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FIELD MACHINERY SYSTEM MODELING AND REQUIREMENTS FOR SELECTED MICHIGAN CASH CROP PRODUCTION SYSTEMS

By

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ABSTRACT

FIELD MACHINERY SYSTEM MODELING AND REQUIREMENTS
FOR SELECTED MICHIGAN CASH CROP PRODUCTION SYSTEMS

By

Devindar Singh

A computer model was developed to design field machinery systems for multicrop farms. The model was utilized to evaluate and compare major crop production systems, typical in southern Michigan, over a range of sizes with respect to costs and requirements for machinery, labor and fuel.

The computer model designs a machinery system based upon field work specifications, field operation calendar date constraints, machinery capacity relations, and field work conditions. The model specifies the size and number of each machinery component, prepares a detailed week-by-week work schedule, gives the distribution of labor needs, calculates fuel requirements for each operation, and makes detailed cost analysis of the selected machinery set.

The model permits three different use categories of two-wheel drive tractors, each of a unique size, to assure "near-full" utilization of power. The machinery system design procedure basically consists of a series of suboptimizations by iterative search, subject to constraints on available power, implement size and speed, and completion of each

operation by the specified date with the specified design probability. The sequence of suboptimizations is: harvesting capacity, large tractor power, small tractor power, number of tractors for alfalfa harvesting (where alfalfa is included in the rotation) and number of units of each implement. An operations schedule is prepared to determine whether the selected machinery system is sufficient to satisfy all date constraints at the given design probability. If any constraint is violated, an adjustment is made in the number of implement units or in the tractor power.

Machinery requirements (number and size of each machinery component) and costs were determined for 29 crop production systems consisting of ten crop rotations involving corn, soybeans, field beans, wheat and alfalfa, and three tillage systems - moldboard plow, chisel plow and no-till. The range of farm sizes considered varied from the maximum crop area that a 2-row combine can harvest to that corresponding to an 8-row combine.

Multicrop balanced rotations increased machinery utilization, decreased (1) machinery requirements on a unit crop area basis by as much as half, (2) machinery investment by as much as 40 percent, and (3) annual machinery related costs by as much as 30 percent over single-crop rotations. Tillage intensity influenced tractor power and fuel requirements, but the effect on machinery investment and machinery related costs was generally less than 15 percent for multicrop rotations. This was because different crops were raised at the reduced tillage intensity using different tillage systems and, therefore, more implements were required. Other conclusions from the study included the following:

1. As farm size increases, annual machinery related costs decrease at a decreasing rate. Maximum reduction occurs when farm size is increased from the maximum area that a 2-row combine can harvest to that corresponding to a 4-row combine.
2. The multicrop rotations have a more even distribution of labor during the year compared to single-crop rotations. However, the annual labor requirements per unit area are not considerably affected by the crop rotation. For rotations involving alfalfa, the labor requirements are very high during three 2-week harvesting seasons of alfalfa.
3. Fuel requirements decrease with a decrease in tillage intensity for every crop rotation. But the variation in fuel requirements among rotations is generally less than 25 percent.

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C C	Continuous corn crop rotation
S S	Continuous soybeans crop rotation
C S	Corn-soybean crop rotation
C FB	Corn-field bean crop rotation
C C S W	Corn-corn-soybean-wheat crop rotation
C C FB W	Corn-corn-field bean-wheat crop rotation
C W A A	Corn-wheat-alfalfa-alfalfa crop rotation
C S W A A	Corn-soybean-wheat-alfalfa-alfafa crop rotation
C C S W A A	Corn-corn-soybean-wheat-alfalfa-alfalfa crop rotation
C C FB W A A	Corn-corn-field bean-wheat-alfalfa-alfalfa crop rotation
MBTS	Moldboard plow tillage system
CHTS	Chisel plow tillage system
NTTS	No-till tillage system
HLTI	Highest level of tillage intensity
MLTI	Medium level of tillage intensity
LLTI	Lowest level of tillage intensity
TMRC	Total annual machinery related costs per hectare
IMI	Initial machinery investment per hectare
FWH/D	Field working hours/day

1. INTRODUCTION

Several recent studies have raised questions about declining resource productivities (output per unit of resource input) or declining rates of increase in resource productivity in agriculture (Committee on Agricultural Production Efficiency, 1975; Heichel, 1973; Pavelis, 1973; and Pimentel et al., 1973). Energy, land, labor, capital, as well as other resource productivities have been addressed. In many instances, technological adjustments have caused agricultural resource productivity changes and these adjustments simply reflect the economic (as perceived by decision-maker) substitution of one set of resources for another. The economic forces for adjustments are the integrated result of physical laws governing the production processes, constraints upon the processes, and the relative prices of resources (Holtman and Connor, 1976). This study is concerned with the analysis and assessment of these relationships for field machinery, labor and fossil fuel in the production of certain major Michigan field crops.

Field crops are a major agricultural product of Michigan; 24.5 percent of Michigan farms with sales of $2500 and over were classified as cash grain farms in 1969 Census of Agriculture (Volume 1, part 13, section 1). They are the second most common type of farms in Michigan after dairy farms (28.5 percent). Corn, soybeans, field beans, wheat and oats are the main cash crops of Michigan. Sixty-three percent of the cash grain farms were growing corn, 44.7 percent soybeans, 48 percent field beans, 77 percent wheat and 40.6 percent oats, in 1969. Alfalfa hay is also an important crop in Michigan. About half of all Michigan farms were growing alfalfa hay in 1969.

Field machinery costs are a major component of the total farm budget. A Michigan study (Holtman et al, 1976) estimated that field machinery accounts for 24 percent of annual costs and 21 percent of capital requirements in the production of crops on a dairy farm. Furthermore extreme variations exist among farms due to cropping practices and management. A Pennsylvania extension publication (Waters and Daum, undated) showed that machinery costs for corn production in 1969 varied from $35 to $116 per hectare.

Field machinery productivity per unit of cropland area can be significantly increased either by increasing machinery utilization or by reducing the intensity of tillage for a particular crop. Machinery utilization can be increased by using a crop rotation that distributes work more evenly over the cropping year.

The crop rotation, i.e. the nature of field work distribution would significantly influence peak labor requirements. The total labor requirements may also be affected by the crop rotation. Reduction in the tillage intensity would reduce operator labor required for field work.

Fossil fuel requirements would decrease with a decrease in tillage intensity but would remain unaffected by the nature of field work distribution over the cropping year. Fossil fuel requirements may also change with a change in the crop rotation.

The design conditions on field machinery system requirements are extraordinary in Michigan. In comparison to most midwestern agricultural areas, Michigan has a shorter growing season and much lower fraction of calendar days suitable for field work in the crucial planting and harvesting periods (Tulu et al., 1974). Therefore, the economic advantage associated with increasing machinery productivity per unit of cropland area is more important in climates like that of Michigan.

Procedures for tradeoff analysis need to be developed to evaluate production resource requirements and costs in relation to alternative physical and technical organization (scale and technology) of the production unit. This study developed such a procedure for major field crops of southern Michigan. The crops considered were corn, soybeans, field beans, wheat and alfalfa. The technologies selected were those that are used on farms in southern Michigan. However, all forms of technology were not considered. Instead, an attempt was made to select only those technologies that represent "points" on the spectrum of current or potential technologies. Thus, tillage systems representing three levels of tillage intensity were selected. Tillage systems considered were: no-till, chisel plow and moldboard plow. The names of these tillage systems refer to the primary tillage operation in each case. Farm size levels (cropland area) considered were related in general to the size range currently in existence in the southern part of the state - a range which was sufficient for evaluating the relevant economies or diseconomies of scale.

1.1 Selection of an Appropriate Approach

There are two ways to approach such a study. Actual operating systems using each crop production system can be located and analyzed from the information gathered on site. This approach is difficult because comparable systems using the same technology, similar management and having comparable weather patterns and land base have to be located over a suitable range of sizes. Also, in order to compare different cropping systems with respect to several variables, all variables have to be held constant except one, to observe the effect of that one variable. As this cannot be done in the real world, a synthetic modeling approach was used.

To design a field machinery system which satisfies specified physical performance characteristics and probabilistic calendar date constraints, a large number of calculations are required. Since results were required for a number of crop production systems, a computer program was developed for designing field machinery systems.

1.2 Objectives of the Study

The following objectives of the study were formulated:

1. To develop a computer model to design field machinery systems for multicrop farm situations that will enable comparison of different crop production systems with respect to costs and requirements for machinery, labor, and fossil fuels for field work.
2. To evaluate and compare major crop production systems of southern Michigan over a range of sizes. Crop production

systems considered should include most economically and agronomically feasible mix of crops of corn, soybeans, field beans, wheat and alfalfa using a no-till, chisel plow or moldboard plow tillage system.

1.3 System Boundaries and Desirable Model Characteristics

A number of system constraints and model characteristics were established at the onset:

1. The model should be developed for an individual farming operation (an individual firm) that exists solely for the production of field crops. There should be no competition for men, machine or field time from other farm enterprises.
2. The model should be able to handle field operations for any mix of crops of corn, soybeans, field beans, wheat and alfalfa using no-till, chisel plow or moldboard plow tillage system.
3. The model should be able to take into consideration the probabilistic nature of weather and its effect on field machinery requirements.
4. The model should be able to design "realistic" field machinery systems and produce a schedule of operations which is consistent with normal practices for selected crop production systems over a suitable range of farm sizes.
5. The range of sizes considered for each cropping system should, in general, be related to the range currently in existence in southern Michigan and to the range which is sufficient for evaluating relevant economies or diseconomies of scale.

6. The technology considered should consist of self-propelled combines and two-wheel drive tractors. This will simplify the model structure and still be able to represent most of the Michigan farms. Therefore, farm sizes considered should be large enough to require the use of self-propelled combines, but big farms that use four-wheel drive tractors should not be considered.
7. Since data of equal reliability on timeliness cost of different operations is not available for all crops, timeliness cost should appear as a constraint rather than as a component of an objective function. The model should produce results for different cropping systems which are comparable.
8. In Michigan custom hiring, leasing, and other types of sharing of equipment, may occasionally be practiced, but is not common. Therefore, each firm should have complete control of its machinery system.
9. In addition to the field machinery set, the model should provide weekly labor requirements, fuel consumption and monetary costs associated with the machinery set for each crop production system.
10. The results should be obtained for well-drained Miami-Conover loam soils which are common in southern Michigan.

2. REVIEW OF LITERATURE

The design of field machinery systems involves calculation of machine productivities, estimation of suitable field work time, selection of an appropriate performance criteria and development of a suitable procedure for optimizing performance criteria subject to specified constraints.

2.1 Machine Productivities

The major factors influencing the productivity of a machine are size, operating speed, field efficiency and energy requirements.

The available sizes of various machines can be obtained from price lists of farm machinery manufacturers such as the Agricultural Whole Goods Price List of Deere and Company, or from Implement and Tractors Red Book (1977).

Field efficiency is a measure of relative productivity of a machine under field conditions. It accounts for failure to utilize the theoretical operating width of the machine and for time losses due to turning, idle travel, material handling, cleaning clogged equipment, and field repair and maintenance. It is not a constant value for a specific machine but varies widely. Hunt (1977) described various factors affecting the field efficiency of a machine. Typical ranges in operating speed and field efficiency for most types of machines are given in the Agricultural Engineers Yearbook (1977), which summarizes data prior to 1971, and elsewhere (Hunt, 1977; Bowers, 1970).

Field machine energy requirements consist of functional requirements and rolling resistance requirements. Functional requirements are those that relate directly to the processing of soils, seeds, chemicals or crops. Rolling resistance power requirements arise from the necessity for moving heavy machinery over soft field surfaces. Functional requirements depend upon soil and crop conditions which are highly variable. Tillage draft varies with soil type, soil moisture, root development, organic matter content and depth of penetration. Forward speed also significantly affects plow draft (Agricultural Engineers Yearbook, 1977). To provide an indication of the degree of variability, relative drawbar pulls for moldboard plows in different soils are listed below (Hunt, 1977):

Sandy soil	1.0	Clay loam	2.3	Heavy clay sod	3.6
Sandy loam	1.6	Clay	2.8	Moist gumbo	5.5
Silt loam	2.0	Heavy clay	3.3	Dry adobe	7.8

Draft of tillage implements is normally reported per unit of effective width or per row. Rolling and functional requirements are combined for most tillage and ground driven machines (Hunt, 1977). Ranges of draft, energy or power requirements for most field machines are listed in the Agricultural Engineers Yearbook (1977) and elsewhere (Hunt, 1977; Bowers, 1970). White (1975b) published draft requirements of various machines under Michigan conditions.

2.2 Suitable Field Work Days

The relation of the fraction of calendar days suitable for field work to climatic and soil conditions has been modeled for Michigan (Tulu et al., 1974), as well as for several other areas. Various techniques have been used to determine this relation.

Records of observed numbers of suitable field work days have been reported by Link (1962) from the personal diary of the manager of the Ames, Iowa, Agronomy Farm (1932-1939, 1942-1961) and by Morey et al. (1972) from field observers in central Indiana (1952-1968). The observations of suitable days were made on a single farm or for a particular region in all cases restricting their validity to that situation. Fulton and Ayres (1976) reported observed numbers of suitable days in Iowa at different probability levels for field operations throughout the crop season based on records of Iowa Crop and Livestock Reporting Service.

Carpenter and Brooker (1970) determined suitable days for corn harvesting in Missouri from historical climatological records. A day on which any one of the following conditions occurred was assumed to be an unsuitable day for corn harvesting:

Daily precipitation > (Temp. + 17.78)/8.749

Two-day accumulated precipitation > (Temp. + 17.78)/4.374

Three-day accumulated precipitation > (Temp. + 17.78)/2.187

Four-day accumulated precipitation > (Temp. + 17.78)/1.094

Five-day accumulated precipitation > (Temp. + 17.78)/0.547

Snowfall ≥ 25 mm

Snowdepth ≥ 25 mm

All temperatures were average daily temperature in °C. They also assumed that soil would be frozen on any day with an average temperature less than -6.7°C (20°F) and classified such days as suitable for harvesting regardless of precipitation if snowfall and depth of snow were both less than 25 mm. No validation of the model was reported.

Several investigators have used soil moisture content as a criterion for suitable field work days. Shaw (1965a) used a soil moisture budgeting technique to estimate the moisture content in the top 152 mm of soil profile from daily precipitation and evaporation for Clarion-Webster soils of Iowa. He assumed that soil was workable any day when it was not frozen and the available soil moisture in the top 152 mm of the profile was less than or equal to 19 mm (available water capacity = 23 mm). He compared the number of predicted days suitable for field operations to the record of suitable days from the old Agronomy Farm, Ames, Iowa (Link, 1968). The correlations between the observed and predicted number of days during March, April, and May ranged from 0.87 to 0.93.

Bolton et al. (1968) developed a soil moisture accounting technique to estimate soil moisture content on any day from records of rainfall and pan evaporation. From a two-year record of days suitable for field operations at the Delta Branch Experiment Station, Stoneville, Mississippi, they classified a day as a workday if the soil moisture in the 152 mm surface layer was 80 percent of field maximum for tillage operations and 85 percent for nontillage operations for silty clay and sandy soils. For clay soils moisture must be at or below 78 percent of field maximum for all field operations.

Link (1968) also used a moisture budgeting technique to estimate daily soil moisture contents. He proposed the plastic limit as the maximum value for the soil to be trafficable, and suggested that field conditions suitable for tillage operations could be defined by a maximum soil moisture content below the plastic limit and some minimum soil moisture content.

Rutledge and McHardy (1968) partitioned the soil into six moisture zones and used a soil moisture budget developed by Baier and Robertson (1966) to estimate the soil moisture content in each zone from climatological records. They also calculated values of soil shear strength required for tillage of Alberta soils, and concluded that required shear strength would be developed at soil moisture contents at or below field capacity. They obtained a good correlation with observed days suitable for tillage when 95 percent of available water capacity was used as the maximum soil moisture content in the top three zones and the restriction of no snow on the ground was included.

Peterson and Frisby (1969) used wind tunnel studies to develop an equation for the drying rate of soil at moisture contents above field capacity. Frisby (1970) used this equation and a soil moisture budgeting technique for predicting the number of good days available for primary tillage in the spring and fall for a soil in central Missouri. He classified a day as suitable for tillage if the soil moisture content was equal to or less than field capacity and if precipitation was less than 2.5 mm.

Morey et al. (1971) used a soil moisture budgeting technique developed by Shaw (1963) and tractability criteria based primarily on the results of Rutledge and McHardy (1968) to estimate the number of days suitable for harvesting corn in central Indiana. A suitable day was defined as one having less than 2.5 mm of precipitation and a moisture content less than 95 percent of available water capacity in the top 152 mm of the soil profile.

