.89	.89	.78	.92	.97
0-3	.94	.97	1.0	.89	.92	.92	.97	.97	.94	.94	.97	1.0
0-4	.97	1.0		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
0-5	1.0											
Precipitation (inches)												
0-0.25	.52	.81	.69	.46	.67	.50	.57	.58	.73	.56	.61	.88
0-0.50	.76	.85	.88	.68	.74	.68	.82	.81	.92	.83	.70	1.0
0-0.75	.88			.86		.82	.93	.85	.96	.87	.94	
0-1.0	.92	.96	.96	.93	.85	.86	.96		1.0	.91		
0-1.25			1.0	.96	.89	.95		.88				
0-1.50	1.0	1.0		1.0	.96					.96		
0-1.75						1.0		.92		1.0		
0-2.0					1.0							
0-2.25							1.0				1.0	
0-2.50								1.0				
0-2.75												
0-3.0												
0-5.0												

TABLE C.2 *(Continued)*

	October						November					
	4-8	9-13	14-18	19-23	24-28	29-2	3-7	8-12	13-17	18-22	23-27	28-30
Rainy days												
0	.44	.56	.64	.47	.56	.58	.44	.47	.28	.14	.42	.69
0-1	.72	.80	.86	.86	.83	.75	.80	.75	.58	.50	.72	.92
0-2	.92	.97	.92	.92	.97	.92	.89	.92	.89	.80	.89	1.0
0-3	1.0	1.0		1.0	1.0	1.0	.97	1.0	.97	.94	1.0	
0-4			.97				1.0		1.0	1.0		
0-5			1.0									
Precipitation (inches)												
0-0.25	.70	.81	.62	.68	.62	.67	.85	.79	.81	.84	.71	.91
0-0.50	.85		.77	.89	.75	.80	.90	1.0	.88	1.0	.86	1.0
0-0.75	1.0	1.0	.92		.88	.93	1.0		.96		1.0	
0-1.0			1.0	.95	.94				1.0			
0-1.25					1.0	1.0						
0-1.50												
0-1.75				1.0								
0-2.0												
0-2.25												
0-2.50												
0-2.75												
0-3.0												
0-5.0												

TABLE C.2 *(Continued)*

	Location 4 (Melfort)											
	August					September						
	5-9	10-14	15-19	20-24	25-29	30-3	4-8	9-13	14-18	19-23	24-28	29-3
Rainy days												
0	.22	.22	.28	.22	.11	.30	.30	.33	.28	.28	.44	.25
0-1	.47	.64	.61	.47	.53	.50	.64	.67	.53	.61	.78	.61
0-2	.92	.92	.80	.80	.75	.80	.80	.89	.83	.80	.89	.83
0-3	1.0	1.0	.97	.92	.89	.94	.94	.94	.94	.97	.94	.94
0-4	1.0	1.0	1.0	1.0	1.0	.97	1.0	1.0	.97	1.0	1.0	1.0
0-5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Precipitation (inches)												
0-0.25	.68	.61	.50	.54	.53	.40	.32	.50	.42	.54	.65	.74
0-0.50	.78	.93	.65	.78	.66	.56	.68	.67	.69	.77	.80	.89
0-0.75	.89		.85	.86	.81	.72	.84	.88	.85	.85	.95	.96
0-1.0	.93	1.0	.96	.89	.91	.80	.92	1.0	.88	.92		1.0
0-1.25			1.0	.93	.97	.84	1.0		.96	1.0		
0-1.50	.96					.88						
0-1.75	1.0											
0-2.0				.96	1.0							
0-2.25									1.0		1.0	
0-2.50						.92						
0-2.75						1.0						
0-3.0				1.0								
0-5.0												

TABLE C.2 *(Concluded)*

	October						November					
Rainy days	4-8	9-13	14-18	19-23	24-28	29-2	3-7	8-12	13-17	18-22	23-27	28-30
0	.39	.42	.47	.44	.42	.33	.36	.44	.33	.28	.39	.58
0-1	.75	.78	.75	.72	.78	.86	.67	.72	.56	.50	.56	.94
0-2	.97	.92	.94	.86	.94	.94	.86	.83	.78	.75	.83	1.0
0-3	.97	1.0	.97	.94	.97	.97	.94	1.0	.97	.97	.97	1.0
0-4	1.0	1.0	.97	1.0	1.0	.97	1.0	1.0	1.0	1.0	.97	1.0
0-5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Precipitation (inches)												
0-0.25	.64	.67	.68	.60	.71	.71	.70	.70	.58	.62	.59	.73
0-0.50	.82	.81	.79	.80	.90	.88	.91	.95	.83	.85	.73	.93
0-0.75	.86	.90	.89	.85	.95	.96	.96	1.0	.88	1.0	.95	1.0
0-1.0	.95	.95	.95	.90	1.0	1.0	1.0		1.0		1.0	
0-1.25		1.0	1.0	1.0								
0-1.50												
0-1.75												
0-2.0												
0-2.25												
0-2.50	1.0											
0-2.75												
0-3.0												
0-5.0												

TABLE C.3

ACTUAL AND ESTIMATED COMBINING DAYS

Period	Number of Days: Actual Combining[1/]	Number of Days: Estimated Combining[2/]	Number of Days: Estimated Combining[3/]	Number of Days: With Rain	Precipitation in 5-day Period (inches)
		Location 1 (Swift Current)			
1964					
Aug. 3-4	2	2	2		
5-9	5	5	5		
10-14		1		3	0.26
15-19		4		1	1.20
20-24		1		3	0.27
25-29	1	4	2	1	0.02
30-3		1		3	1.57
Sept. 4-8		4		1	0.12
9-13		3	1	2	0.11
14-16	2	3	3		
Total	10	28	13		
1965					
Aug. 10-14	4	5	5		
15-19	4	5	5		
20-24	1	4	2	1	0.23
25-29				4	1.73
30-3		3		2	2.03
Sept. 4-8		4		1	0.04
9-13		4		1	0.04
14-18				5	0.79
19-23				3	0.34
24-28		3		2	0.23
29-3		5			
Oct. 4-8	2	4	4	1	0.05
9-10	1	2	2		
Total	12	39	18		
1966					
Aug. 15-19		3		2	0.84
20-24	2	4	1	1	0.26
25-29	2	4	2	1	0.25
30-3	3	4	4	1	0.02
Sept. 4-8	4	5	5		
9-10	2	1	1	1	0.07
Total	13	21	13		
		Location 2 (Outlook)			
1961					
Aug. 7-9	3	3	3		
10-14	4	5	5		
15-19	5	5	5		
20-24	3	5	5		
25-29	4	5	5		
Total	19	23	23		