Selirio and Brown (1972) estimated spring workdays in Ontario from climatological records. Based on two years of soil moisture measurements and observation of work conditions, they concluded that cultivation was possible when the soil moisture content was about 90 percent of the field capacity value to a depth of 120 mm regardless of soil moisture content in the lower zones. A day was assumed to be suitable for field work if the top 120 mm of the soil was at or below 90 percent of field capacity, daily snowfall was less than 25 mm and maximum air temperature was above 0°C (32°F).

Holtman et al. (1973) used a combination of the soil moisture budgets developed by Shaw (1963) and Baier and Robertson (1966) to estimate available soil moisture in the top 152 mm of the soil profile. They defined a day as suitable for corn harvesting if the available water capacity in the upper 76 mm of the soil profile was below 95 percent on light soils. For heavy well drained soils, they proposed that percent available water capacity in the second 76 mm of the soil profile must also be below 98 or 99 percent. They did not determine vehicle mobility when soil was frozen.

Tulu (1973) extended the work of Holtman et al. to frozen soil. The models of Fridley and Holtman (1972) were employed to compute soil freezing and thawing dates required for soil moisture budget. He assumed a day was suitable for corn harvesting if the soil was frozen or if thawed the available water capacity in the upper 76 mm of soil profile was below 95 percent. For spring tillage and planting operations, a workday was assumed if the available water capacity in the upper 76 mm of soil profile was below 95 percent and in the second 76 mm of the soil profile was below 98.5 percent. He verified the model results with observed workdays from three northern Indiana farms for 1970.

Kish and Privette (1974) estimated the number of field work days available for tillage on South Carolina soils based on a soil moisture budget of the upper 305 mm of the soil. The percentage of field capacity at or below which soils were assumed to be tillable varied from 70 to 95. They did not report any field soil moisture measurements to support considered limits.

Hassan and Broughton (1975) stated that tractability criteria for seed bed preparation appeared to be affected by the moisture state in the upper 25 mm and second 51 mm of soil profile based upon limited field observations. The limiting percentages of available water capacity in the upper 25 mm and next 51 mm of soil profile for clay, clay loam and sandy loam soils of the MacDonald College Farm, St. Lawrence Lowlands, Quebec were reported by them to be 10, 97; 50, 93; and 66, 98.2; respectively.

Ayers (1975) used soil moisture budgeting techniques developed by Shaw (1963, 1965b) for predicting suitable days for corn harvesting in Iowa. Records of good and bad field days from the old Agronomy Farm, Ames, Iowa (Link, 1962) were used to select the values of the decision parameters by sensitivity analysis. The values of parameters in the model that had the best agreement with the eight-year observations were:

Maximum precipitation yesterday	13.7 mm
Maximum precipitation today	
Unfrozen soil	6.9 mm
Frozen soil	2.5 mm
Maximum available soil moisture, 0-152 mm	26.7 mm
Maximum snowfall	25.4 mm
Maximum depth of snow on the ground	0.00 mm

Elliot et al. (1977) developed a soil moisture balance model to predict days available for soil tillage in Illinois during the spring months. Percent of the available soil moisture in the upper 150 mm of soil was used as a tillage criterion, 80 percent for fine sandy loam soils and 90 percent for silt loam soils. They tested the model against field work day data from the Illinois Cooperative Crop Reporting Service and local daily field observations of favorable workdays and found it to be sufficient to predict available tillable days on a monthly basis.

2.3 Selection Criterion

The selection criterion used in machinery system design is most often an economic one, i.e. least cost or maximum profit (Hunt, 1963; Frisby and Bockhop, 1968; Burrow and Siemens, 1974; MacHardy, 1966a,b). The costs considered are machinery, labor and timeliness.

2.3.1 Machinery costs

Machinery costs are divided into two categories, fixed costs and variable costs. Variable costs increase proportionally with the use of the machine, while fixed costs are independent of use. The costs of interest on machinery investment, taxes, housing, and insurance are dependent on calendar year time and are independent of use. The costs of fuel, lubrication, daily service and maintenance are associated with use. Depreciation and cost of repairing seem to be a function of both use and time. But, most often depreciation is included in the fixed cost category and repair cost in the variable cost category.

Detailed procedures for estimating machinery costs are available in Hunt (1977) and elsewhere (Agricultural Engineers Yearbook, 1977; Bowers, 1970). Estimates of these costs can be found in extension bulletins of various Agricultural Engineering departments (Stapleton and Hinz, 1974; Eidsvig and Olson, 1969; Waters and Daum, undated). Fairbanks and Larson (1971) have published costs of using farm machinery based on a survey of the best farmers in Kansas. Hunt (1974) has reported the results of an eight-year monitoring of the repair and maintenance costs of 745 machines on Illinois farms.

2.3.2 Labor costs

For a grower-operator of a farm, the labor costs are the opportunity cost of operator time used for operating machinery. If hired labor is used, the cost may be on an hourly or annual basis. On an hourly basis, total labor cost is directly proportional to machine operating time. When labor is hired on an annual basis, total labor cost is independent of machine operating time.

Burrows and Siemens (1974) computed labor cost assuming that each man was hired at an annual salary, full time, only to operate machinery. Hughes and Holtman (1974) assumed hired labor on an hourly basis.

2.3.3 Timeliness costs

Timeliness is a measure of ability to perform a job at a time that gives optimum quality and quantity of product. If the machine system does not have enough capacity to perform the job with desired results, the value of crop loss is considered an economic penalty for poor timeliness.

Timeliness penalty costs include reduced yield from improper tillage, seedbed preparation and planting operations; losses associated with improper timing of machine operations to biological needs of the maturing plant; and any reduction in product quality that may be attributed to untimely machine operations. Some operations may have near zero timeliness costs. Others, particularly the harvest of highly perishable products, may have very high timeliness costs (Agricultural Engineers Yearbook, 1977).

A timeliness loss curve (relationship between crop value and the operation date) varies with operation, crop, farm location, and even from one year to another. Hunt (1977) and Bowers (1970) gave estimates of timeliness loss factor (fractional reduction in yield or value of the crop per acre-day of delay) for some specific crops and operations. They assumed a linear reduction in yield (or value) of crop after an optimum date.

Since reliable data for timeliness costs of all operations and for all crops is not readily available for all locations, some investigators (Hughes and Holtman, 1974; Bowers, 1975) considered timeliness as a system design constraint. Suitable calendar periods for each operation were established and machinery system size was optimized subject to timeliness constraints.

2.4 Machinery System Design Procedures

Reference literature contains much data on the costs of operating farm field equipment, but few publications have considered the problem of capacity or size selection. The essential methodology for matching the size of ground engaging implements to tractor power and for calculating productivity is given in the Agricultural Engineers Yearbook (ASAE, 1977).

Hunt (1963, 1966) presented procedures for selecting field machinery on an economic basis. Annual cost equations for each implement were written in terms of effective width of implement and for the tractor in terms of maximum PTO power. Each annual cost equation included a term for timeliness cost associated with that operation. The least cost size for each machine was determined independently of the others by differentiating the annual cost equation with respect to the pertinent variable and setting the differential equal to zero. Hunt (1972) described a similar procedure for determining the economic power level for big tractors. Scarborough and Hunt (1973) modified these programs by including algorithms for determining optimum replacement periods for the equipment and for scheduling operations which are competitive in nature.

Link and Bockhop (1964) approached selection from a scheduling viewpoint. They presented an analytical approach for matching a machinery system to a set of farm job requirements and evaluating the match for timeliness of operation. Probabilities of completion of field work within specified periods were used. Frisby and Bockhop (1968) used Link's model to determine acreage yielding maximum income for a given machinery system. Three separate job sequences for the culture of a single crop, corn, were considered. Machinery ownership cost and the value of crop lost due to incomplete harvest were subtracted from gross income to calculate income for a given farm size with a given machinery system. Plowing capacity and harvesting capacity were not balanced in some systems. They suggested that these systems be modified by increasing plowing capacity until the maximum acreage limited by harvesting capacity is obtained.

MacHardy (1966a) described a method using Lagrange Multipliers for determining the minimum cost machinery combination. The method determines implement productivities and tractor horsepower such that annual fixed machinery cost is a minimum. MacHardy (1966b) described a procedure for selecting machinery size by minimizing the sum of annual fixed machinery and timeliness costs. Using cumulative distribution curves for consecutive good and bad days and a Monte Carlo approach, a grain combining operation was simulated. A search on size yielded the optimum.

Burrows and Siemens (1974) developed a computer program to determine least cost machinery mix for corn-soybean farms in the corn belt. A search was conducted on a simulation which considered machinery, labor, and corn planting timeliness costs. The simulation was based on workday probabilities developed from data given by Link (1968) for the Ames, Iowa, Agronomy Farm. The optimum machinery set and the number of men required was determined by making several trials. For each search trial all tractors and combines were equal in size. In scheduling field operations a tractor was continually assigned to a field operation until the operation was completed.

Hughes and Holtman (1974) developed a computer program for selecting and sizing machinery systems based upon calendar date constraints on field operations. Field operations were organized into subsets. Each subset was a group of field operations that must be performed either simultaneously or sequentially during a specific time period. Timeliness costs were not considered explicitly. Rather, a calendar period constraint was assumed for each subset of operations. It was assumed that all field operations used the same fixed percentage of rated tractor drawbar power at all times and subset time was divided among operations according to the energy requirements of the operations. The effective horsepower required for the system was the maximum of that required for any one subset. It was possible to reduce this maximum horsepower by manually modifying the distribution of work among subsets (where agronomically feasible) and re-running the program.

Bower (1975) described a similar procedure for machinery selection which he used for a 50,000 hectare farming operation in Yugoslavia. A tractor size was assumed and implements were matched to the tractor. A timeliness constraint was included by requiring that operations be completed before yields started reducing at an accelerated rate. Calendar date constraints were adjusted manually to obtain the least cost feasible allocation of field work over time.

The timeliness cost data of equal reliability for field operations of all the crops to be considered in this study is not available for southern Michigan conditions. Therefore, the algorithms that design machinery systems by optimizing an economic objective function could not be used for this study. And also, since a large number of crop production systems was to be compared over a range of sizes, the computer algorithms that do not completely automate design calculations were not suitable for this study. Therefore, it was decided to develop a new computer algorithm that satisfied all the system constraints and have desirable model characteristics described in section 1.3.

3. SYSTEM MODEL

The system model described herein designs a field machinery system for a multicrop farm situation based on time constraints. The machinery system design procedure basically consists of a series of suboptimizations by iterative search, subject to constraints on the completion of each operation by the specified date with the specified design probability. For each suboptimization, suitable field work time that can be expected for a given design probability level is calculated for each operation. A machine width or power level is assumed and the productivity of each operation is calculated subject to constraints on available power, implement size and speed. The field time required for each operation is determined by dividing total crop area by the productivity of the operation. This result is compared with the available field time within the specified calendar date constraints. If there is a difference between the available field time and the required field time, the assumption is adjusted and the procedure repeated until a smallest multiple of basic machine width or 0.75 PTO kW (1 HP) power level is reached that makes the required field time equal to or less than the available field time. The selection procedure proceeds in a sequence of this type of suboptimizations on harvesting capacity, tractor power, and implements. In each suboptimization maximum multiple use of each unit of equipment is made.

The sequence of suboptimizations establishes a lower bound on the number and size of each required machinery component. An operation schedule is prepared to determine whether the selected machinery system is sufficient to satisfy all date constraints at the given design probability. If any date constraint is violated, an adjustment is made in the number of implement units or in the tractor power. An operations schedule is also developed for an average year (50 percent probability) to provide an indication of the timeliness cost involved with the selected machinery set, and to determine the labor distribution during the year. Cost calculations are made to estimate the average annual costs of the selected machinery system.

Figure 3.1 shows a simplified general flow diagram of the procedure. The listing and other details of the computer program which was developed by the author for this study are given in the forthcoming Agricultural Economics Report Number 331 (Singh and Connor, 1978). Here the methodology is described using as an example a 446 hectare (1102 acre) corn-corn-soybean-wheat cash crop farm in southern Michigan.

3.1 Input Data

The required input data consist of:

1. Farm size,
2. Crop rotation,
3. Field operations to be performed,
4. Starting and finishing date constraints for each operation,
5. Field work hours per working day for each operation,
6. The desired design probability for meeting all date constraints and,

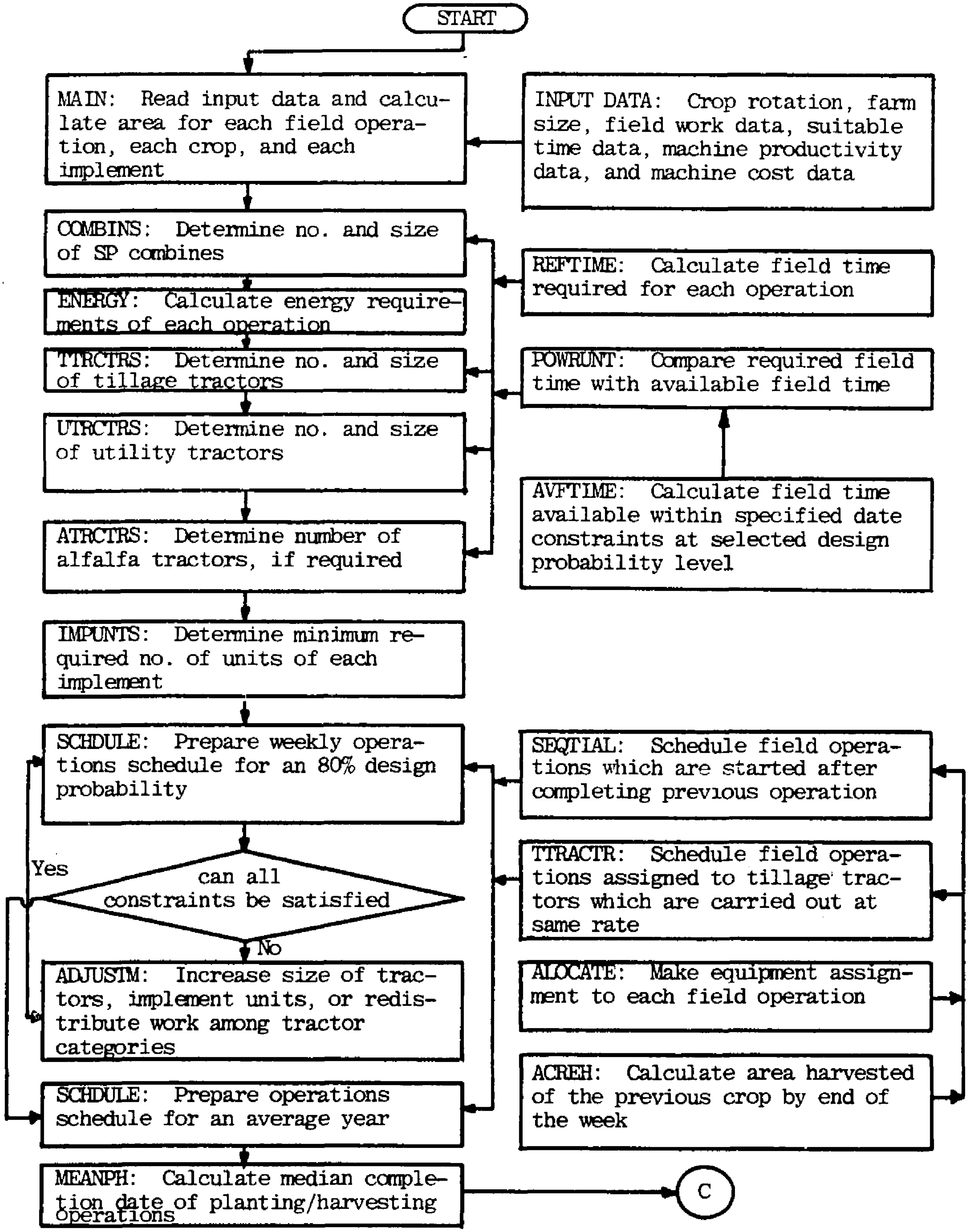


Figure 3.1 Simplified General Flow Diagram for Machinery System Design.