TABLE C.3 *(Continued)*

Period	Number of Days: Actual Combining[1/]	Estimated Combining[2/]	Estimated Combining[3/]	With Rain	Precipitation in 5-day Period (inches)
1962					
Aug. 16-19	3	3	1	1	0.32
20-24	2	5	5		
25-29	1	1		3	1.97
30-3		4		1	0.31
Sept. 4-8		3		2	1.39
9-13		4		1	0.05
14-18	4	5	3		0.05
19-23	3	5	5		
24-26	3	3	3		
Total	16	33	17		
1963					
Aug. 7-9	2	2	2	1	0.06
10-14		3		2	0.33
15-19		3		2	0.59
20-24	2	4	2	1	0.28
25-29		3		2	0.71
30-3	3	5	5		
Sept. 4-8	5	5	5		
9-13	2	3	2	2	0.13
14-18		1		3	0.83
19-23	3	5	2		
24-28	5	5	5		
29-30	1	2	2		
Total	23	41	25		
1964					
Aug. 18-19	2	2	2		
20-24		4	3	1	0.08
25-29	3	3	1	2	0.18
30-3		3		2	0.85
Sept. 4-8		1		3	0.53
9-13		5	2		
14-17	3	3	2	1	0.11
Total	8	21	10		
1965					
Sept. 7-8	2	2	2		
9-13	3	4	2	1	0.26
14-18				5	0.46
19-23		3		1	0.16
24-28	2	4	3	1	0.04
29-3	3	5	5		
Oct. 4-7	4	4	4		
Total	14	22	16		

TABLE C.3 *(Continued)*

Period	Number of Days: Actual Combining1/	Number of Days: Estimated Combining2/	Number of Days: Estimated Combining3/	Number of Days: With Rain	Precipitation in 5-day Period (inches)
1966					
Aug. 30-3	3	5	5		
Sept. 4-8	5	4	4	1	0.04
9-13	4	4	4	1	0.03
14-18	3	5	5		
19-23	3	4	4	1	0.02
24-28	3	4	4	1	0.05
29-3	3	3	2	2	0.12
Oct. 4-8	4	5	5		
9-10	4	2	2		
Total	32	36	35		
Location 3 (Saskatoon)					
1963					
Aug. 21-24	4	4	4	3	0.55
25-29		1		3	0.38
30-3	4	5	3		
Sept. 4-8	4	4	3	1	0.18
9-13	3	1	1	3	0.18
14-18	1	1		3	0.97
19-23	3	5	3		
24-28	1	5	5		
Total	20	27	19		
1964					
Aug. 18-19	1	1		1	0.20
20-24	2			4	0.38
25-29	2	4	1	1	0.02
30-3	2			4	1.16
Sept. 4-8	1	1		3	0.55
9-13	1	4		1	0.04
14-18		4	2	1	0.07
19-23	1	3	2	2	0.13
24-28		5	5		
29-3	2	4	3	1	0.17
Oct. 4-8	4	5	5		
9-10	2	2	2		
Total	18	33	20		
1965					
Aug. 21-24	3	3	3	1	0.03
25-29	4	3		2	0.79
30-3		1		3	0.53
Sept. 4-8	1	3	1	2	0.05
9-13		3		2	0.43
14-18				4	0.24
19-23		1		3	0.26
24-28		5	3		
29-3	5	4	4	1	0.02
Oct. 4-5	2	2	2		
Total	15	25	13		

TABLE C.3 *(Concluded)*

Period	Number of Days: Actual Combining 1/	Estimated Combining 2/	Estimated Combining 3/	With Rain	Precipitation in 5-day Period (inches)
1966					
Sept. 1-3	3	3	3		
4-8	5	4	1	1	0.45
9-13		3	2	2	0.12
14-18	5	5	5		
19-23	5	5	5		
24-28	5	5	5		
Total	23	25	21		
Location 4 (Melfort)					
1964					
Sept. 15-18	4	4	4		
19-23	3	3		2	0.31
24-28		4	4	1	0.08
29-3				4	0.23
Oct. 4-8	2	5	4		
9-13	5	5	5		
14-16	3	3	3		
Total	17	24	20		
1965					
Aug. 23-24	1	1	1	1	0.02
25-29	2	4	1	1	0.33
30-3		1		3	0.89
Sept. 4-8	3	5	3		
9-13	3	3	2	2	0.19
14-18				5	0.67
19-23				4	1.14
24-28		4			
29-3	1	5	3		
Oct. 4-8	4	4	4	1	0.05
9-10	2	2	2		
Total	16	29	16		
1966					
Aug. 13-14	1	1	1	1	0.20
15-19		3		2	0.77
20-24	3	5	4		
25-29	1	1		3	0.56
30-3	2	5	4		
Sept. 4-8	3	4	1	1	0.40
9-13		3		2	0.37
14-18	5	5	5		
19-23	5	5	5		
Total	20	32	20		

1/ Actual Records from at least one farmer.
2/ Part Lags } see text for definition.
3/ Full Lags }

APPENDIX D

TILLAGE AND SEEDING MACHINERY CHARACTERISTICS

The seeding simulation model was used to evaluate five machinery systems. This number of systems and their relative size was determined after a preliminary examination of available tractor sizes. From this examination it appeared that the available tractors could be satisfactorily placed into five groups. Within each group it was assumed that the tractor was as fully loaded as possible (assuming only 65 per cent of maximum drawbar horsepower is available for pulling an implement) by a heavy duty cultivator, a disker (with seeding attachment), and a drag harrow, respectively. The tractors classified within each system are given in the following table.

TABLE D.1

TRACTOR MODELS

Company	System				
	I	II	III	IV	V
	(Model numbers)				
Massey-Ferguson	MF 135	MF 165	MF 175	MF 1100	MF 1130
John Deere	JD 1020	JD 2020	JD 3020	JD 4020	JD 5020
International Harvester		IH 656	IH 756	IH 856	IH 1256
	Average PTO Horsepower				
	38.37	55.97	68.24	96.44	123.29

The list price of these models was estimated from company price lists, plus an estimated freight charge from the factory to

Regina, Saskatchewan. Prices were based on a mean price for a standard machine with necessary options for efficient operation. The prices used are given below.