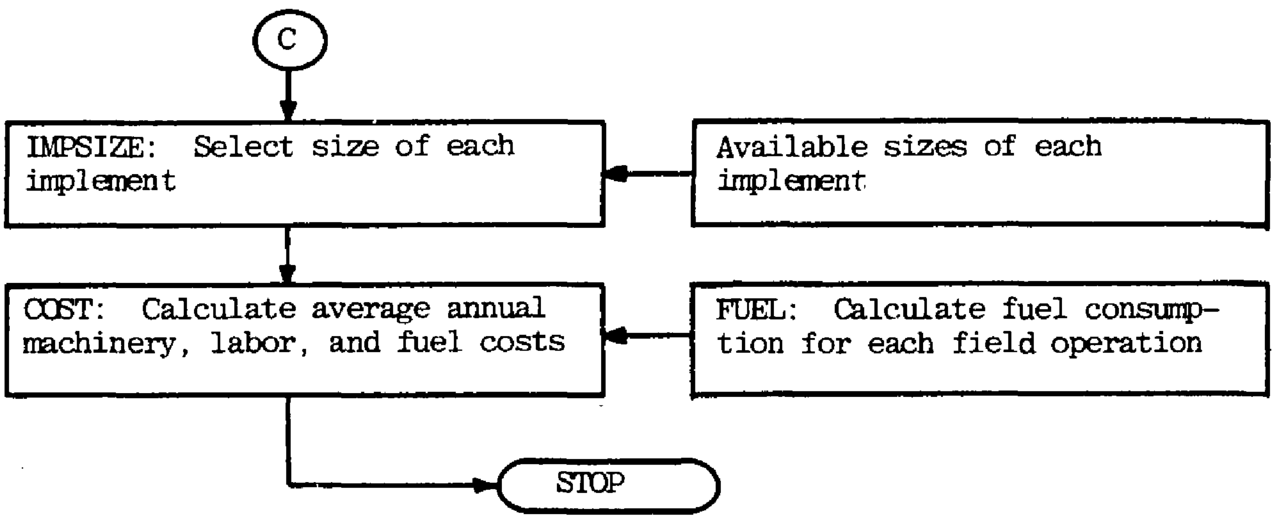


Figure 3.1 (continued)

7. Mean and standard deviation of fraction of suitable days in each week of the year for each type of operation.

The input data used in this study is given in Appendix A.

3.1.1 Field work specifications

All field operations were considered explicitly. Transportation, drying, processing, and farmstead operations were not considered. However, their influence can be reflected by adjusting working hours per suitable working day. The field work data used in this study is shown in Table A.1 (Robertson, 1977).

3.1.2 Calendar date specifications for field work

The calendar year was divided into 52 weeks in the model. The calendar date constraints which are needed in the model must be specified in terms of a weekly starting date as given in Table A.2B; as the suitable day data was calculated for these weeks.

Calendar date constraints for the planting and harvesting operations of each crop were specified based upon cropping practices representative of southern Michigan. They were so selected that satisfaction in 80 percent of all seasons was desired. Finishing date of preplant tillage operations was specified equal to the finishing date constraint of the planting operation for that crop. If a tillage operation was permitted in the fall, its starting date constraint was specified equal to the starting date constraint of the harvesting operation of the previous crop. But, if a tillage operation was not permitted in fall, its starting date constraint was set equal to the earliest spring date on which tillage operations could be started (April 10, Table A.2B). Fall tillage operations, if not completed in fall, were discontinued for the period between November 27 and April 9. During most years very little, if any, tillage can be done during this period in southern Michigan. If a field operation was required to be done immediately preceding planting, its starting date constraint was specified equal to the planting operation. Starting and finishing date constraints for crop husbandry operations that are performed in between planting and harvesting were specified based on contemporary practices of the region.

The field operations were arranged sequentially in order of decreasing priority. The priority was assigned according to the finishing date constraint. The harvesting operation which had the earliest finishing date after June 30th was assigned the highest priority and was the first operation in the sequence. The field operation (harvest or non-harvest) which had a later but next earliest finishing date was assigned next highest priority and so on. Calendar date constraints assumed in this study for each field operation are shown in Table A.1 (Lucas, 1976). Field work data and calendar date constraints for the example farm are given in Table 3.1 which is derived from Table A.1

3.1.3 Labor policy specifications

Labor was assumed to be available to operate all tractors simultaneously when harvesting is not in progress. Harvesting operations often require additional help for unloading, hauling, and processing of the crop harvested, as well as for the operation of the harvester. Some

Table 3.1 Field Work Input Data for the Example Farm.

Crop rotation	= corn-corn-soybean-wheat
Farm size	= 446 hectares (1102 acres)
Design probability	= 80 percent
Number of tillage tractors to be idled for each harvester operating in the field	= 0

Field operation	Starting date Mo/Day	Finishing date* Mo/Day
Harvest wheat	7/17	8/07
Harvest soybeans	9/18	10/16
Moldboard plow for wheat	9/18	10/16
Disk harrow-drag for wheat	9/18	10/16
Seed drill wheat	9/18	10/16
Harvest corn after wheat	10/09	11/13
Harvest corn after corn	10/09	11/13
Topdress nitrogen on wheat	3/06	4/03
Spray herbicide on wheat	4/17	5/08
Disk for corn after corn**	10/09	5/22
Spread fertilizer for corn after wheat	4/10	5/22
Spread fertilizer for corn after corn	4/10	5/22
Moldboard plow for corn after wheat	4/10	5/22
Moldboard plow for corn after corn	4/10	5/22
Disk harrow for corn after wheat	4/24	5/22
Disk harrow for corn after corn	4/24	5/22
Plant corn after wheat+	4/24	5/22
Plant corn after corn	4/24	5/22
Disk for soybeans**	10/09	5/28
Moldboard plow for soybeans	4/10	5/28
Disk harrow for soybeans	5/15	5/28
Plant soybeans++	5/15	5/28
Spray herbicide on soybeans	5/15	6/05
Apply ammonia for corn after wheat	5/29	6/26
Apply ammonia for corn after corn	5/29	6/26
Row cultivate corn after wheat	6/05	6/26
Row cultivate corn after corn	6/05	6/26
Row cultivate soybeans	6/19	7/03

* The field operation must be completed before this date.
** If the field operation was not finished during fall, it was discontinued on November 26 and was resumed on April 10 in the following spring.
\+ Herbicides applied during the planting operation.
++ Fertilizer applied during the planting operation.

tractors may have to be freed from tillage operations because labor may not be available for tillage operations or tractors may be engaged in hauling operations. Provision was made in the program whereby zero, one, or two tractors could be idled for each operating harvester. In this example no tillage tractor was idled for each harvester operating in the field. Sufficient additional labor and machinery was assumed to be available to transport harvested crop to the farmstead.

Work on Sundays was not permitted but no other holidays were considered. The practice of using machinery two shifts per working day was also not considered. Field work hours per day for different types of operations that were assumed in this study for southern Michigan conditions are given in Table A.2A. These values were selected to reflect typical practices during the peak work season, as it is that period which largely determines machinery requirements.

3.1.4 Mean and standard deviation of fraction of suitable days

Tulu's (1974) suitable work days model was used to calculate 20-year daily suitable day sequences for all non-harvest operations and for corn harvesting from Weather Bureau records (1953-1968 from Detroit City Airport and 1969-1972 from East Lansing). Tulu's corn combining criterion was used for spraying, fertilizer spreading, cornstalk shredding, and corn harvesting operations. The tillage criterion was used for all fall and spring tillage and planting operations. The mean and standard deviation of the fraction of calendar days suitable for field work were calculated for each week from these sequences for each type of operation. The sequences of calculated mean and standard deviation were smoothed using following equation:

$$PS_i = (P_{i-2} + 2 \cdot P_{i-1} + 3 \cdot P_i + 2 \cdot P_{i+1} + P_{i+2})/9 \quad (1)$$

where

PS_i = smoothed value of mean (or standard deviation) for the week i.

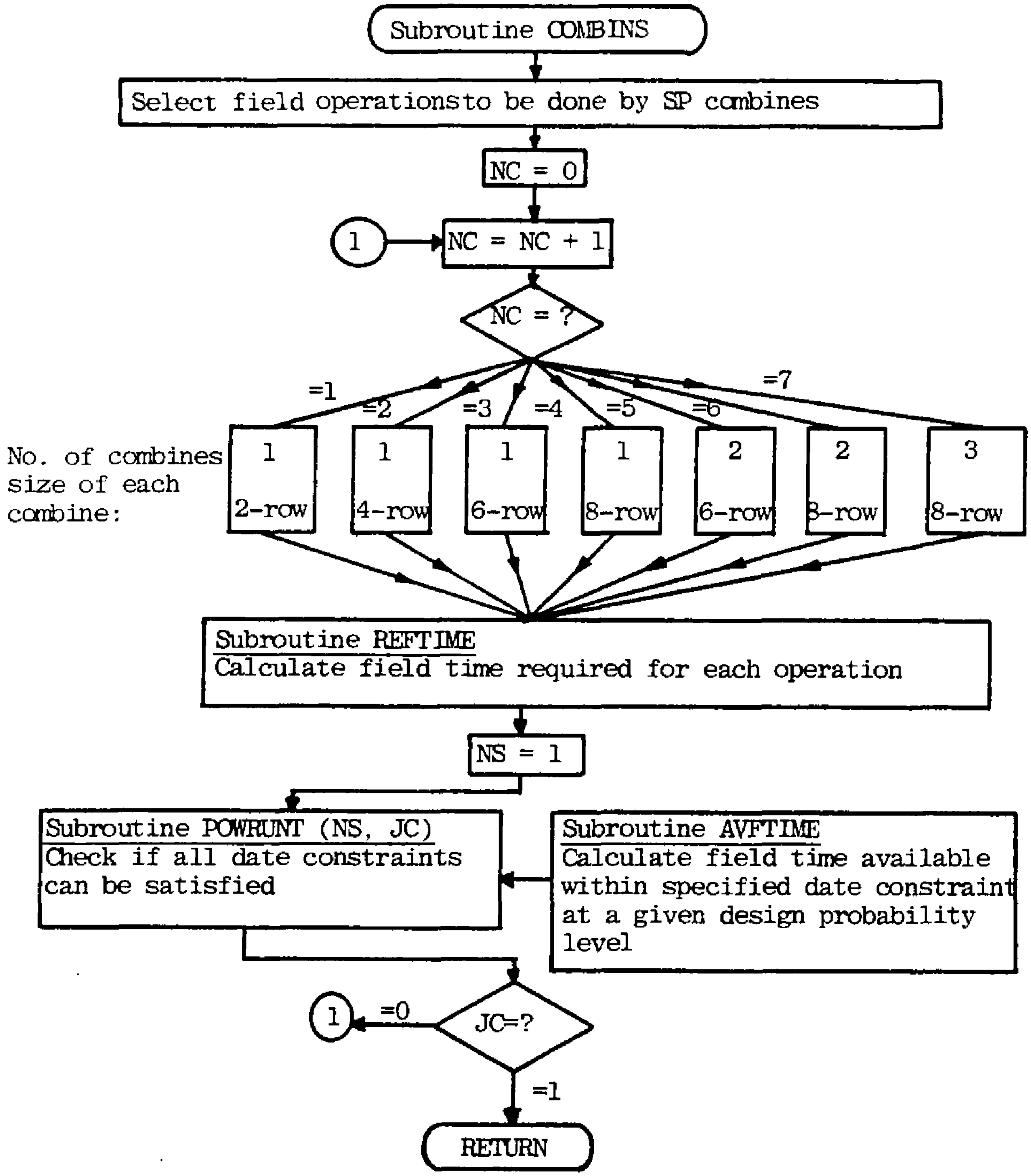
P_i = actual value of mean (or standard deviation) for the week i.

The smoothed sequences are shown in Table A.2B.

The mean and standard deviation of the fraction of suitable work-days for soybean, field bean, and wheat harvesting were estimated from a personal communication (Adams, 1975). Alfalfa harvesting statistics were estimated from data given by Millier and Rehkugler (1972). These estimates are displayed in Table A.2C. Tables A.2B and A.2C were used as an exogeneous input to the model.

3.2 Harvester Size

It was assumed that all harvesting operations, other than alfalfa harvesting are done by self-propelled combines. Units with interchangeable heads were assumed. Four sizes of combines were permitted in the model. Assumed size, speed, field efficiency, and effective field capacity of the four basic sizes for the various harvesting operations are given in Table A.3A. The methodology used for determining number and size of combines is shown in Figure 3.2



JC = 1 indicates that all operations have been completed within specified date constraints, and JC = 0 indicates not.

NS = 1 indicates to the subroutine POWRUNT to return to calling statement if a date constraint is violated, and NS = 2 indicates to finish as much area of each operation as possible with the given power unit.

Figure 3.2. Flow Diagram for Combine Size Selection.

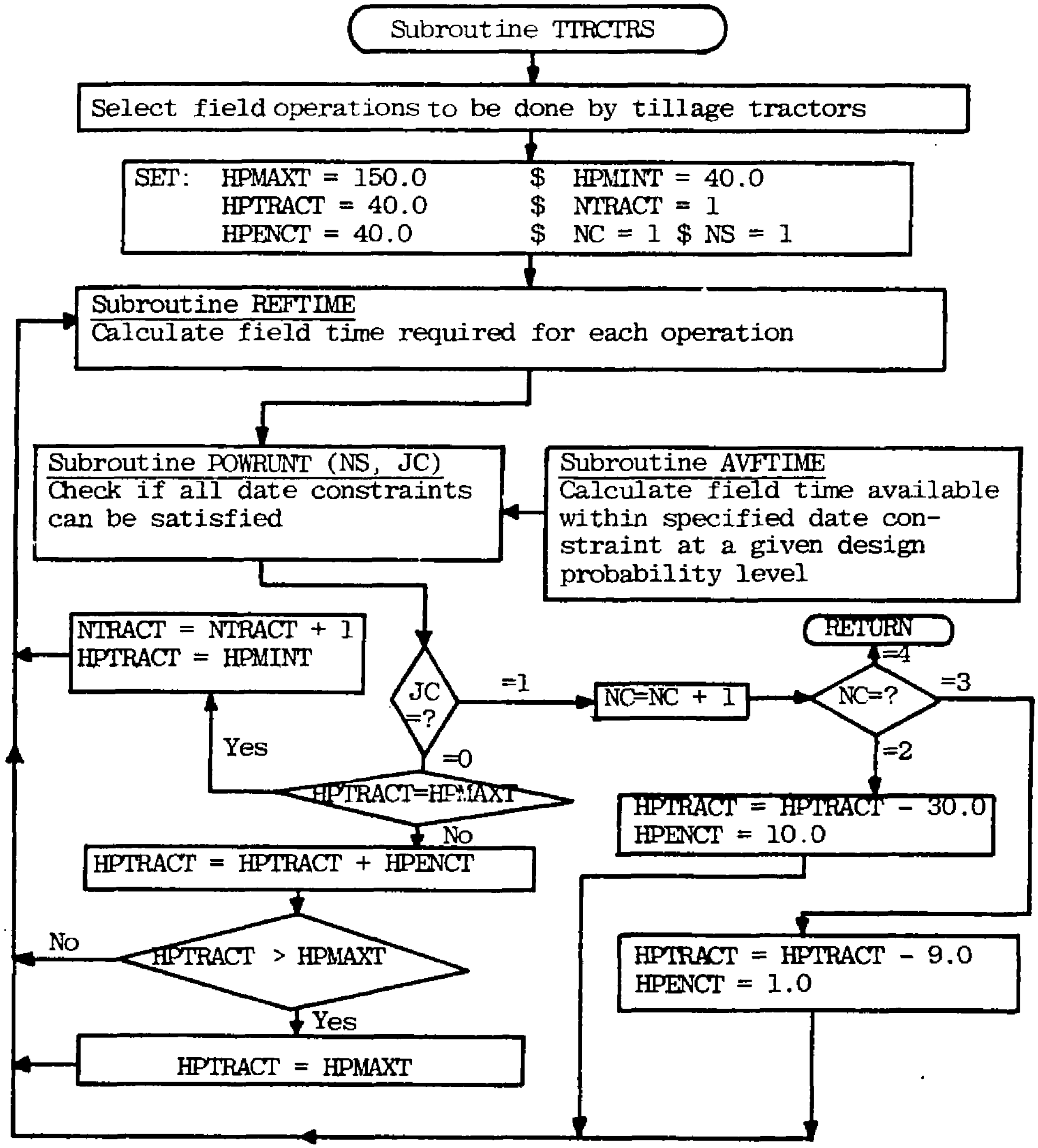
3.3 Tractor Size

Three sizes of two-wheel drive tractors may appear in a selected machinery system. This option provides full utilization of tractor power for most operations. All preplant tillage operations and no-till planting operations are assigned to tillage tractors of equal size, which is constrained to the range of 29.8 PTO kW (40 HP) to 111.9 PTO kW (150 HP). The number and size of tillage tractors was determined by the procedure outlined in Figure 3.3. The procedure contains a provision (not shown in Figure 3.3, to keep the flow diagram simple), whereby as many as two tractors can be idled for each operating harvester.

Utility tractors of equal size, in the range of 22.4 PTO kW (30 HP) to 67.1 PTO kW (90 HP), were used for all other field operations. If possible, the selection process (Figure 3.4) restricts the number of utility tractors to one by using available tillage tractors for these operations. However, utility tractors were not assigned preplant tillage operations to supplement the tillage tractors. This keeps the required labor and number of implement units to minimum.