TABLE D.2

TRACTOR LIST PRICES, 1968

(Canadian dollars)

Company	System I	II	III	IV	V
Massey-Ferguson	4,010	5,887	6,746	10,684	14,209
John Deere	3,900	5,570	7,330	9,986	14,409
International Harvester		6,454	8,103	10,128	12,494
Average price	3,955	5,971	7,393	10,266	13,704

The size of disker was chosen to load the tractor fully as far as possible with the available models on the market. In doing so, it was assumed that the disker had a draft requirement of 250 lbs. per foot of width, and that it was to be pulled at 4 mph. The tractor drawbar horsepower was assumed to be 65 per cent of maximum PTO horsepower. The size of diskers used and their prices (including disks, seeding attachment, fertilizer attachment, and a hitch) are given in the following two tables:

TABLE D.3

DISKER MODELS

Company	System I	II	III	IV	V
Massey-Ferguson	MF 9'	MF 12'	MF 15'	MF 18'	MF 27'
John Deere	JD 8'	JD 12'	JD 16'	JD 20'	JD 28'
International Harvester		IH 12'	IH 18'	IH 24'	IH 28'
Average width	8'	12'	16'	21'	28'
Rate of work1/ (acres/hour)	2.8	4.2	5.6	7.4	9.8

1/ Assuming 60 per cent field efficiency.

TABLE D.4

DISKER LIST PRICE

(Canadian dollars)

Company	System I	II	III	IV	V
Massey-Ferguson	2,094	2,281	2,634	2,948	5,265
John Deere	1,558	2,075	2,543	3,045	4,618
International Harvester		2,275	2,881	4,621	5,169
Average price	1,827	2,210	2,686	3,538	5,017

The width of cultivator was also chosen so as to fully load the tractor as far as possible with the models available within the companies. In so doing, it was assumed that the cultivator had a draft requirement of 250 lbs. per foot of width and that the cultivator was to be pulled at 4 mph. The tractor drawbar horsepower was again assumed to be 65 per cent of maximum PTO horsepower. The sizes of cultivators used and their prices are given in the following two tables.

TABLE D.5

CULTIVATOR MODELS

Company	System I	II	III	IV	V
Massey-Ferguson	MF 10'	MF 12'	MF 15'	MF 22'	MF 26'
John Deere	JD 10'	JD 12'	JD 16'	JD 22'	JD 32'
International Harvester	IH 9'	IH 15'	IH 18'	IH 24'	IH 29'
Average width	10'	13'	16'	23'	29'
Rate of work[1/] (acres/hour)	4.0	5.2	6.4	9.2	11.6

1/ Assuming 82.5 per cent field efficiency.

TABLE D.6

CULTIVATOR LIST PRICE

(Canadian dollars)

Company	System I	II	III	IV	V
Massey-Ferguson	1,075	1,252	1,334	2,485	2,715
John Deere	1,100	1,198	1,435	2,556	3,398
International Harvester	922	1,338	2,099	2,555	3,034
Average price	1,032	1,263	1,623	2,532	3,049

The size of harrow was also chosen to fully load the tractor. Since all companies do not make drag harrows, it was not possible to choose from within the companies. Harrows can be obtained in sections of three- or four-foot widths. In determining the harrow width for each system, it was assumed that harrows had a draft requirement of 50 lbs. per foot of width, and that they were to be pulled at 5 mph. The sizes of harrows used are shown in the following table.

TABLE D.7

SIZE OF HARROWS USED

	System I	II	III	IV	V
Width (feet)	36	52	64	92 2/	120 2/
Rate of work 1/ (acres/hour)	18	26	32	46	60

1/ Assuming 82.5 per cent field efficiency.

2/ It is acknowledged that for practical reasons equipment of this width is likely to be rare. In practice, this third operation is likely to be done with a smaller tractor and harrows. However, in order to avoid introducing an extra dimension into the simulation model, it was decided to maintain the comparison of physically comparable systems even though they may be little used in actual farming situations.

The price of harrows was determined using the price of the IH 401 as a guide. It was assumed that drawbar costs were linear and that a farmer could have a drawbar made at the same price per foot as the IH 401. The price of the IH 401 was $650.38 for a 20-foot section or approximately $32.60 per foot of width. The list price of harrows has been included in the following table summarizing the list price of machinery used in respective systems.

TABLE D.8

SUMMARY OF LIST PRICES

(Canadian dollars)

	System				
	I	II	III	IV	V
Tractor	3,955	5,971	7,393	10,266	13,704
Disker	1,827	2,210	2,686	3,538	5,017
Cultivator	1,032	1,263	1,623	2,532	3,049
Harrow	1,177	1,700	2,100	3,000	3,500

TABLE D.9

ESTIMATED PRICE TO FARMER[1/]

(Canadian dollars)

	System				
	I	II	III	IV	V
Tractor	3,401	5,135	6,358	8,829	11,785
Disker	1,571	1,901	2,310	3,043	4,315
Cultivator	888	1,086	1,396	2,178	2,622
Harrow	1,012	1,462	1,806	2,580	3,010
Total	6,872	9,584	11,870	16,630	21,732

1/ 86 per cent of list price. See Royal Commission on Farm Machinery, Special Report on Prices of Tractors and Combines in Canada and Other Countries (Ottawa: Queen's Printer, 1969) p. 102.

Estimation of Fixed Costs

Fixed costs are made up of depreciation, interest on investment, shelter charges and insurance. Depreciation charges were based on the assumption that the farmer will trade his machinery every eight years, and that during this period the machinery depreciates at the rate of 8.5 per cent per annum. Interest charges were based on a charge of 8 per cent on the average value of the machinery over the eight-year period. Shelter charges, being rather minimal, were assumed to be $3, $4, $5, $6 and $7 respectively, for the tractor only -- primarily for the sake of distinguishing between systems. Insurance charges were based on a rate of $1.50 per $100 value of the tractor, where the tractor value is the average eight-year value. The fixed costs used in the model are given in Table D.10.

TABLE D.10

FIXED COSTS PER ANNUM ON THE BASIS OF EIGHT-YEAR OWNERSHIP

(Canadian dollars)

	System				
	I	II	III	IV	V
Depreciation	438	611	758	1,060	1,385
Interest	412	575	712	1,009	1,315
Shelter (tractor)	3	4	5	6	7
Insurance (tractor)	51	77	95	132	177
Total	904	1,267	1,570	2,207	2,884

Estimation of Variable Costs

Variable costs consist of fuel, repairs, maintenance, labour and seed costs. Detailed information is not available for each size group; hence variable costs per acre were assumed to be the same for each system, with the exception of labour which was included as an hourly rate.

Fuel Costs -- From Nebraska test data, fuel consumption is approximately one Imperial gallon for each 13.13 HP hour produced. Diesel fuel costs 18 cents per gallon; hence fuel costs are approximately 11 cents per acre for disking, 9 cents per acre for cultivating, and 2 cents per acre for harrowing.

Repair Costs -- Data for parts repair costs were taken from two sources. One source is the records kept by the Swift Current

Research Station, and the other is the Agricultural Machinery Administration Test Reports. Parts repair costs from these two sources were averaged to provide an estimate of per acreage repair costs.