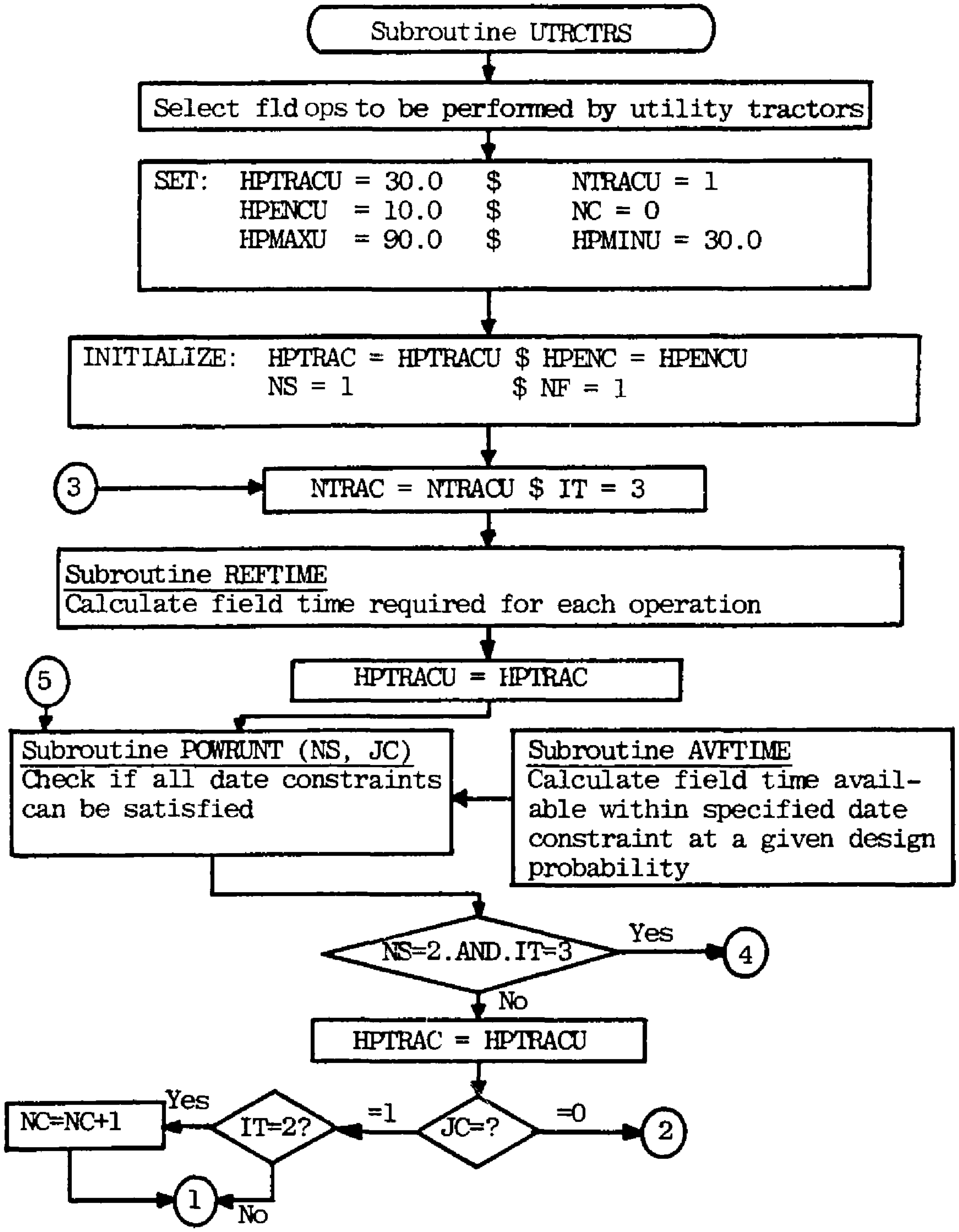
Alfalfa mowing-conditioning and baling operations were done by tractors of 29.8 PTO kW (40 HP) size, hereafter called alfalfa tractors. The selection process (Figure 3.5) minimizes the number of alfalfa tractors by using available utility and tillage tractors for alfalfa harvesting operations, if possible. However, alfalfa tractors were used exclusively for alfalfa harvesting operations.

Tillage tractors were used for the operations assigned to utility tractors or alfalfa tractors only for the time for which they were free from the operations to which they are normally assigned. Similarly,



HPTRACT = horsepower of each tillage tractor
NTRACT = number of tillage tractors
HPENCT = horsepower increment for tillage tractor size selection
HPMAXT = maximum horsepower permitted for each tillage tractor
HPMINT = minimum horsepower permitted for each tillage tractor
JC, NC = See Figure 3.2

Figure 3.3. Flow Diagram for Estimating Size and Number of Tillage Tractors.



HPTRACU = horsepower of each utility tractor
NTRACU = number of utility tractors
HPMAXU = maximum horsepower permitted for each utility tractor
HPMINU = minimum horsepower permitted for each utility tractor
HPENC = horsepower increment
NS, JC = See Figure 3.2.

Figure 3.4. Simplified Flow Diagram for Estimating Size and Number of Utility Tractors.

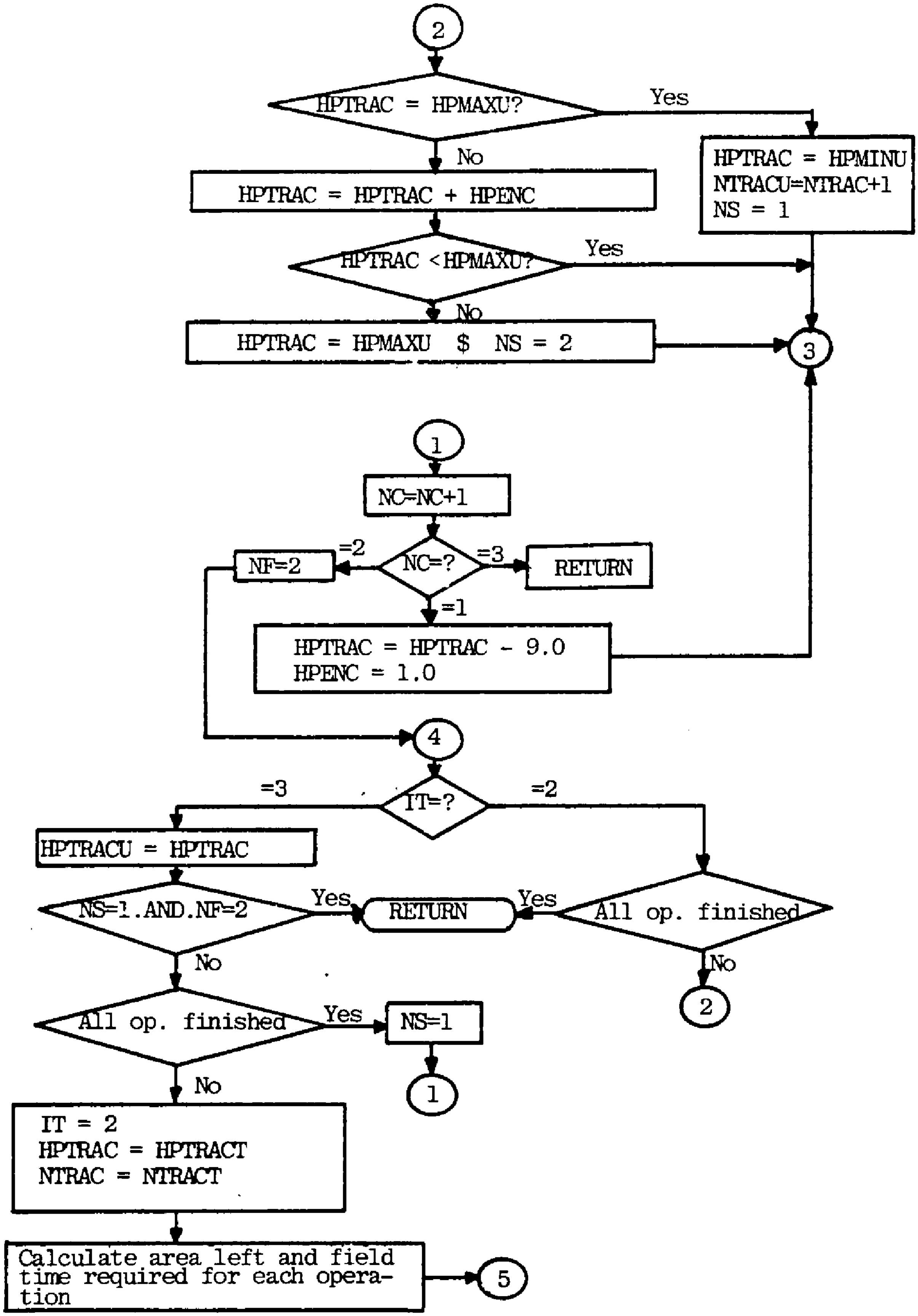
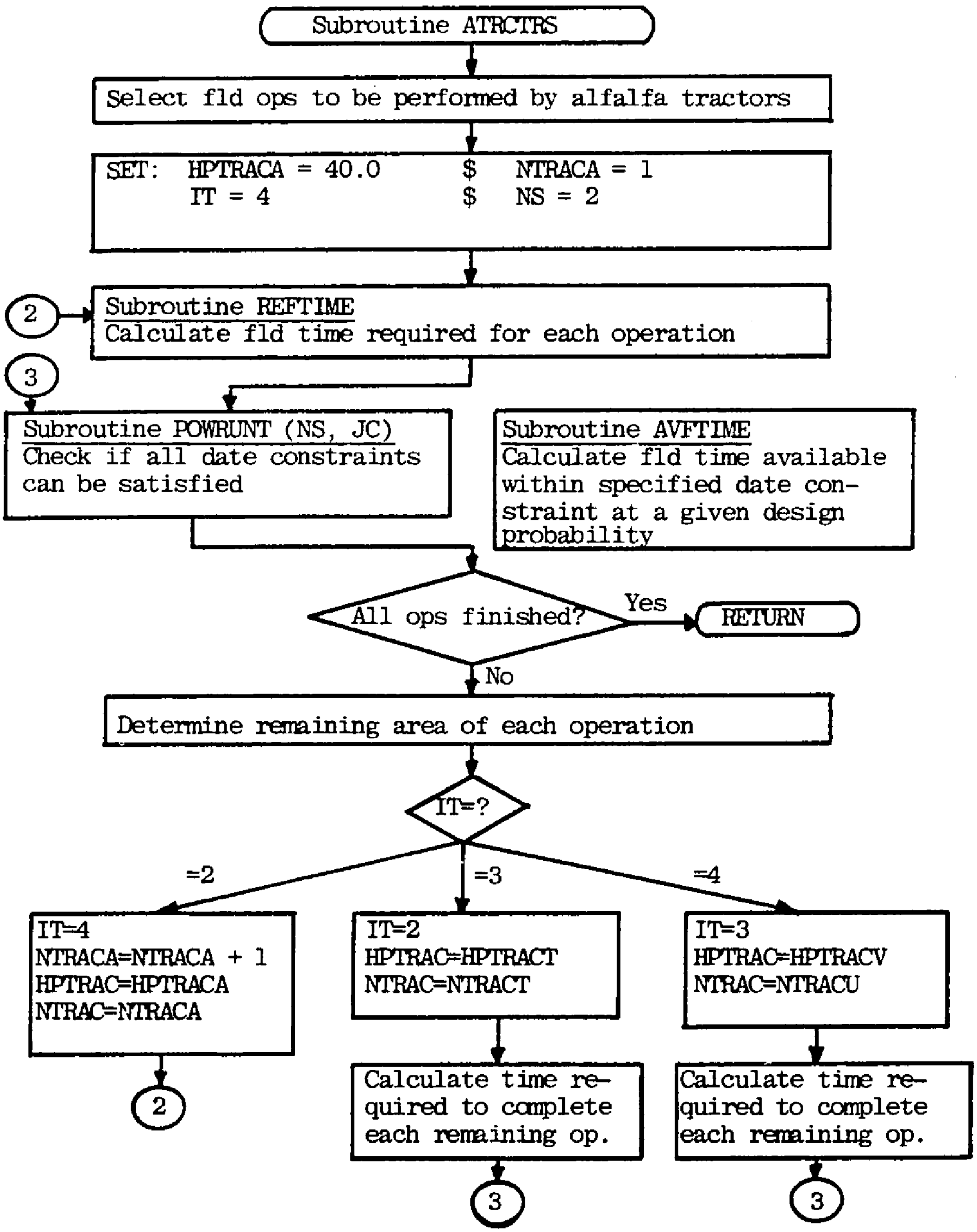


Figure 3.4. (continued)



HPTRACA = horsepower of each alfalfa tractor
NTRACA = number of alfalfa tractors

Figure 3.5 Simplified Flow Diagram for Selecting Number of Alfalfa Tractors.

utility tractors were used for alfalfa harvesting operation only for the time for which they were free from the operations to which they are normally assigned. The procedure for accomplishing this is not shown in Figures 3.3 through 3.6 to keep the flow diagrams simple.

The principle of assignment of work to different sizes of tractors according to load requirements, which is the basis of the above selection procedure, is supported by field observations. Hunt (1972) noted in a small survey that farmers generally assign heavy draft operations to big tractors and use smaller tractors for light field work. This procedure also minimizes the labor requirements since the heavy tillage work is assigned to big tractors.

3.4 Available Field Work Time

Available field work time for an operation depends upon the calendar period specified for it, the fraction of calendar days suitable for work, and field-work hours per workday. The fraction of calendar days suitable for work is weather dependent and was calculated on a probabilistic basis. A design probability of completion was employed. Suitable workdays cacluated at 80 percent design probability can be interpreted as meaning that on the average the calculated workdays or more would occur in 80 percent of all seasons.

To compute the field working hours available at design probability, it was assumed that the weekly fractions of calendar days suitable for field work were normally distributed and that successive weeks were statistically independent. Thus, the fraction of calendar time suitable for work during N successive weeks was normally distributed. The N-week fraction population mean and variance were the arithmetic means of the weekly means and variances. The fraction of calendar days suitable in the N-week period for the design probability was computed and for weekly scheduling was transformed back to a weekly basis using a proportional ratio (first bracketed term in equation 2). The formula used for these computations was:

$$Hour_{ik} = (\bar{x}_{ik} / \sum_{i=L}^{M} \bar{x}_{ik}) * [\sum_{i=L}^{M} \bar{x}_{ik} - Z\alpha(\sum_{i=L}^{M} s^2{}_{ik})^{1/2}] * ND * H_k \qquad (2)$$

where

$Hour_{ik}$ = field working hours available during week i for the k th operation

$\bar{x}_{ik}$ = mean of fraction of calendar days suitable for field work during week i for the k th operation

s_{ik} = standard deviation of fraction of calendar days suitable for field work during week i for the k th operation

L = first week of the period

M = last week of the period

ND = number of calendar days work is permitted during the week = 6

H_k = field working hours per day for the k th operation

$Z\alpha$ = a number from the normal cumulative distribution table corresponding to the design probability level = 0.84 for design probability of 0.8

It is known that the assumption of normality is not valid for periods of one week (Tulu, 1973). However, as the length of the period is increased, the probability distribution of weekly fraction of suitable working days approaches normality.

3.5 Required Field Work Time

Field time required for any operation depends upon the energy requirements of the operation, tractor power available to the implement, constraints on size and speed of the implement, machine reliability and relative productivity of the machine under field conditions.

The assumption was made that the energy required per unit area for a particular operation is speed invariant. This is not generally true. For example energy consumption for moldboard plows increases as some power of speed (Agricultural Engineers Yearbook, 1977). However, if machine speed is restricted to a narrow range, the energy required can be assumed to be speed invariant.

The average unit draft values that were used in this study are given in Table A.3B. These are average unit draft values estimated for a well drained Miami-Conover loam soil and include the rolling resistance of the implement and tractor (White, 1975b). The energy requirements of PTO-operated implements were converted into unit draft values to facilitate calculations.

Farm tractor power is rated according to the maximum observed PTO horsepower, as determined by the Nebraska Tractor Tests. A significant part of this power is not available for implement use at the drawbar during field operations. Some of the power is lost in transmission to the axle. Typical ratio of PTO to axle power is 0.96 for tractors with a gear-type transmission (Zoz, 1972). Power is also lost at the interface between the soil and the tire. Tractive efficiency is a measure of this power loss and is defined as the ratio of drawbar power to axle power. Tractive efficiency values of 0.75 for untilled and 0.6 for tilled field work (Agricultural Engineers Yearbook, 1969) were used in this study. Zoz (1972) has presented a more elaborate method of predicting tractor's drawbar performance under various field conditions. The assumed tractive efficiency values can also be deduced from his data. To reduce engine wear and to provide capacity for varying loads and inevitable overload situations that occur in farming operations, the average load should be less than the maximum capability. A load factor (LFAC) of 0.8 was assumed in this study (White, 1975a).

The sizes of implements which were considered in this study are given in Table A.4A. Only those implement sizes were considered which were listed in the Agricultural Whole Goods Price List of Deere and Company (1975) or in the Official Guide to Tractors and Farm Equipment (Spring 1976). Speed constraints for various operations assumed in the study are presented in Table A.3B and were taken from White (1975b) or the Agricultural Engineers Yearbook (1977).

Machine reliability is a measure of the percentage of field time during which the machine is in operating condition. In this study reliability for each machine was assumed equal to unity.

Field efficiency is a measure of the relative productivity of a machine under field conditions. Average values of field efficiency used in this study, selected from Bowers (1970) or the Agricultural Engineers Yearbook (1977), are given in Table A.3B.

The effective field capacity (area worked per unit of field time) for each tractor-powered implement was computed from tractor power using the following relationship:

$$EFC_j = HPTRAC*0.96*TE_j*LFAC*RE_j*e_j/(D_j/360) \quad j = 1,2,...NTIMP \quad (3)$$

where

EFC_j = effective field capacity of operation j (ha/h)

HPTRAC = tractor PTO power (kW)

TE_j = tractive efficiency for operation j (fraction)

LFAC = the ratio of tractor power used in performing an operation to rated power of tractor (0.80)

RE_j = reliability of machine for operation j (fraction)

e_j = field efficiency of machine for operation j (fraction)

D_j = unit draft of machine for operation j (N/m)

NTIMP = number of tractor-powered implements

360 = (3600 s/h x 1000 W/kW)/10000 m^2/ha

Adjustments were made if size and speed constraints on the implement were violated. If EFC_j was greater than that which could be obtained with the biggest available size of implement at the maximum operating speed ($EFCMAX_j$), it was equated to $EFCMAX_j$.

If EFC_j was less than that which could be obtained with the smallest available size of implement at the minimum operating speed ($EFCMIN_j$), tractor power was increased until $EFC_j \geq EFCMIN_j$.

A further constraint was put on effective field capacities of row planter and cultivator implements by restricting their size to the same integer multiple of corn head size.

The field time required for an operation was calculated by dividing the area to be worked by the effective field capacity of the operation.

3.6 Methodology for Determining Tractor and Combine Size

The essential methodology for determining number and size of combines, tillage tractors, utility tractors and alfalfa tractors, hereafter called power units, is as follows: A power unit size is selected and field time required for each operation is computed. Required field time (RFT) is compared with available field time (AFT). The procedure for comparing RFT with AFT is contained in the subroutine POWRUNT whose simplified flow diagram is shown in Figure 3.6. If there is any difference between RFT and AFT, the power unit size is adjusted. The smallest power unit that makes RFT $\leq$ AFT is selected.

The subroutine POWRUNT is called for one type of power unit at a time. All units of one type should be of the same size. The selection procedure assumes that none of the tractors would be idled due to the unavailability of an implement unit. Therefore, all units of one type work simultaneously on one operation at a given time.

Operations are scheduled according to the finishing date priority established in the input data. However, a lower priority operation can be scheduled in a week in which it is not possible to schedule any higher priority operation.

The selection procedure assures that the number of power units of selected size of each type are able to finish the field operations assigned to that type of power unit within the specified calendar date constraints, individually as well as collectively, at the specified design probability level.

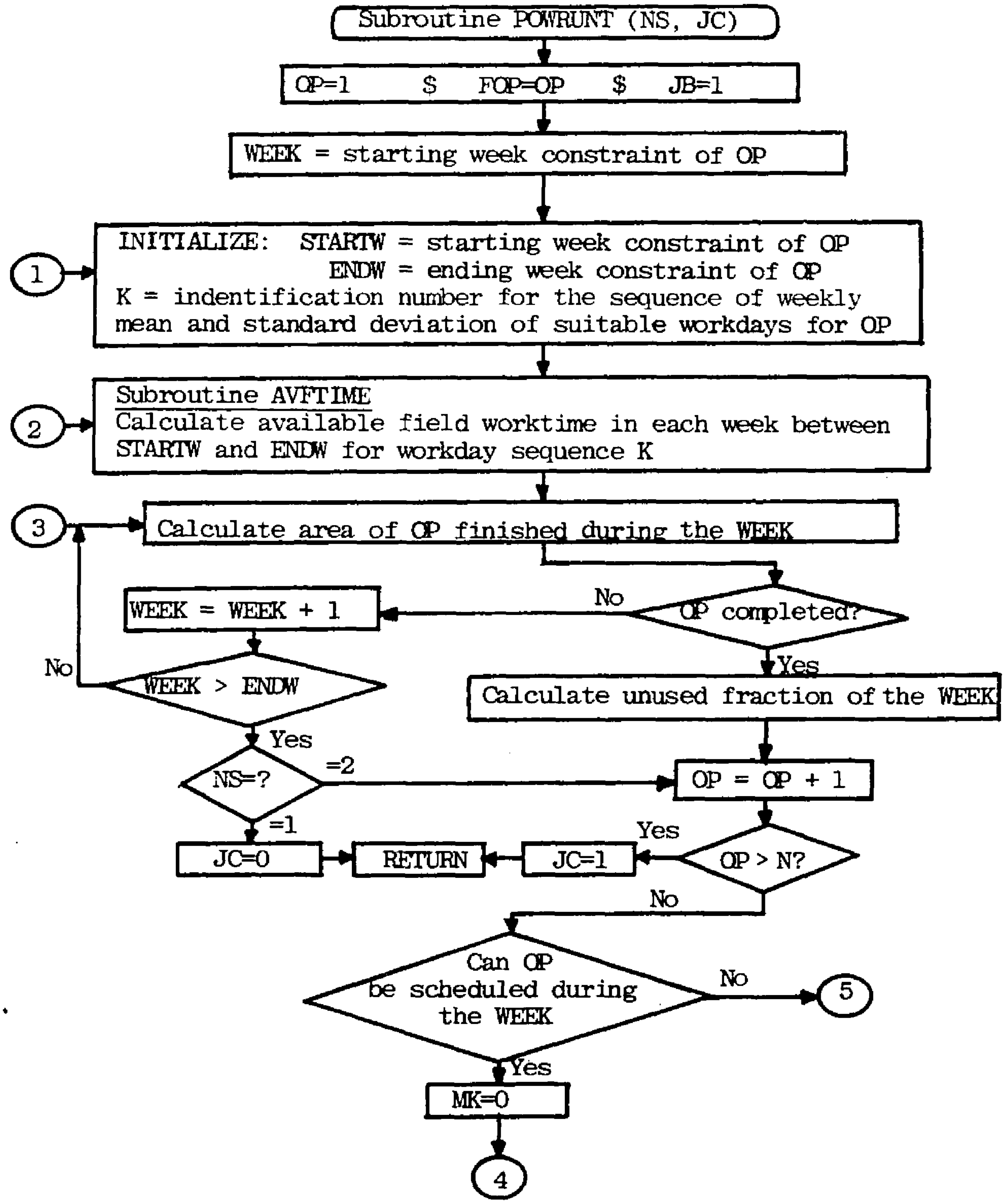
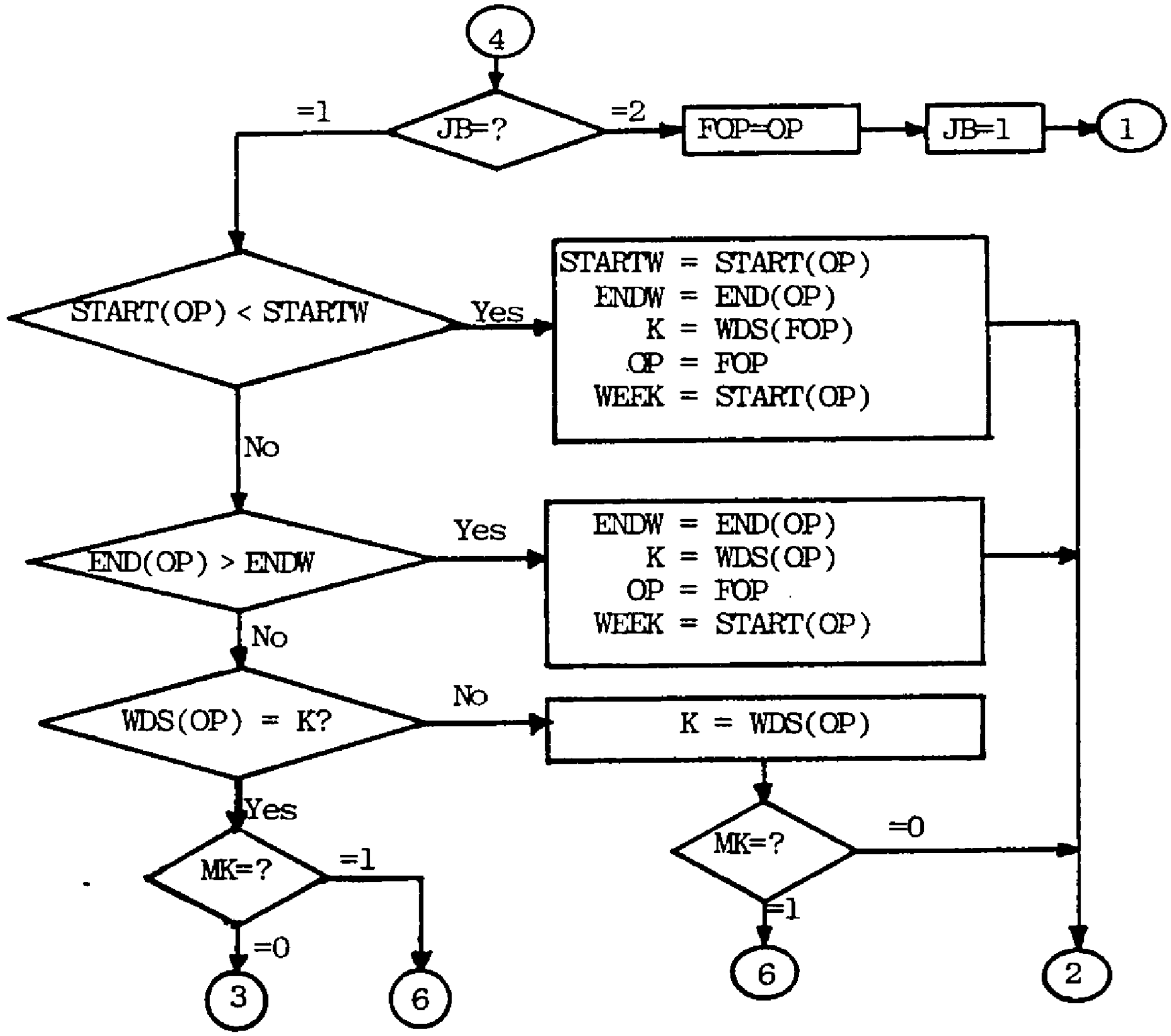


Figure 3.6 Simplified Flow Diagram for the Subroutine POWRUNT



OP = operation
START(OP) = starting week constraint of OP
END(OP) = ending week constraint of OP
WDS(OP) = identification number for the sequence of weekly mean and standard deviation of suitable workdays for OP
FOP = first operation of a sequence of operations which are performed without any time gap in between
N = number of operations
JB = 2 indicates that field work is being started after a time gap, and JB = 1 indicates field work is continuous
MK = 1 indicates that a lower priority operation is being performed while a higher priority operation cannot be scheduled, and MK = 0 indicates that operations are being performed according to the established priority.

Figure 3.6. (continued)

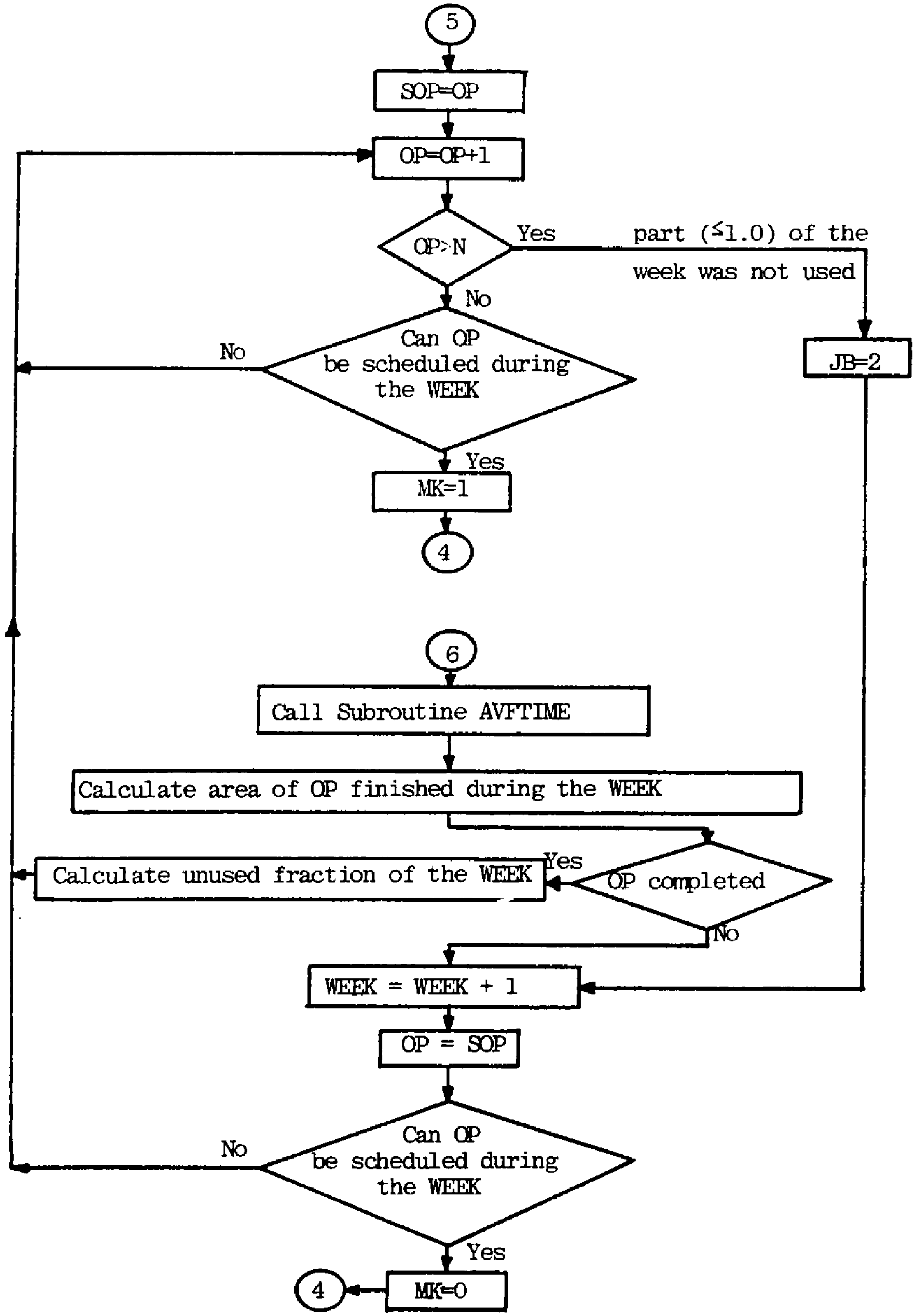


Figure 3.6. (continued)

3.7 Implement Size and Number

The smallest available implement which maximized tractor power utilization subject to the speed constraints was selected. The number of units of each implement was initially estimated assuming that none of them would be idled due to the unavailability of a tractor. The minimum number of units of each implement which could finish all field operations assigned to the implement, within the specified date constraints at design probability level, were selected. This simple procedure does not guarantee that implement units so determined would be adequate for a proper operations schedule. Rather, it provides a lower bound on the number of units required. The required number of units were established when the existence of a feasible operations schedule was demonstrated.

Table 3.2 shows the machinery set selected and annual machine use for the example farm (Table 3.1).

3.8 Operations Schedule

The operations schedule is a summary of activities for each week beginning with the first harvesting operation after June 30th. An operations schedule computed for the design probability was prepared to determine if the selected machinery system was sufficient to satisfy all date constraints.

In preparing operations schedule, two methods were used to distribute total weekly work time of each power unit among field operations.

Table 3.2 Field Machinery Set Selected and Annual Machine Use for the Example Farm.