TABLE D.11

TRACTOR REPAIR COSTS BASED ON SWIFT CURRENT RESEARCH STATION DATA

Year	Unit No.	Hour Meter Reading	Hours Operated Over Period	Parts Costs $
1962	112	3,167.5	473.2	99.69
	124	2,779.0	267.7	629.63
1963	101	2,721.0	360.0	63.65
	112	3,611.0	429.9	96.92
1965	101	2,897.0	351.4	79.17
	126	2,861.0	128.0	57.15
1966	118	3,150.2	310.2	230.41
			2,320.4	1,256.62

Average parts repair cost at 3,000 hours = 54¢/hr.

TABLE D.12

CUMULATIVE REPAIR COST FOR TRACTOR-LIFE BASED ON SWIFT CURRENT RESEARCH STATION DATA

Tractor	Cumulative Tractor-Life Hours	Parts Costs $
1	3,901	906.13
2	5,251	1,419.45
3	3,300	218.62
4	3,150	213.99
5	8,605	2,755.57
6	6,105	1,368.26

The average parts repair cost for all six models is 22.7¢/hr. However, if only those tractors that operated 4,000 hours or more are considered, the cost is increased to 27.7 cents. Since the variation within the sample is wide, it is impossible to estimate parts repair costs with great accuracy. On this basis it was assumed that parts repair costs were 30 cents per hour for tractors in the 50-60-HP range. Tractor repair costs will then be

30¢ ÷ 4.2 acres = 7.1¢ per acre for disking; 30 ÷ 5.2 = 5.8¢ per acre for cultivating; and 30 ÷ 26 = 1.2¢ per acre for harrowing.

TABLE D.13

DISKER REPAIR COSTS

Disker	Acres	Parts $
	Swift Current Data	
1	7,828	643.36
2	2,680	27.52
3	2,680	21.11
4	6,378	338.31
5	5,830	178.87
6	4,105	27.77
	AMA Data	
1	4,000	128.73
2	3,500	311.95
3	3,200	133.70
4	3,276	99.03
5	3,130	266.28
6	46,607	2,176.63

If the data from these two sources are averaged, a repair cost of 4.6 cents per acre is obtained. This was the value used in the simulation model.

TABLE D.14

CULTIVATOR REPAIR COSTS

Cultivator	Width (feet)	Acres	Parts $
	Swift Current Data		
1	14	4,371	142.76
2	12	9,598	398.80
3	14	21,575	877.33
4	16	6,115	675.60
5	18	5,258	150.04
6	10	4,077	173.69
	AMA Data		
1	16	3,900	182.55
2	15	3,600	212.43
3	22	5,170	891.00
4	12	3,070	167.39
5	15	4,000	457.31
6	20	4,900	296.28
7	14	3,270	335.16
8	20	4,908	548.43
9	23	8,025	1,385.31

The average repair cost from these two sources is 7.5 cents per acre. Much of the cultivator repair costs are in the form of sweep wear. From AMA test data, this is estimated to be of the order of 4.4 cents per acre; that is, more than half of the above figure that was used in the model.

Maintenance Costs -- Maintenance costs are low. They include primarily oil changes, filter changes, and grease, which amounts to something in the order of 4.5 or 5.0 cents per hour. On a per-acre basis this amounts to 5.0¢ ÷ 4.2 acres = 1.2¢ per acre for disking; 5.0 ÷ 5.2 = 1.0¢ per acre for cultivating; and 5.0 ÷ 26 = 0.2¢ per acre for harrowing -- all with 50-60-HP tractors. Maintenance charges per acre are assumed constant regardless of tractor size.

Labour Cost -- To obtain a value for labour cost a charge of $1.50 per hour was assumed. Acreage labour costs will vary depending upon the capacity of the particular machine involved. The following table indicates the labour charges on an acreage basis.

TABLE D.15

LABOUR COST

(Canadian dollars)

	System				
	I	II	III	IV	V
Disking	0.535	0.357	0.268	0.203	0.153
Cultivating	0.357	0.288	0.234	0.163	0.129
Harrowing	0.111	0.077	0.062	0.043	0.033
Total	1.02	0.72	0.56	0.40	0.32

Seed Cost -- Seed was assumed to cost $2 per acre.

TABLE D.16

SUMMARY OF VARIABLE COSTS (PER ACRE)

(Canadian dollars)

	System				
	I	II	III	IV	V
Fuel	0.22	0.22	0.22	0.22	0.22
Repairs	0.27	0.27	0.27	0.27	0.27
Maintenance	0.02	0.02	0.02	0.02	0.02
Labour	1.02	0.72	0.56	0.40	0.32
Seed	2.00	2.00	2.00	2.00	2.00
Total	3.53	3.23	3.07	2.91	2.83

APPENDIX E

FIELD CONSTRAINTS ON TILLAGE

The weather effects on tillage and seeding operations were taken into account, using a procedure developed by P. R. Rutledge under the direction of Dr. F. V. MacHardy at the University of Alberta (36, 37). Though the study was originally done in Alberta, the program was used by its developer to analyze the weather, soil and traction effects at Swift Current and Melfort. The procedure, as outlined by Rutledge and MacHardy, can be summarized in the following terms: The general relationship between the weather and soil tractability may be examined in two parts. The first part is that of relating climatological variables to soil moisture content. The second part is that of relating soil moisture content to soil tractability. The relationship between climatological variables and soil moisture content has been fairly well established in recent years. Basically it involves balancing moisture additions to the soil (precipitation) with moisture losses from the soil (evapotranspiration).

To do this,

> ...soil moisture was estimated using the "Versatile Soil Moisture Budget", developed by Baier and Robertson (4). In this moisture budget the soil was divided into six soil moisture zones holding 0.20 inch, 0.30 inch, 0.50 inch, 1.0 inch, 1.0 inch, and 1.0 inch of water respectively. These zones were based on a fixed depth of water in an attempt to make the budget independent of soil type. Hence, the thickness of the soil layer concerned depended upon its moisture holding capacity.(37)

The budget required an estimate of latent evaporation. This was determined separately by Baier and Robertson. Using three parameters -- minimum and maximum temperature, and solar radiation received at the top of the atmosphere -- they estimated latent evaporation with a correlation coefficient of 0.68. By including additional factors of sunshine hours, dew point, day length and wind mileage, they raised the correlation coefficient to 0.84. In other words, 70 per cent of the variation in latent evaporation could be explained by variation in the above factors.

> The moisture budget required an estimate of soil moisture at the beginning of each season. It was assumed that the moisture content of each soil moisture zone was at one half capacity at the beginning of the first season at each station. The moisture content at the beginning of each successive season was estimated by adding a fraction of the winter precipitation to the previous fall moisture content. The fraction of the winter precipitation that is absorbed by the soil varies with latitude. At Swift Current, Staple and Lehane found that between November and April, between 1940-1950, 33 percent of the precipitation was conserved. At Beaverlodge, Carder found that from harvest to freeze up [up] to 13 percent of the precipitation was conserved whereas from freeze up till spring breakup only 5 percent was conserved....

For purposes of this study, it was assumed that for Swift Current, 35 per cent of the winter precipitation was conserved; at Melfort, 25 per cent was conserved.

> The results obtained by Nichols indicate the following relationship between soil parameters and soil shear strength:
>
> $$Fs = \frac{Pu - M}{Pn} (0.06\ Pn + P + 1.8) \quad \ldots\ldots\ldots 1$$
>
> where
>
> Fs = shear strength (psi)
>
> Pu = upper plastic limit [liquid limit]
>
> M = moisture content (percent)
>
> Pn = plasticity number = 0.6C–12
>
> C = clay content (percent)
>
> P = confining pressure (psi)
>
> This equation does not give an accurate estimate of shear strength for non-plastic soils, i.e. soils with a low clay content. However, traction difficulties are less likely to be a problem on non-plastic soils than on plastic soils.
>
> Assuming the soil confining pressure to be 16 psi and the tractor operating with 15 percent slip, the soil shear strength required to enable the tractor to develop a drawbar pull of 42.5 percent

> of its...[gross weight] was 11 psi, and 9.6 psi for tilled loam and Fall Rye seeding respectively. Applying equation 1, a shear strength in this range would be developed at a moisture content that approximates field capacity of most plastic, Alberta soils.
>
> A season was considered to include the months April through October, consequently some consideration had to be given to snowfall. R. W. Longley, Professor of Meteorology, University of Alberta, Edmonton, suggested that if there was snow on the ground in the Spring of the year, the temperature would not likely rise above 45°F. In the Fall, because of heat in the ground the snow may be gone at a temperature of 40°F. Hence it was considered that snow remained on the ground in the Spring when temperatures did not exceed 45°F during the day, and in the Fall when the temperatures did not exceed 40°F.
>
> The moisture content, above which it was impossible to perform tillage operations, appeared to be at or near field capacity. Field capacity was the upper limit of the soil moisture budget. An attempt to classify the data into work days and non-work days was made by assuming that if the moisture content in any of the top three zones was above 99.5 percent of capacity, field operations were not possible. No consideration was given to snowfall in this run. Based on the results of two years check data...the number of non-work days appeared to be under-estimated. It was also apparent from this trial run, that some consideration of snowfall would improve the correlation in early Spring and late Fall.
>
> A second run was made in which a day was considered to be a non-work day if the moisture content in any of the top three zones was above 95 percent of capacity, or if there was snow on the ground. The inclusion of three zones was justified only in medium or heavy soils (Loam or Silty Clay Loam). In Sandy soils only two zones needed to be considered. Hence, an additional run was made to determine probability values for sandy soils. Both of these runs showed much closer correlation with the check data, than did the first run....

Probability values for non-work days are presented in Tables E.1 - E.4.

> The probability values determined using criteria of 99.5 percent of moisture capacity in the top three moisture zones yielded almost the same values as those determined using [criteria of] 95 percent of moisture capacity in the top [three] zones, except in the months in which snow was a factor.

> This may be explained in two ways. In the case of a large rainfall, the top two zones are dried below 95 percent of capacity by the time the third zone is dried to 99.5 percent of capacity. In the case of smaller rains that do not affect the third zone, it does not make a great deal of difference whether 95 percent or 99.5 percent is chosen as criteria, since the time required to reach either moisture content is quite short.
>
> Tillage operations may be performed in coarse textured soils at moisture contents near field capacity without harm to soil structure. As a result, the probabilities estimated using either method should satisfactorily reflect real conditions. In finer textured soils tillage at high moisture content is harmful to soil structure, and the 95 percent criteria must be used. The probability of a non-work day estimated on this basis may in fact still be conservative, however, on the basis of physical ability to pull a tillage implement, the estimates appear to be in the right neighborhood. Caution must be exercised when using these probabilities for extremely fine textured soils.(37)

Using the Rutledge program the following results were obtained and used in Model 3.

TABLE E.1

PROBABILITY OF A NON-WORKDAY, MEDIUM TO HEAVY SOIL, SWIFT CURRENT (SASKATCHEWAN) 1931-60

Date	April	May	June	July	August	September	October
1	1.00	0.47	0.30	0.13	0.30	0.20	0.13
2	1.00	0.43	0.23	0.10	0.07	0.23	0.13
3	0.93	0.30	0.23	0.20	0.17	0.20	0.17
4	0.93	0.33	0.27	0.27	0.17	0.13	0.23
5	0.93	0.23	0.30	0.30	0.27	0.27	0.30
6	0.90	0.30	0.23	0.13	0.13	0.17	0.37
7	0.90	0.23	0.33	0.30	0.20	0.07	0.30
8	0.87	0.20	0.47	0.33	0.20	0.10	0.27
9	0.83	0.17	0.33	0.27	0.07	0.10	0.23
10	0.83	0.13	0.37	0.27	0.17	0.17	0.17
11	0.80	0.10	0.23	0.20	0.17	0.17	0.27
12	0.73	0.13	0.23	0.17	0.10	0.13	0.17
13	0.57	0.00	0.17	0.13	0.07	0.17	0.13
14	0.57	0.10	0.27	0.33	0.10	0.20	0.10
15	0.43	0.03	0.27	0.17	0.07	0.20	0.17
16	0.43	0.10	0.33	0.10	0.10	0.23	0.20
17	0.47	0.20	0.13	0.20	0.03	0.20	0.17
18	0.37	0.20	0.20	0.03	0.07	0.17	0.20
19	0.20	0.20	0.37	0.23	0.03	0.23	0.20
20	0.40	0.10	0.27	0.27	0.10	0.27	0.20
21	0.33	0.13	0.40	0.17	0.07	0.27	0.30
22	0.40	0.23	0.27	0.07	0.20	0.27	0.30
23	0.40	0.17	0.20	0.03	0.17	0.33	0.30
24	0.47	0.17	0.27	0.07	0.33	0.27	0.30
25	0.43	0.17	0.43	0.17	0.33	0.27	0.30
26	0.50	0.13	0.30	0.03	0.20	0.27	0.27
27	0.50	0.10	0.37	0.17	0.30	0.30	0.30
28	0.43	0.07	0.43	0.03	0.27	0.23	0.27
29	0.40	0.10	0.37	0.13	0.23	0.27	0.27
30	0.33	0.23	0.20	0.20	0.40	0.27	0.33
31		0.40		0.23	0.23		0.37