Machine	Size	Field capacity (ha/h-unit)	Annual use (h/unit)
Two tillage tractors	90.2 PTO kW		274
Utility tractor	53.7 PTO kW		496
SP combine	8-row*		263
Corn head	8-row*	1.62	138
Grain head	4.9 m	1.66^{+}	125
Two moldboard plows	5-0.41 m bottom	1.28	174
Disc harrow	5.2 m	3.11^{++}	200
Grain drill	4.0 m	2.39	47
Planter	8-row*	2.38	141
Ammonia applicator	6-row*	2.36	94
Row cultivator	8-row*	3.25	103
Spin spreader	12.2 m**	6.87	49
Sprayer	6.1 m**	3.53	63

*Row width = 0.76 m
**Width covered in one pass
$^{+}$Field capacity for wheat harvesting = 1.92 (ha/h)
$^{++}$Field capacity for corn stalk discing = 4.36 (ha/h), and for discing with drag attached = 2.72 (ha/h)

The total weekly work time of all tillage tractors was distributed among all preplant tillage operations of a crop in such a manner that by the end of the week cumulative area completed of each operation was the same, as far as feasible with available equipment (Section 3.8.2). For alfalfa harvesting, the tractor time was allocated between mowing-conditioning and baling operations in such a manner that both operations were carried out at identical rates. For all other operations, the power unit time was distributed among operations sequentially. Starting with the highest priority operation, as much of the total available weekly work time of the appropriate power unit was allocated to the operation as required to finish the operation (Section 3.8.1).

Operations were scheduled on a weekly basis according to the priority established in the input data. The general procedure used for preparing an operations schedule was as follows: the field operations that could be scheduled during the week based on calendar date constraints were selected. From among these operations, field operations assigned to SP combines were selected and scheduled sequentially (Section 3.8.1). Field operations assigned to alfalfa tractors were selected and scheduled sequentially. Then all other operations were scheduled as follows: from among the crops whose field operations could be scheduled during the week, the crop corresponding to the highest priority non-harvesting operation was selected. The non-harvesting field operations of that crop which could be scheduled during the week were chosen. Starting from the first operation, each operation was checked to see if it was a preplant tillage operation. If it was, then all preplant tillage operations of this crop were selected and scheduled simultaneously (Section 3.8.2). But if it was not, then it was scheduled sequentially. When all the operations of a crop had been scheduled, the next crop was taken and the procedure was repeated until all crops had been considered. A schedule for the week was printed.

A check was made for violation of the completion date constraint for each operation at the end of each week. If a violation occurred, an adjustment was made in the number of implement units or tractor power, or the work was redistributed among the three types of tractors (Section 3.8.4). If no violation occurred, the next week was taken and the whole procedure was repeated until all weeks had been considered.

Table 3.3A shows the operations schedule for two weeks for the example farm. Table 3.3B depicts the associated equipment assignments for those weeks. 82.03 hectares of moldboard plowing for corn after wheat had been completed before the week of April 24. Disc harrowing and planting operations were started in the week of April 24. An attempt was made during the week of April 24 to make the cumulative area completed of disc harrowing operation equal to that of moldboard plowing operation. However, since only one disc harrow was available, only one tillage tractor could be utilized for disc harrowing and the other tillage tractor was used for moldboard plowing. But it was possible in the next week to allocate the tillage tractor time between moldboard plowing and disc harrowing in such a manner that cumulative area completed of each operation became the same.

Table 3.4 shows a summary of operations schedule for the whole year for the example farm. The computer program also prepares a summary of machine schedule for the whole year.

An operations schedule was also prepared for an "average" year (50 percent probability level) using the procedure outlined above.

Table 3.3A Operations Schedule for the Weeks of April 24 and May 1 for the Example Farm.

Operation	Hours worked	Hectares completed	Cumulative hectares completed	Available work hours*
For the week of April 24				
Corn after wheat				
Moldboard plow	21.2	27.15	109.18	21.2
Disc harrow	21.2	65.93	65.93	21.2
Plant	23.0	54.64	54.64	23.0
Total field work hours	65.4			
For the week of May 1				
Corn after wheat				
Moldboard plow	1.8	2.31	111.50	27.4
Disc harrow	14.6	45.56	111.50	27.4
Plant	23.9	56.85	111.50	29.7
Corn after corn				
Moldboard plow	27.2	34.83	34.83	27.4
Disc harrow	11.2	34.83	34.83	27.4
Plant	5.8	13.85	13.85	29.7
Total field work hours	84.5			

*Available field work time per unit machine during the week, calculated by equation (2).

Table 3.3B Machine Schedule for the Weeks of April 24 and May 1 for the Example Farm.

Power Unit	Tillage Tractor #1		Tillage Tractor #2		Utility Tractor #1	
Implement	Hours worked	Hectares completed	Hours worked	Hectares completed	Hours worked	Hectares completed
			For the week of April 24			
Corn after wheat						
Moldboard plow	21.2	27.15	0.0	0.0	0.0	0.0
Disc harrow	0.0	0.0	21.2	65.93	0.0	0.0
Planter	0.0	0.0	0.0	0.0	23.0	54.64
Total field work hours	21.2		21.2		23.0	
			For the week of May 1			
Corn after wheat						
Moldboard plow	1.8	2.31	0.0	0.0	0.0	0.0
Disc harrow	14.6	45.56	0.0	0.0	0.0	0.0
Planter	0.0	0.0	0.0	0.0	23.9	56.85
Corn after corn						
Moldboard plow	11.0	14.04	16.2	20.80	0.0	0.0
Disc harrow	0.0	0.0	11.2	34.83	0.0	0.0
Planter	0.0	0.0	0.0	0.0	5.8	13.85
Total field work hours	27.4		27.4		29.7	

Table 3.4 Summary of Operations Schedule for the Example Farm (hectares completed of each operation in each week).

Operation	April			May					June				July			September		October					Nov	Total
	10	17	24	01	08	15	22	29	05	12	19	26	17	24	31	18	25	02	09	16	23	30	05	
Corn after wheat																								
Harvest																			38.7	54.4	18.4			111.5
Spread fertilizer	111.5																							111.5
Moldboard plow	42.2	30.8	27.2	2.3																				111.5
Disc harrow			65.9	45.6																				111.5
Plant			54.6	56.9																				111.5
Apply ammonia								91.4	17.1															111.5
Row cultivate									111.5															111.5
Corn after corn																								
Harvest																					31.7	44.9	31.9	111.5
Disc																			38.7	54.4	18.4			111.5
Spread fertilizer	111.5																							111.5
Moldboard plow				34.8	57.3	19.4																		111.5
Disc harrow				34.8	57.3	19.4																		111.5
Plant				13.8	78.3	19.4																		111.5
Apply ammonia									2.4	98.5	10.6													111.5
Row cultivate											111.5													111.5
Soybeans																								
Harvest																33.6	33.6	33.5	10.8					111.5
Disc																					31.7	44.9	31.9	111.5
Moldboard plow						44.7	66.8																	111.5
Disc harrow						44.7	66.8																	111.5
Plant						44.7	66.8																	111.5
Spray herbicides						44.7	56.7	10.1																111.5
Row cultivate											11.8	99.7												111.5
Wheat																								
Harvest													37.2	37.2	37.1									111.5
Moldboard plow																33.6	33.6	33.5	10.8					111.5
Disc harrow-drag																33.6	33.6	33.5	10.8					111.5
Seed drill																33.6	33.6	33.5	10.8					111.5
Topdress nitrogen																								111.5
Spray herbicide		111.5																						111.5

It served to determine the labor distribution during the year. Median completion dates for harvesting and planting operations of each crop were calculated from this operations schedule (Appendix B) to provide an indication of the timeliness cost involved with the selected machinery set. Table 3.5 depicts median completion dates for harvesting and planting operations for the example farm.

Table 3.5 Median Completion Dates for Harvesting and Planting for the Example Farm (at 50 percent probability level).

Crop	Harvesting	Planting
Corn after wheat	10/09[1] + 7.1[2]	4/24[1] + 9.9[2]
Corn after corn	10/09 + 20.0	4/24 + 13.0
Soybeans	9/18 + 10.8	5/15 + 4.7
Wheat	7/17 + 10.4	9/18 + 10.8

[1]Starting date constraint (month/day)
[2]Days after starting date constraint

3.8.1 Scheduling of non-tillage operations

All field operations, other than preplant tillage operations, were scheduled sequentially in each week according to the priority established in the input data. Starting from the highest priority operation, the maximum area of each operation that could be finished during the week, subject to certain constraints, was calculated and equipment assignment was made (Section 3.8.3). The area of an operation that could be finished during a week by a type of power unit was constrained such that:

1. The cumulative area* completed of the operation does not exceed:
   a. ACRECFP - the cumulative area completed of a previous non-harvesting operation of the same crop, if there is any.
   b. ACRECFH - the cumulative area completed of a harvesting operation of the previous crop, if there is any.
2. The cumulative area completed of the operation by the type of power unit does not exceed the total area of the operation assigned to that type of power unit.
3. Total time of the type of power unit used for the operation does not exceed the total available free time of that type of power unit for the week.
4. Total time of the required implement units used for the operation does not exceed the total available free time of the implement units for the week.

3.8.2 Scheduling of tillage operations

All preplant tillage operations of a crop were carried out in the proper sequence at rates which produced land fit for planting as early as possible based on available equipment. This was accomplished by allocating tillage tractor time among these operations in two steps. In the first step, cumulative area (ACRECF) to which all preplant operations of a crop could be carried out by the end of the week, subject to certain constraints, was determined. The total weekly work time of all tillage tractors was allocated among these operations so as

*Cumulative area completed of an operation refers to the total area of the operation finished from the start of the operation to the end of the week.

to bring completed cumulative area of each of these operations equal to ACRECF. In the second step, the tillage tractor time left, if any, was allocated among preplant tillage operations of this crop using the procedure for sequential operations (Section 3.8.1). The whole procedure was repeated for the next crop to allocate any remaining tillage tractor time.

ACRECF was constrained by:

1. ACRECFP,
2. ACRECFH,
3. Shortest available free time for any of the implement which is required for the preplant tillage operations of the crop,
4. Available free time of the tillage tractors, and
5. Smallest total area assigned to tillage tractors of any of the preplant tillage operation of the crop.

3.8.3 Equipment assignment

After determining the area of an operation that could be finished during the week, equipment assignment was made. The area was first assigned to each appropriate power unit and then to each unit of the required implement. The same procedure was used to assign area to power units or to implement units. Starting with the first unit, as much area was assigned to each unit as possible. The area assigned to each unit was constrained by:

1. The area of the operation that is unassigned to a unit
2. The area that the unit can complete during the week in the available free time.

3.8.4 Adjustments made, if selected machinery set was inadequate for a realistic schedule

A check was made for the violation of the completion date constraint for each operation at the end of each week. Whenever a violation for an operation occurred, an adjustment was made in the number of units of the implement which was used for the operation, or in power of the tractor(s) to which the operation was assigned. The adjustment was based upon the tractor category to which the operation was assigned. If the operation was assigned to tillage tractors and if the number of units of the implement were less than the number of tillage tractors, number of implement units was increased by one (see 1 below). But if the number of units of the implement were equal to number of tillage tractors, tillage tractor power was increased (see 3 below). If the operation was assigned to utility tractors, it was determined whether all units of the implement were engaged for the whole week. If so, it was then assumed that the number of units of this implement was insufficient and was increased by one (see 1 below). However, if the number of units of this implement was equal to number of utility tractors, or if all units of the implement were not busy for the whole week, utility tractor size was increased (see 2 below). If the operation was assigned to both categories of tractors, utility and tillage, a check was made whether utility tractors had finished their share of work. If so, number of units of the implement was increased by one, subject to the upper constraint equal to the sum of utility and tillage tractors. Otherwise, the procedure for operations assigned to utility tractors was repeated.

A violation may occur because:

1. <u>The number of implement units is inadequate</u>: The tractors may be forced to remain idle because of the unavailability of an implement unit. To correct the problem, the program increases the number of units of the implement corresponding to the operation for which violation occurred by one, subject to the upper constraint equal to the number of corresponding tractors. The operations schedule is then prepared again from the beginning.
2. <u>Utility tractor(s) is forced to remain idle</u>: Utility tractor(s) may be forced to remain idle for part of the time if preplant tillage operations cannot be performed at a rate that enables the utility tractor(s) to work full time. This may result in violation of the completion date constraint for operations assigned to the utility tractors. The program rectifies the problem by increasing the size of utility tractor(s) in increments of 0.75 PTO kW (1 HP), and recalculating the productivity of each operation, and preparing the operations schedule from the beginning again. If selected number of utility tractors of maximum permitted size cannot finish the work, the program transfers unfinished work from utility tractor(s) to tillage tractor(s).
3. <u>Tillage tractor(s) is forced to remain idle</u>: Tillage tractor(s) may be forced to remain idle for part of the time if harvesting operations cannot be accomplished at a rate that enables tillage tractor(s) to work full time. This may result

in violation of a completion date constraint for a tillage operation. To rectify the problem, the program increases the size (in increments of 0.75 PTO kW (1 HP)) or number of tillage tractor(s) and recalculates the productivity of each operation and starts preparation of operations schedule from the beginning.

3.9 Labor

The labor required for operating machines and the distribution of labor during the year are important considerations for farm management. The weekly operations schedule (for 50 percent probability) was used to calculate labor requirements. Field labor hours required during each week were calculated by summing field work hours used for different operations during the week. Total required field working hours during each work week of the year for the example farm are plotted in Figure 3.7.

The number of men required per week were computed from the following relationship:

$$NMEN_i = \sum_{r=1}^{n} \sum_{k=1}^{NOP} \frac{WHOUR_{ikr}}{HOUR_{ik}} \qquad (4)$$

where

$NMEN_i$ = number of men required during week i

$WHOUR_{ikr}$ = field work hours during week i for which operation k was performed by power unit r (tractor or SP combine)

$HOUR_{ik}$ = field work hours available during week i for the kth operation

n = number of field operations

NOP = number of field operations

The number of men required during each work week of the year for the example farm is shown in Figure 3.7. A fractional man can be interpreted as meaning that the man is required for only a part of the week.

The ratio of field time to the total time labor is paid is defined as scheduling efficiency. The total labor hours required for operating field machinery during the year were computed by dividing total field work hours by scheduling efficiency (0.85) and then multiplying by a factor of 1.3. Thirty percent extra labor was added to account for labor time spent in repairs, off-season machinery maintenance and tooling up. Total annual labor required for the example farm is shown in Table 3.8.

3.10 Fuel

Diesel fuel was assumed to be used in all power units. Fuel consumption for each field operation was caculated separately. The fuel efficiency, FUELEFF (litres/kWh), was computed as a function of load on the power unit for tractor powered operations (equation 5; Hunt, 1966). The data used for developing this equation is reported in Table 2.2, Hunt, 1977.

$$FUELEFF = 2.64\ PR + 3.90 - 0.20\ (738\ PR + 173)^{1/2} \qquad (5)$$

where

PR = the ratio of equivalent PTO power required to that maximum available from the PTO.

Fuel consumption for combining corn was assumed to be 14.97 litres/hectare (1.6 gallons/acre; Ayres, 1976), for combining soybeans 10.29 litres/hectare (1.1 gallons/acre; Ayres, 1976) and for other combining

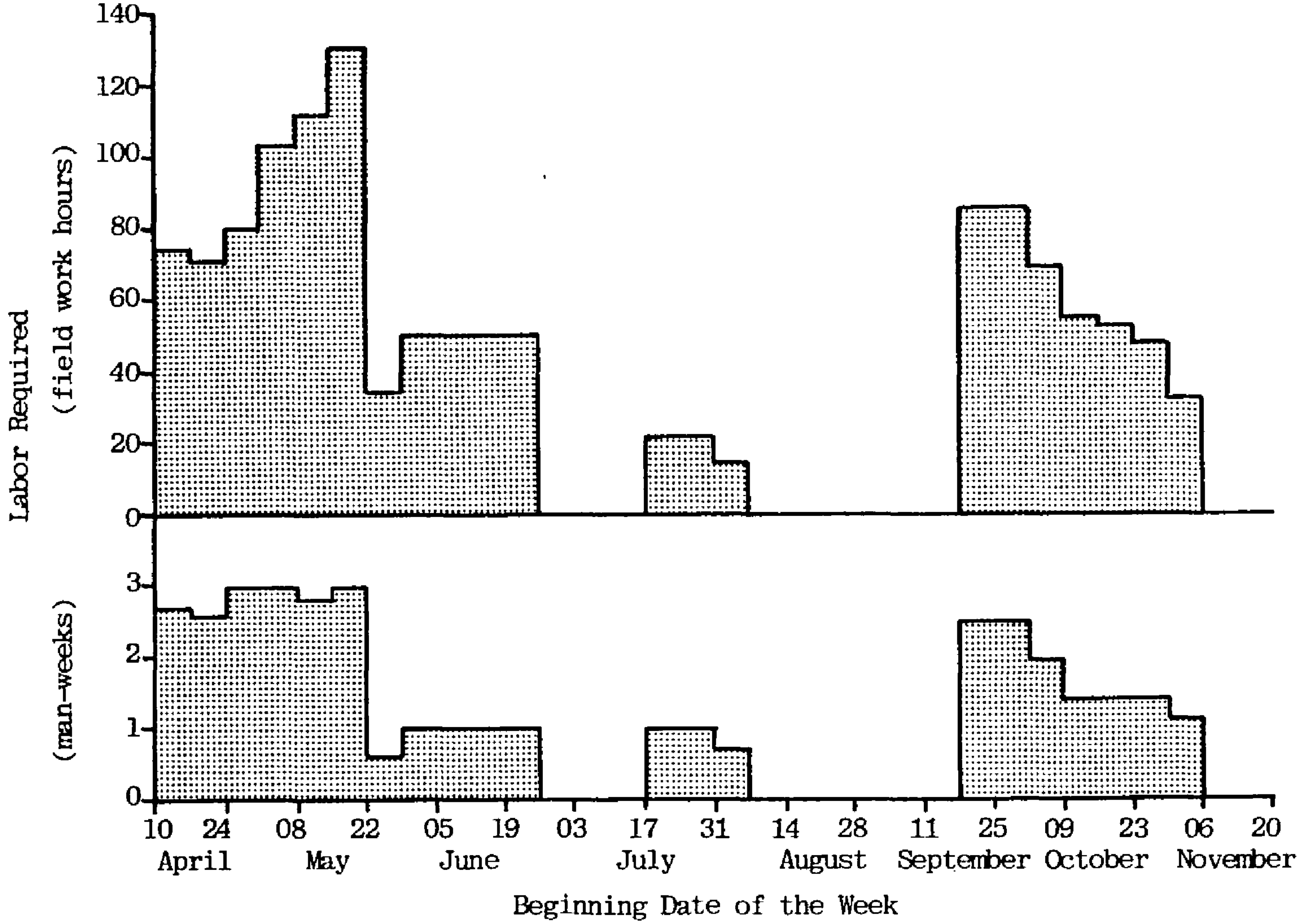


Figure 3.7. Labor Distribution at the Example Farm for an Average Year.

operations 13.56 litres/hectare (1.45 gallons/acre; Bowers, 1970), irrespective of the size of combine or condition of crop.

Fuel consumption for each field operation of the example farm is shown in Table 3.6 and the total annual fuel consumption is shown in Table 3.8.

3.11 Cost Analysis

Cost calculations were made, as described below, to estimate the average annual cost of the machinery system selected.

3.11.1 List prices of machines

The list prices of tractors, combines, and rotary cutters were taken from the Official Guide to Tractors and Farm Equipment (Fall 1976). A regression relationship was developed for relating two-wheel drive diesel tractor list price to tractor size in PTO power. Current models of all makes were considered. Tractor size range considered was from 22.4 to 111.9 PTO kW (30 to 150 HP). This range was divided into 12 groups, each group representing a range of 7.5 PTO kW (10 HP). Four tractors of different makes were selected from each power group in order to give equal weight to all tractor sizes. Price, size, and make of each selected tractor are given in Table A.4B. Several regression relationships were developed. The coefficient of determination (R^2) was highest (0.99) for the following relation, which was adopted:

$$\text{List Price} = \underset{(8.33)}{233.26}\ (\text{PTO kW}) - \underset{(0.072)}{0.308}\ (\text{PTO kW})^2 \qquad (6)$$

Table 3.6 Fuel Requirements for Field Operations of the Example Farm.

Operation	Tractor category used	Load factor (PR)	FUELEFF (litres /kWh)	Fuel consumption (litres/ ha)	Total fuel consumption (litres)
Corn after wheat					
Harvest				15.0	1668.6
Spread fertilizer	Utility	.31	39.8	1.1	121.9
Moldboard plow	Tillage	.80	64.7	18.0	2001.8
Disc harrow	Tillage	.80	64.7	7.9	875.8
Plant	Utility	.80	64.7	4.3	481.7
Apply ammonia	Utility	.80	64.7	4.7	525.5
Row cultivate	Utility	.80	64.7	4.2	469.2
Corn after corn					
Harvest				15.0	1668.6
Disc	Tillage	.80	64.7	5.6	625.5
Spread fertilizer	Utility	.31	39.8	1.1	121.9
Moldboard plow	Tillage	.80	64.7	18.0	2001.8
Disc harrow	Tillage	.80	64.7	7.9	875.8
Plant	Utility	.80	64.7	4.3	481.7
Apply ammonia	Utility	.80	64.7	4.7	525.5
Row cultivate	Utility	.80	64.7	4.2	469.2
Soybeans					
Harvest				10.3	1147.2
Disc	Tillage	.80	64.7	5.6	625.5
Moldboard plow	Tillage	.80	64.7	18.0	2001.8
Disc harrow	Tillage	.80	64.7	7.9	875.8
Plant	Utility	.80	64.7	4.3	481.7
Spray herbicides	Utility	.25	35.6	1.6	181.5
Row cultivate	Utility	.80	64.7	4.2	469.2
Wheat					
Harvest				13.6	1512.2
Moldboard plow	Tillage	.80	64.7	18.0	2001.8
Disc harrow-drag	Tillage	.80	64.7	9.0	1000.9
Seed drill	Utility	.48	58.3	4.0	452.8
Topdress nitrogen	Utility	.31	39.8	1.1	121.9
Spray herbicide	Utility	.25	35.6	1.6	181.5

Utility and alfalfa tractors were assumed to be 4 years old when acquired for use. The purchase price of these units was assumed to be 48 percent of the list price of a new tractor of the same size (Hunt, 1977).

List prices used in the model for combines were the averages of prices of different makes of combines of the same size. The makes and the models that were used to compute average prices of different sizes of combines and their prices are shown in Table A.4C along with the average price of each size. The prices of corn heads, grain heads, and pick up heads were also similarly determined and are shown in Tables A.4D, A.4E and A.4F, respectively.

List prices of all other implements were taken from the Agricultural Whole Goods Price List of a machinery manufacturer. In general, the models used were "middle of the range" models, i.e. they were neither the lowest nor highest priced models. The price of each standard unit, and wherever required, the price of implement wheels and tires, chisels, sweeps, and plow bottoms were included. Attachments or extra options were not considered for any equipment. Table A.4A shows the prices assumed in this study for all tractor powered field machines.

3.11.2 Machinery costs

Machinery costs include depreciation, repair and maintenance, interest, housing, insurance and tax. Depreciation was calculated by the straight line method, assuming a ten percent salvage value. The useful life of a machine was calculated by dividing the estimated wearout life of the machine (Bowers, 1970; Agricultural Engineers Yearbook, 1977) by the annual use of the machine. Maximum useful life of each machine was assumed equal to 8 years in this study.

Repair costs over the wear-out life of a machine were taken as a fixed percentage of the purchase price of that machine and were prorated according to annual machine use. The assumed values for total repair costs in wear-out life, as a percent of initial purchase price, were taken from the Agricultural Engineers Yearbook (1977). Some recent studies (Hunt, 1974) have indicated that actual repair costs are significantly less than these values. But since reliable information on total repair costs of all machines was not available from any other source, Agricultural Engineers Yearbook (1977) values were used. The effect of reduced repair costs would not be significant on total machinery costs (Section 5.6.4).

Annual costs for interest, housing, and insurance were calculated as fixed percentages of the list price of the machine. Since there is no tax on field machinery in Michigan, tax was not included in the machinery costs.

Assumed machinery cost factors are given in Table A.5. Machinery costs for the example farm are shown in Table 3.7.

Annual labor cost was calculated by multiplying annual labor hours by the hourly wage rate. Assumed values of labor rate, diesel price, and engine oil and filter expenses are given in Table A.5. Table 3.8 shows all categories of annual machinery related costs for the example farm.

Table 3.7 Machinery Costs for the Example Farm.

Machine	Price ($)	Deprecia- tion ($/yr)	Int- erest ($/yr)	Ins. + Housing ($/yr)	Repair ($/yr)	Total ($/yr)
Two tillage tractors	37115	4176	1837	371	1016	7400
Utility tractor	4657	524	231	47	462	1263
SP combine	33103	3917	1639	331	2612	8499
Corn head	11753	1322	582	118	810	2831
Grain head	3452	388	171	35	60	654
Two moldboard plows	5973	672	296	60	623	1651
Disc harrow	5469	615	271	55	655	1595
Grain drill	3746	421	185	37	175	819
Planter	8840	994	438	88	1243	2764
Ammonia applicator	3300	371	163	33	312	879
Row cultivator	2913	328	144	29	180	681
Spin spreader	1749	197	87	18	85	386
Sprayer	1620	182	80	16	85	364
Sum	123690	14108	6123	1237	8317	29785
Cost/hectare	277.33	31.63	13.73	2.77	18.65	66.78

Table 3.8 Average Annual Machinery Related Costs for the Example Farm.

	Total	$/year	$/hectare
Investment in machinery	$123690		277.33
Machinery costs		29,785	66.78
Labor costs	1998 hours	6,495	14.55
Fuel and oil costs	23968 litres of diesel fuel	2,803	6.28
Total machinery related costs		39,083	87.63

4. IMPLEMENTATION OF THE MODEL

Analyses were made for ten crop rotations (Table 4.1), involving corn, soybeans, field beans, wheat and alfalfa. The rotations range from a single crop to rotations involving several crops. Some of these crop rotations are common in southern Michigan while interest is increasing in others.

Three tillage systems (no-till, chisel plow, and moldboard plow) were selected for this study. They represent "points" on the spectrum of technologies presently used in southern Michigan. All three tillage systems are not used for all crops. The no-till system is normally used only for corn, the chisel plow system for corn, soybeans and wheat, and the moldboard plow system is used for all crops.

Three levels of tillage intensity were considered for each crop rotation. The tillage system used for each crop at each level of tillage intensity for each rotation is shown in Table 4.1. Since soybeans are not normally raised using the no-till system in Michigan, there are 29 crop production systems that were selected for analysis. Table A.1 shows field operations that were assumed for each crop under each tillage system, along with the selected calendar date constraints for each (Robertson, 1977; Lucas, 1976). The calendar date constraints were selected in such a manner that if the operation was completed within the selected period with the specified design probability (80 percent), operation timeliness would be acceptable.

Table 4.1 Description of the Selected Cropping Systems.

Crop rotation*	Highest level of tillage intensity (HLTI)	Middle level of tillage intensity (MLTI)	Lowest level of tillage intensity (LLTI)
C C	C MB**	C CH^{+}	C NT^{++}
S S	S MB	S CH	–
C S	C S MB MB	C S CH CH	C S NT CH
C FB	C FB MB MB	C FB CH MB	C FB NT MB
C C S W	C C S W MB MB MB MB	C C S W MB CH CH CH	C C S W NT NT CH CH
C C FB W	C C FB W MB MB MB MB	C C FB W MB CH MB CH	C C FB W NT NT MB CH
C W A A	C W A A MB MB MB	C W A A MB CH MB	C W A A NT CH MB
C S W A A	C S W A A MB MB MB MB	C S W A A MB CH CH MB	C S W A A NT CH CH MB
C C S W A A	C C S W A A MB MB MB MB MB	C C S W A A MB CH CH CH MB	C C S W A A NT NT CH CH MB
C C FB W A A	C C FB W A A MB MB MB MB MB	C C FB W A A MB CH MB CH MB	C C FB W A A NT NT MB CH MB

*C - corn, S - soybeans, FB - field beans, W - wheat, A - alfalfa.
**MB - Moldboard plow tillage system.
$^{+}$CH - Chisel plow tillage system.
$^{++}$NT - No-till tillage system.

Except for the field work data shown in Table A.1, all other aspects of the technology used for the crop production systems were fixed. The same soil, climate, machine characteristics and management policies were applied to all systems, and thus were assumed to have no influence on the comparisons to be made among systems. Appendix A shows the complete set of input data used.

4.1 Comparisons

The 29 crop production systems (Table 4.1) were analyzed using the data in Appendix A and the computer program, discussed in Chapter 3, to determine the effect of: 1. tillage intensity, and 2. crop rotation on:

a. cost and size of field machinery,

b. total labor for field work and distribution of labor during the year, and

c. fuel requirements for field work

A sensitivity analysis was made to measure the effect of the following design parameters on machinery requirements and costs:

1. Design probability level,
2. Field working hours per day,
3. Number of tillage tractors idled for each harvester operating in the field, and
4. Machinery cost factors

The C C S W crop rotation and the HLTI were selected to illustrate the effect of above design parameters.

4.2 Timeliness Costs

For a given crop rotation and tillage system, the costs related to the set of machinery used are the costs for machinery (including fuel and oil), labor, and timeliness. The computer model described in Chapter 3 was used to calculate machinery and labor costs. Timeliness costs were not considered explicitly. Rather, calendar date constraints for the field operations of each crop were held constant as far as feasible in order to keep the timeliness of operations constant across all cropping systems. Nevertheless, timeliness of operations, as determined by median completion date, did vary from one cropping system to another.

The timeliness of operations varies with the size of machinery which is largely determined by the power requirements during the peak work season. A change in crop production system may change the length or calendar period of the peak work season, and consequently power requirements and timeliness of operations.

The timeliness of operations, for a given crop rotation and tillage system, also varied with the farm size. However, the timeliness of planting operations did not vary as much as that of harvesting operations. This was so because tractors were assumed to be available at 0.75 kW (1 PTOHP) size increments; whereas SP combines were assumed to be available only at 2-row size increments.

The combine size was determined by the harvesting period of the crop for which the ratio of the available field time (at the selected design probability level) to the required field time (crop area/ productivity of the given combine size for the crop) for the harvesting operation was smallest of all the crops involved in the crop rotation. Hereafter this smallest ratio is called R. For a given combine size, as the farm size was increased, the value of R decreased, and consequently timeliness cost of the harvesting operation increased. At a certain farm size, the value of R became one; and a further increase in the farm size necessitated selection of a larger capacity combine. Selection of a larger capacity combine, at that farm size, caused a considerable increase in the value of R; and consequently decreased timeliness cost. Thus, to keep timeliness costs of harvesting operations as nearly equal as feasible, it was essential to keep the value of R constant for all systems to be compared. Therefore, to compare crop rotations, combine size was fixed (at 2, 4, 6, or 8-row) and farm size was varied so that the value of R was nearly equal to one. For a given crop rotation and combine size, the maximum farm size that makes R equal to one is hereafter referred as the maximum area that the given combine size can harvest in one season.

For rotations involving alfalfa, the maximum farm sizes that 6 and 8-row combines can harvest in one season were bigger than 475 hectares. Such big cash crop farms are rare in Michigan. Therefore, analysis of these rotations was restricted only to maximum farm sizes that 2 and 4-row combines can harvest in one season.

5. RESULTS

Field machinery requirements for the selected crop production systems (Table 4.1) were calculated using the computer model described in Chapter 3 and input data of Appendix A. Required field machinery systems for the selected Michigan crop production systems are given in Appendix C, Table C.1. Cost calculations were made using the cost factors given in Table A.5 to determine average annual machinery related costs for these systems. Machinery related costs are shown in Section 5.1 below.

5.1 Effect of Tillage Intensity

The effect of tillage intensity on size, use, and costs of field machinery was determined by varying the level of tillage intensity for the ten crop rotations shown in Table 4.1, keeping all other parameters fixed; and comparing the field machinery requirements. The design probability was fixed at the 80 percent level. Sufficient additional labor and machinery was assumed to be available to transport the harvested crops to the farmstead. Therefore, no tillage tractor was kept idle when a harvester was operating in the field. Other data were the same as given in Appendix A.

Three levels of tillage intensity, described in Chapter 4, were considered. The tillage system used for each crop at each tillage intensity level is given in Table 4.1. The machinery requirements and costs for each crop rotation are shown in Tables 5.1 through 5.10.

In general, reduction in the tillage intensity reduced the size of tractors and tractor powered implements and thereby the annual cost of the field machinery. Machinery utilization increased with the use of the chisel plow tillage system (CHTS) over that of the moldboard plow tillage system (MBTS) because fall chisel plowing was permitted while fall moldboard plowing was not (because of an erosion risk). Machinery utilization was also higher for the no-till tillage system (NTTS) compared to the MBTS.