TABLE E.2

PROBABILITY OF A NON-WORKDAY ON SANDY SOIL,
SWIFT CURRENT (SASKATCHEWAN) 1931-60

Date	April	May	June	July	August	September	October
1	1.00	0.27	0.20	0.07	0.20	0.10	0.00
2	0.73	0.23	0.10	0.07	0.03	0.13	0.00
3	0.60	0.13	0.13	0.20	0.13	0.10	0.03
4	0.53	0.13	0.17	0.20	1.10	0.03	0.10
5	0.43	0.10	0.20	0.27	0.23	0.17	0.17
6	0.50	0.20	0.13	0.13	0.07	0.10	0.27
7	0.53	0.17	0.30	0.27	0.17	0.03	0.17
8	0.47	0.07	0.33	0.30	0.17	0.07	0.13
9	0.50	0.07	0.10	0.23	0.03	0.10	0.10
10	0.47	0.07	0.10	0.17	0.17	0.13	0.07
11	0.37	0.07	0.10	0.17	0.13	0.07	0.17
12	0.20	0.10	0.13	0.07	0.07	0.03	0.10
13	0.23	0.00	0.13	0.10	0.03	0.10	0.10
14	0.27	0.10	0.17	0.27	0.10	0.17	0.03
15	0.30	0.03	0.20	0.10	0.07	0.13	0.10
16	0.20	0.10	0.23	0.07	0.10	0.13	0.13
17	0.23	0.17	0.13	0.17	0.03	0.17	0.17
18	0.23	0.10	0.17	0.03	0.07	0.10	0.20
19	0.10	0.10	0.33	0.23	0.03	0.20	0.20
20	0.30	0.10	0.20	0.23	0.10	0.17	0.20
21	0.17	0.13	0.30	0.07	0.07	0.17	0.30
22	0.37	0.20	0.13	0.03	0.20	0.13	0.30
23	0.40	0.03	0.17	0.03	0.17	0.23	0.30
24	0.37	0.07	0.27	0.07	0.27	0.20	0.30
25	0.37	0.07	0.30	0.13	0.20	0.17	0.30
26	0.40	0.07	0.20	0.03	0.13	0.13	0.23
27	0.37	0.07	0.30	0.13	0.20	0.13	0.27
28	0.37	0.03	0.33	0.03	0.13	0.07	0.20
29	0.30	0.07	0.23	0.13	0.10	0.10	0.20
30	0.17	0.17	0.07	0.20	0.23	0.13	0.30
31		0.30		0.17	0.07		0.33

TABLE E.3

PROBABILITY OF A NON-WORKDAY, MEDIUM TO HEAVY SOIL, MELFORT (SASKATCHEWAN) 1931-60

Date	April	May	June	July	August	September	October
1	1.00	0.77	0.40	0.37	0.27	0.37	0.73
2	1.00	0.70	0.40	0.30	0.23	0.47	0.70
3	1.00	0.73	0.37	0.37	0.17	0.37	0.67
4	0.97	0.70	0.40	0.27	0.30	0.37	0.70
5	0.97	0.57	0.37	0.23	0.20	0.40	0.73
6	0.97	0.53	0.37	0.23	0.30	0.40	0.77
7	0.97	0.47	0.40	0.20	0.13	0.43	0.77
8	0.97	0.43	0.27	0.37	0.23	0.57	0.73
9	1.00	0.53	0.17	0.33	0.20	0.47	0.70
10	1.00	0.57	0.13	0.23	0.10	0.47	0.70
11	0.97	0.50	0.13	0.23	0.13	0.50	0.70
12	0.97	0.37	0.20	0.17	0.20	0.53	0.70
13	0.97	0.37	0.20	0.23	0.17	0.57	0.73
14	0.97	0.33	0.23	0.37	0.13	0.53	0.73
15	0.97	0.17	0.37	0.33	0.20	0.57	0.77
16	0.97	0.23	0.40	0.23	0.23	0.50	0.77
17	0.97	0.30	0.33	0.20	0.20	0.60	0.77
18	0.93	0.23	0.37	0.13	0.23	0.63	0.70
19	0.97	0.30	0.33	0.17	0.17	0.60	0.73
20	0.97	0.20	0.33	0.20	0.20	0.57	0.77
21	0.93	0.17	0.27	0.33	0.13	0.63	0.80
22	0.90	0.20	0.17	0.27	0.17	0.63	0.80
23	0.87	0.17	0.27	0.17	0.17	0.63	0.83
24	0.90	0.13	0.20	0.20	0.27	0.60	0.83
25	0.83	0.20	0.37	0.20	0.23	0.63	0.83
26	0.83	0.23	0.40	0.13	0.23	0.67	0.83
27	0.77	0.17	0.60	0.13	0.17	0.67	0.87
28	0.73	0.17	0.50	0.23	0.23	0.67	0.90
29	0.77	0.33	0.47	0.27	0.20	0.67	0.90
30	0.67	0.37	0.33	0.10	0.33	0.77	0.90
31		0.37		0.20	0.30		0.90

TABLE E.4

PROBABILITY OF A NON-WORKDAY ON SANDY SOIL,
MELFORT (SASKATCHEWAN) 1931-60

Date	April	May	June	July	August	September	October
1	1.00	0.37	0.30	0.23	0.17	0.20	0.33
2	1.00	0.40	0.27	0.23	0.20	0.27	0.37
3	1.00	0.30	0.10	0.27	0.10	0.23	0.37
4	0.93	0.27	0.07	0.17	0.23	0.20	0.37
5	0.83	0.07	0.17	0.13	0.10	0.20	0.37
6	0.90	0.17	0.13	0.20	0.23	0.27	0.37
7	0.83	0.17	0.20	0.13	0.10	0.17	0.37
8	0.80	0.17	0.10	0.23	0.23	0.33	0.33
9	0.80	0.23	0.03	0.23	0.13	0.20	0.40
10	0.77	0.20	0.07	0.20	0.10	0.23	0.43
11	0.67	0.17	0.13	0.17	0.07	0.13	0.47
12	0.67	0.17	0.17	0.13	0.13	0.20	0.40
13	0.63	0.07	0.13	0.17	0.17	0.20	0.43
14	0.57	0.10	0.17	0.27	0.10	0.23	0.43
15	0.57	0.00	0.27	0.27	0.13	0.27	0.50
16	0.63	0.10	0.33	0.17	0.20	0.17	0.50
17	0.50	0.20	0.23	0.17	0.13	0.30	0.47
18	0.43	0.13	0.20	0.07	0.20	0.23	0.40
19	0.47	0.20	0.17	0.13	0.07	0.30	0.40
20	0.47	0.10	0.27	0.20	0.13	0.30	0.43
21	0.50	0.03	0.17	0.27	0.13	0.30	0.50
22	0.53	0.17	0.17	0.17	0.13	0.27	0.50
23	0.50	0.13	0.23	0.10	0.13	0.33	0.53
24	0.50	0.07	0.10	0.17	0.20	0.33	0.50
25	0.37	0.10	0.27	0.20	0.17	0.30	0.50
26	0.30	0.13	0.30	0.10	0.23	0.33	0.50
27	0.40	0.10	0.53	0.10	0.13	0.33	0.53
28	0.40	0.13	0.37	0.17	0.17	0.27	0.60
29	0.37	0.20	0.27	0.17	0.07	0.20	0.63
30	0.30	0.20	0.17	0.10	0.27	0.33	0.73
31		0.13		0.17	0.17		0.70

APPENDIX F

BIOLOGICAL TOLERANCES IN CEREAL-SEEDING

Penalty for Untimely Seeding

Each variety of cereal crop has a genetic yield potential which, because of less than ideal growing conditions, is generally never realized. Low yields are normally blamed on low precipitation, but recently it has been suggested that relatively low yields recorded in the past may conceivably be a reflection not so much of a moisture limitation, but of low fertility, adverse soil structure, undue loss of water by run-off and evaporation, outbreaks of disease or rusts, and of insects such as grasshoppers, poor seed-bed preparation, weed infestations and so on (4). Since most of these factors, together with many others not listed, will vary in intensity or importance from one time of year to another, many such effects may manifest themselves in the form of a lost revenue penalty for untimely seeding.

In fact many of the "requirements" for successful cereal cropping, in other words the determinants of yield variations, are well known (23). They include minimum (39^{o}F) and optimum (68^{o}F - 72^{o}F) soil temperatures for germination, and critical ambient temperatures (90^{o}F) after flowering which appear to be associated with low yields. The probability of a day with a maximum temperature of 90^{o}F is greatest in the third week of July. They also include light requirements -- since short days promote vegetation growth whereas long days promote flowering.

Moisture requirements vary at different stages in the life of the plant, and total requirements vary from place to place and season to season. Soil texture plays an important part in water availability, but rainfall pattern is the dominant influence. The expected level of rainfall varies markedly over the normal growing period on the Prairies, as seen from Table F.1.

TABLE F.1

AVERAGE MONTHLY PRECIPITATION IN SASKATCHEWAN, 1931-66

Location	April	May	June	July	Aug.	Sept.	Oct.
				(inches)			
Swift Current	0.95	1.26	2.77	1.88	1.82	1.25	0.80
Melfort	0.95	1.35	2.78	2.30	1.82	1.60	1.00

Weeds also affect yields, since they compete for light, water and nutrients. When the supply of these factors gets short or is critical to a stage of development, the growth of weeds can restrict crop yields. Since various weeds have water and temperature requirements different from those of cereals, it follows that their competitive advantage will be greater at certain times in the potential growing season.

Further, the number of growing days required for a crop to reach maturity depends on the variety, conditions at seeding, soil moisture and fertility. High temperature and drought tend to force premature heading and ripening. Alternatively, early drought may only slow the rate of development of the plants. Ample rainfall conditions followed by water stress may hasten maturity. Late seeding may result in short days and low temperatures during the growing period, which delay maturity.

In these various ways, the conditions affecting plant growth interact with the "husbandry dating tolerances" of the plants in a crop to cause variations in yield. The effect of time of seeding on yield has been assessed, at least to some degree, in field trials at many centres. The most complete evaluation has been made at Saskatoon, the results of which are summarized in Table F.2. These show the characteristic yield depression effects of both early and late seeding. The transition from one to the other is emphasized in Table F.3.

Data on cereal yields related to time of seeding were obtained from stations in North Dakota and Montana, as well as from Swift Current in Saskatchewan and Beaverlodge in Alberta. At all locations the same pattern of yield loss was demonstrated, though the

TABLE F.2

EFFECT OF SEEDING DATE ON CEREALS AT SASKATOON, 1929-48

Crop	Date of Seeding	Yield Per Acre (bushels)	Date of Maturity	Weight Per Bushel (lbs.)
Spring Wheat	April 15-20	26.2	Aug. 5	61.63
	May 1	27.6	Aug. 10	62.10
	May 15	28.1	Aug. 19	62.14
	June 1	27.5	Sept. 1	61.28
	June 15	22.3	Sept. 14	58.51
Durum Wheat	April 15-20	28.4	Aug. 9	62.31
	May 1	30.3	Aug. 14	62.97
	May 15	30.5	Aug. 23	62.86
	June 1	27.2	Sept. 6	60.53
	June 15	22.0	Sept. 17	54.97
Oats	April 15-20	51.2	Aug. 5	35.06
	May 1	56.4	Aug. 10	35.85
	May 15	55.7	Aug. 15	36.06
	June 1	48.3	Sept. 1	35.44
	June 15	48.7	Sept. 12	34.34
Barley 2R	April 15-20	41.5	Aug. 1	51.16
	May 1	44.9	Aug. 5	51.50
	May 15	45.2	Aug. 12	51.55
	June 1	41.5	Aug. 25	50.85
	June 15	40.7	Sept. 11	49.61
Barley 6R*	April 15-20	39.4	July 31	49.81
	May 1	37.8	Aug. 5	50.59
	May 15	40.8	Aug. 13	49.97
	June 1	36.0	Aug. 23	47.03
	June 15	35.9	Sept. 10	46.41

* 1941-48.

TABLE F.3

PENALTY FOR EARLY OR LATE SEEDING OF CEREALS, SASKATOON, 1929-48

Seeding Date	Wheat		Durum		Oats		Barley 2R	
	Bushel Loss	Percentage Loss	Bushel Loss	Percentage Loss	Bushel Loss	Percentage Loss	Bushel Loss	Percentage Loss
April 10	3.6	12.8	4.5	14.8	11.0	19.5	8.3	18.3
20	1.6	5.7	1.7	5.6	3.5	6.2	3.1	6.8
30	0.5	1.8	0.3	1.0	0.3	0.5	0.6	1.3
May 10	0.1	0.4	0.1	0.3	0.3	0.5	0.0	0.0
20	0.1	0.4	1.1	3.6	1.9	3.4	0.7	1.5
30	0.5	1.8	3.0	9.8	4.5	8.0	2.4	5.3
June 10	3.3	11.7	6.3	20.6	8.5	15.0	5.5	12.2
15	5.7	20.2	8.5	27.8	10.5	18.6	7.3	16.1

absolute level of the losses varied from place to place and from year to year. Since the Saskatoon data were the most comprehensive -- in both range of seeding dates considered, and number of years' observations -- it was decided to establish an optimum seeding date for Locations 1 and 4 respectively, and to apply the Saskatoon loss pattern to those locations by moving the range of losses in relation to the seeding dates.

The same loss pattern appears to be encountered progressively later in the season as we move north from Montana, through Swift Current and Saskatoon, to the Peace River country. For the purposes of the simulation Model 3, it was assumed that the same loss pattern (in terms of percentage of yield lost) was encountered at both Swift Current and Melfort as has been shown to exist for Saskatoon. The time at which the losses were at a minimum was adjusted to coincide with the optimum seeding period at both test locations.

The yield loss was calculated on the basis of an "expected yield". The average yield in the Swift Current area over the period 1938-67 was 15.4 bushels per acre. At Swift Current Research Station during the years 1941-58, wheat yield averaged 22.7 bushels per acre. Potential wheat yields for the same area estimated by de Jong and Rennie (5) to be 32 bushels per acre on fallowed land and 26 bushels on stubble. In determining the "expected yield" on which to base penalty costs, allowance was made for the effect of better husbandry practices; and the average wheat yield for the Swift Current area was assumed to be 25 bushels per acre.

The average yield in the Melfort area during the period 1938-67 was 25 bushels per acre. Records of yields are not available for the Melfort Research Station, so no comparison can be made with the average yields for the area. The potential yield estimated by de Jong and Rennie for Melfort is 58 bushels per acre on fallow and 47 bushels per acre on stubble. At Swift Current the ratio between the yield obtained at the Research Station and the average yield for the area is 22.7:15.4. By applying a similar ratio at Melfort, wheat yields might be expected to be in the order of 37 bushels per acre.

If the average price of wheat is assumed to be $1.80 per bushel, then we would expect a gross revenue of $1.80 x 25 = $45 at Swift Current and \$1.80 x 40 = \$72 at Melfort. In order to obtain a value for net revenue, it is necessary to subtract a value for production costs. After allowing for seed costs, cost of seeding, spraying, harvesting, and so on, costs were somewhat arbitrarily assumed to be \$15 per acre at Swift Current and \$22 per acre at Melfort, reducing the net revenue to \$30 per acre and \$50 per acre at Swift Current and Melfort respectively.

The yield loss penalties calculated in dollar terms on the basis of these assumptions are shown in Table F.4.

Starting Date of Spring Tillage

The date on which the farmers first begin seeding, as well as the date by which most farmers have begun seeding, has been recorded by the Saskatchewan Department of Agriculture in all districts for a period of 25 years. For purposes of this model it was assumed, for want of better knowledge, that spring tillage operations started seven days before the early starting farmers first began seeding. From the 25 observations of seeding date obtained, a probability distribution was produced to serve as a basis for selecting a starting date for the model. This probability distribution is given in Table F.5.

Since there is a penalty for seeding too early, as well as for seeding too late, it seemed desirable to set a date before which seeding could not start regardless of the starting date for tillage. Since it appears that seeding never starts before April 17 at Swift Current, and never before April 25 at Melfort, these dates were used to restrict early seeding in the simulation model.

Other Seeding Constraints

If, due to a late starting date or due to unusually bad weather, farmers have not completed their pre-seeding cultivation, they may wish to seed directly without further pre-seeding cultivation. Since May 15 appeared to be the optimum day for seeding, it was assumed that pre-seeding cultivation would not continue past that date. An arbitrary penalty of \$1 per acre was assessed on any acreage seeded without prior cultivation.

As the season progressed, penalty charges increased more rapidly. By June 1, penalty charges were \$1.62 at Swift Current

TABLE F.4

YIELD PENALTIES RELATIVE TO SEEDING DATE IN DOLLARS PER ACRE

Seeding Date	Swift Current	Melfort	Seeding Date	Swift Current	Melfort
April 17	3.55	8.60	May 17	0.07	0.24
18	3.23	8.10	18	0.11	0.18
19	2.92	7.60	19	0.14	0.12
20	2.60	7.10	20	0.18	0.06
21	2.42	6.60	21	0.24	0.00
22	2.24	6.10	22	0.31	0.06
23	2.06	5.60	23	0.37	0.12
24	1.88	5.10	24	0.43	0.18
25	1.71	4.60	25	0.50	0.24
26	1.53	4.10	26	0.56	0.29
27	1.35	3.82	27	0.62	0.40
28	1.17	3.54	28	0.68	0.50
29	0.99	3.26	29	0.75	0.60
30	0.81	2.98	30	0.81	0.70
May 1	0.75	2.70	31	1.21	0.80
2	0.68	2.42	June 1	1.62	0.90
3	0.62	2.14	2	2.02	1.00
4	0.56	1.86	3	2.43	1.10
5	0.50	1.58	4	2.83	1.20
6	0.43	1.30	5	3.24	1.30
7	0.37	1.20	6	3.64	1.95
8	0.31	1.10	7	4.05	2.60
9	0.24	1.00	8	4.45	3.25
10	0.18	0.90	9	4.86	3.90
11	0.14	0.80	10	5.26	4.55
12	0.11	0.70	11	6.03	5.20
13	0.07	0.60	12	6.79	5.85
14	0.04	0.50	13	7.56	6.50
15	0.00	0.40	14	8.32	7.15
16	0.04	0.29	15	9.09	7.80

TABLE F.5

ESTIMATED TILLAGE STARTING DATE

Starting Date	Swift Current		Melfort	
	Observed	Probability	Observed	Probability
April 10	1	.04		
11	1	.04		
12				
13	1	.04		
14	2	.08		
15	1	.04		
16	1	.04	1	.04
17	2	.08		
18	3	.12		
19	1	.04	2	.08
20	2	.08	1	.04
21	2	.08		
22	1	.04	1	.04
23	1	.04		
24	1	.04		
25			1	.04
26	1	.04	1	.04
27	1	.04		
28	1	.04		
29			1	.04
30	2	.08	1	.04
May 1			2	.08
2			3	.12
3			2	.08
4			2	.08
5			1	.04
6				
7				
8			2	.08
9			2	.08
10				
11			1	.04
12			1	.04
	25	1.00	25	1.00

and $2.60 at Melfort. At this point a farmer may, in practice, consider hiring an additional man to speed the seeding operation by working double shifts. In this model, it was assumed that the rate of work was doubled if seeding was delayed past June 1. A penalty of $2 per acre was assessed on any acreage seeded after June 1.

If seeding is not complete by June 15, the high penalty plus the risk of a frozen crop make it unlikely that seeding of wheat will continue. It has therefore been assumed that seeding stopped on June 15 and a penalty was charged commensurate with the lost revenue from the unseeded acres.

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