The amount of reduction in the total field machinery related costs on a per unit area basis (TMRC) varied for different crop rotations. Reduction in the TMRC was larger for those rotations in which the tillage intensity was reduced for all crops. Thus, for the continuous corn rotation, the use of the CHTS reduced the TMRC by as much as 20 percent and use of the NTTS reduced the TMRC by as much as 25 percent compared to the MBTS. However, the reduction in the TMRC was much less for those crop rotations in which different crops are grown using different tillage systems at the middle and the lowest level of tillage intensity. For some crop rotations at the middle level of tillage intensity (MLTI) chisel plow and stalk shredder implements were required in addition to the implements required for the same crop rotation at the highest level of tillage intensity (HLTI). Some crop rotations at the lowest level of tillage intensity (LLTI) require the use of all three different tillage systems for different crops. For these rotations, no-till planter, chisel plow, and stalk shredder implements were required at the LLTI in addition to the implements (except row cultivator) required at the HLTI. This is the reason that the TMRC decreased so little with the decrease in tillage intensity for crop rotations involving the crops of alfalfa and field beans.

5.1.1 Continuous corn (C C) crop rotation

Table 5.1 shows the effect of tillage intensity on size, use, and costs of field machinery for the C C rotation. The use of the CHTS reduced tillage tractor power requirements by 61 percent and thereby TMRC by about 20 percent compared to that of the MBTS. Tillage tractor power requirements were less for the CHTS because chisel plowing requires less energy than moldboard plowing and fall chisel plowing was permitted whereas fall moldboard plowing was not. No tillage operation is performed under the NTTS, and the tillage tractor was used for no-till planting and ammonia application operations only. Therefore, the use of the NTTS caused a 67 percent reduction in tillage tractor power requirements and thereby a 25 percent reduction in the TMRC compared to the MBTS. The reduction in the tillage tractor power requirements and the TMRC was not as much as stated above for the 79.3 and 136 hectare farm sizes. For the 79.3 hectare farm size, the smallest permitted tillage and utility tractors were selected and they could not be used to their full capacity. For the 136 hectare farm size, a 4-row no-till planter was not sufficient and therefore an 8-row no-till planter had to be selected which required a 44.7 PTOkW tractor. This tractor could not be utilized to capacity.

Table 5.1A Effect of Tillage Intensity on Size, Use and Costs of Field Machinery for C C Rotation.

Tillage intensity level	Machinery Size and Use: Tillage tractors No. & size (PTOkW)	Tillage tractors Use (hr)	Utility tractors No. & size (PTOkW)	Utility tractors Use (hr)	Initial investment in machinery	Labor costs	Fuel and oil costs	Total machinery related costs
					($/ha)			
	Combine Size = 2-Row					Farm Size = 79.3 Hectares		
Highest	1-55.9	170	1-22.4	231	581.96	34.03	7.04	166.28
Middle	1-29.8	194	1-22.4	235	496.21	35.78	5.63	149.42
Lowest	1-29.8	128	1-22.4	119	516.72	24.36	3.71	138.08
	Combine Size = 4-Row					Farm Size = 136.0 Hectares		
Highest	1-96.2	170	1-32.8	277	507.72	21.52	7.07	138.35
Middle	1-37.3	266	1-29.1	314	374.46	26.39	5.66	116.49
Lowest	1-44.7	146	1-22.4	204	424.08	17.99	3.71	115.00
	Combine Size = 6-Row					Farm Size = 181.3 Hectares		
Highest	2-64.1	170	1-43.3	286	484.32	21.03	7.09	133.56
Middle	1-49.2	269	1-38.8	321	360.97	20.06	5.66	107.42
Lowest	1-43.3	202	1-22.4	272	351.33	16.88	3.71	100.23
	Combine Size = 8-Row					Farm Size = 230.3 Hectares		
Highest	2-81.3	170	1-55.2	291	475.63	16.70	7.09	127.61
Middle	1-62.6	268	1-48.5	332	357.54	16.04	5.08	103.14
Lowest	1-54.4	203	1-22.4	345	337.35	14.90	3.71	95.73

Table 5.1B Median Completion Dates for Planting and Harvesting in C C Rotation.

Tillage intensity level	Total machinery related costs ($/ha)	Planting operations: Corn	Harvesting operations: Corn
		(days after starting date constraint)	
Combine Size = 2-Row		Farm Size = 79.3 Hectares	
Highest	166.28	11.1	14.0
Middle	149.42	10.5	14.0
Lowest	138.08	9.2	14.0
Combine Size = 4-Row		Farm Size = 136.0 Hectares	
Highest	138.35	11.9	14.0
Middle	116.49	12.9	14.0
Lowest	115.00	10.2	14.0
Combine Size = 6-Row		Farm Size = 181.3 Hectares	
Highest	133.56	12.0	14.0
Middle	107.42	13.0	14.0
Lowest	100.23	13.0	14.0
Combine Size = 8-Row		Farm Size = 230.3 Hectares	
Highest	127.61	12.0	14.0
Middle	103.14	13.0	14.0
Lowest	95.73	13.0	14.0

5.1.2 Continuous soybean (S S) crop rotation

The CHTS reduced tillage tractor power requirements by about 40 percent and the TMRC by about 10 percent compared to the MBTS, as shown in Table 5.2. Soybeans are not normally grown by no-till planting without primary tillage in Michigan.

5.1.3 Corn-soybean (C S) crop rotation

The MBTS was used for both corn and soybeans at the HLTI and the CHTS was used at the MLTI. But at the LLTI, corn was raised using the NTTS and the CHTS was used for soybeans.

With the decrease in tillage intensity, maximum reduction in the tillage tractor power requirements and the TMRC occurred for the 214.1 hectare farm size, as shown in Table 5.3. The tillage tractor power requirements were 64 percent less and the TMRC were about 14 percent less for both the MLTI and the LLTI compared to the HLTI and tillage tractor use was higher at both the MLTI and the LLTI compared to the HLTI. There was no sizable difference in median completion dates of planting and harvesting operations among the three levels of tillage intensity, as shown in Table 5.3B. The reduction in the tillage tractor power requirements or the TMRC was not as much for other farm sizes either because the farm size was so small that even the smallest permitted tractor size could not be fully utilized, or because a larger tractor had to be selected to pull the planter that was matched with the combine size. The LLTI did not reduce TMRC any more than that of the MLTI. One reason was that for the LLTI two planters were

Table 5.2A Effect of Tillage Intensity on Size, Use and Costs of Field Machinery for S S Rotation.

Tillage intensity level	Machinery Size and Use: Tillage tractors No. & size (PTOkW)	Tillage tractors Use (hr)	Utility tractors No. & size (PTOkW)	Utility tractors Use (hr)	Initial investment in machinery	Labor costs	Fuel and oil costs	Total machinery related costs
					(\$/ha)			
	Combine Size = 2-Row					Farm Size = 64.3 Hectares		
Highest	1-29.8	214	1-22.4	131	558.19	32.44	5.31	150.09
Middle	1-29.8	157	1-22.4	83	538.64	24.36	4.05	135.61
	Combine Size = 4-Row					Farm Size = 91.9 Hectares		
Highest	1-39.5	231	1-22.4	186	476.39	26.63	5.34	129.58
Middle	1-29.8	225	1-22.4	119	436.78	22.63	4.05	115.74
	Combine Size = 6-Row					Farm Size = 108.9 Hectares		
Highest	1-47.0	230	1-30.6	170	504.02	21.70	5.36	129.95
Middle	1-29.8	266	1-30.6	111	451.66	20.66	4.08	117.10
	Combine Size = 8-Row					Farm Size = 124.2 Hectares		
Highest	1-53.7	230	1-40.3	156	541.21	18.43	5.39	133.76
Middle	1-32.8	276	1-40.3	105	478.49	18.24	4.10	119.85

Table 5.2B Median Completion Dates for Planting and Harvesting in S S Rotation.

Tillage intensity level	Total machinery related costs ($/ha)	Planting operations	Harvesting operations
		Soybeans	Soybeans
		--------(days after starting date constraint)-------	
Combine Size = 2-Row			Farm Size = 64.3 Hectares
Highest	150.09	6.4	12.0
Middle	135.61	6.2	12.0
Combine Size = 4-Row			Farm Size = 91.9 Hectares
Highest	129.58	8.2	12.0
Middle	115.74	8.2	12.0
Combine Size = 6-Row			Farm Size = 108.9 Hectares
Highest	129.95	7.6	12.0
Middle	117.10	9.2	12.0
Combine Size = 8-Row			Farm Size = 124.2 Hectares
Highest	133.76	7.0	12.0
Middle	119.85	9.5	12.0

Table 5.3A Effect of Tillage Intensity on Size, Use and Costs of Field Machinery for C S Rotation.

Tillage intensity level	Machinery Size and Use: Tillage tractors No. & size (PTOkW)	Tillage tractors Use (hr)	Utility tractors No. & size (PTOkW)	Utility tractors Use (hr)	Initial investment in machinery	Labor costs	Fuel and oil costs	Total machinery related costs
					($/ha)			
	Combine Size = 2-Row				Farm Size = 112.5 Hectares			
Highest	1-48.5	255	1-22.4	278	423.76	30.86	6.18	130.08
Middle	1-29.8	275	1-22.4	239	390.50	30.07	4.84	120.69
Lowest	1-29.8	185	1-22.4	214	440.86	25.00	3.88	122.69
	Combine Size = 4-Row				Farm Size = 173.2 Hectares			
Highest	1-74.6	255	1-24.6	392	379.78	23.18	6.20	114.68
Middle	1-29.8	424	1-22.4	368	306.19	27.35	4.84	102.47
Lowest	1-29.8	285	1-22.4	330	339.79	22.26	3.88	101.59
	Combine Size = 6-Row				Farm Size = 214.1 Hectares			
Highest	1-92.5	254	1-30.6	399	392.48	18.83	6.20	113.69
Middle	1-33.6	466	1-30.6	345	305.72	22.49	4.87	97.98
Lowest	1-33.6	314	1-30.6	327	342.51	18.53	3.93	99.06
	Combine Size = 8-Row				Farm Size = 248.9 Hectares			
Highest	1-107.4	254	1-40.3	365	404.22	15.39	6.23	112.01
Middle	1-38.8	468	1-40.3	318	319.63	18.73	4.89	96.62
Lowest	1-44.7	273	1-40.3	318	365.30	14.85	3.95	99.29

Table 5.3B Median Completion Dates for Planting and Harvesting in C S Rotation.

Tillage intensity level	Total machinery related costs ($/ha)	Planting operations		Harvesting operations	
		Corn	Soybeans	Corn	Soybeans
		--------(days after starting date constraint)--------			
Combine Size = 2-Row			Farm Size = 112.5 Hectares		
Highest	130.08	8.8	7.2	15.5	10.6
Middle	120.69	8.0	5.6	15.5	10.6
Lowest	122.69	7.1	5.6	15.5	10.6
Combine Size = 4-Row			Farm Size = 173.2 Hectares		
Highest	114.68	10.4	7.5	16.1	11.3
Middle	102.47	11.2	7.8	16.1	11.3
Lowest	101.59	9.8	7.8	16.1	11.3
Combine Size = 6-Row			Farm Size = 214.1 Hectares		
Highest	113.69	10.4	7.5	16.6	11.8
Middle	97.98	11.6	8.2	16.6	11.8
Lowest	99.06	10.5	8.2	16.6	11.8
Combine Size = 8-Row			Farm Size = 248.9 Hectares		
Highest	112.01	9.5	7.2	16.4	12.0
Middle	96.62	11.7	8.2	16.4	12.0
Lowest	99.29	9.5	7.3	16.4	12.0

selected; one for no-till planting of corn and the other for planting of soybeans. The other reason was that a bigger tillage tractor had to be selected to pull the no-till planter and it could not be utilized to its capacity.

5.1.4 Corn-field bean (C FB) crop rotation

The MBTS was used for both corn and field beans at the HLTI. At the MLTI, corn was grown using the CHTS and field beans using the MBTS. The MLTI reduced tillage tractor power requirements by about 31 percent and the TMRC by about 13 percent compared to the HLTI, as shown in Table 5.4. Reduction in the TMRC for smaller farm sizes was not as much because of the higher labor costs. At the LLTI, the NTTS was used for corn, and field beans were raised using the MBTS. This caused about 32 percent reduction in tillage tractor size and thereby about 8 percent reduction in the TMRC. Initial investment in machinery was relatively high at the LLTI because more implements were required compared to the HLTI.

5.1.5 Corn-corn-soybean-wheat (C C S W) crop rotation

Table 5.5 illustrates the effect of tillage intensity for this rotation. The MBTS was used for every crop at the HLTI. At the MLTI corn after corn, soybeans and wheat were raised using the CHTS but the MBTS was used for corn after wheat. The MLTI reduced tillage tractor size by about 44 percent and consequently TMRC by about 13 percent.

Table 5.4A Effect of Tillage Intensity on Size, Use and Costs of Field Machinery for C FB Rotation.

Tillage intensity level	Machinery Size and Use: Tillage tractors		Machinery Size and Use: Utility tractors		Initial investment in machinery	Labor costs	Fuel and oil costs	Total machinery related costs
	No. & size (PTOkW)	Use (hr)	No. & size (PTOkW)	use (hr)	($/ha)	($/ha)	($/ha)	($/ha)
	Combine Size = 2-Row				Farm Size = 158.6 Hectares			
Highest	1-55.9	352	1-29.8	348	332.11	27.85	6.87	110.83
Middle	1-38.8	454	1-22.4	379	295.56	32.02	6.20	107.81
Lowest	1-38.0	364	1-22.4	344	338.56	28.10	5.24	109.79
	Combine Size = 4-Row				Farm Size = 272.4 Hectares			
Highest	1-96.2	352	1-55.2	369	305.08	16.88	6.92	95.33
Middle	1-66.4	456	1-40.3	405	268.75	19.42	6.25	90.89
Lowest	1-65.6	367	1-40.3	406	300.83	17.82	5.34	92.84
	Combine Size = 6-Row				Farm Size = 363.0 Hectares			
Highest	2-64.1	381	1-67.1	439	272.71	19.37	7.04	92.10
Middle	1-88.0	458	1-55.2	450	245.05	15.35	6.28	81.45
Lowest	1-105.1	360	1-58.9	466	273.52	14.23	5.56	84.36
	Combine Size = 8-Row				Farm Size = 450.0 Hectares			
Highest	2-79.8	385	1-67.1	444	276.04	15.74	6.94	88.36
Middle	1-108.9	459	1-66.4	457	238.95	12.45	6.28	76.83
Lowest	2-53.7	365	1-65.6	509	250.22	16.04	5.41	80.95

Table 5.4B Median Completion Dates for Planting and Harvesting in C FB Rotation.

Tillage intensity level	Total machinery related costs ($/ha)	Planting operations: Corn	Planting operations: Field Beans	Harvesting operations: Corn	Harvesting operations: Field Beans
		(days after starting date constraint)			
Combine Size = 2-Row			Farm Size = 158.6 Hectares		
Highest	110.83	10.3	5.9	14.0	8.8
Middle	107.81	10.5	6.9	14.0	8.8
Lowest	109.79	7.6	6.9	14.0	8.8
Combine Size = 4-Row			Farm Size = 272.4 Hectares		
Highest	95.33	10.1	5.9	14.0	11.5
Middle	90.89	10.1	6.8	14.0	11.5
Lowest	92.84	8.1	6.8	14.0	11.5
Combine Size = 6-Row			Farm Size = 363.0 Hectares		
Highest	92.10	11.2	8.4	14.0	13.4
Middle	81.45	10.7	7.1	14.0	13.4
Lowest	84.36	12.6	7.3	14.0	13.4
Combine Size = 8-Row			Farm Size = 450.0 Hectares		
Highest	88.36	11.1	8.3	13.7	13.7
Middle	76.83	10.1	6.8	13.7	13.7
Lowest	80.95	13.0	6.8	13.7	13.7

Table 5.5A Effect of Tillage Intensity on Size, Use and Costs of Field Machinery for C C S W Rotation.

Tillage intensity level	Machinery Size and Use: Tillage tractors No. & size (PTOkW)	Tillage tractors Use (hr)	Utility tractors No. & size (PTOkW)	Utility tractors Use (hr)	Initial investment in machinery ($/ha)	Labor costs ($/ha)	Fuel and oil costs ($/ha)	Total machinery related costs ($/ha)
	Combine Size = 2-Row					Farm Size = 158.6 Hectares		
Highest	1-64.1	274	1-22.4	355	354.50	26.84	6.20	113.99
Middle	1-36.5	345	1-22.4	359	314.42	29.21	5.26	106.28
Lowest	1-29.8	261	1-22.4	295	327.54	24.56	3.98	101.66
	Combine Size = 4-Row					Farm Size = 272.4 Hectares		
Highest	1-109.6	275	1-32.8	447	290.99	17.67	6.23	91.53
Middle	1-62.6	346	1-30.6	476	256.52	19.47	5.29	85.13
Lowest	1-44.7	299	1-23.9	480	255.61	18.71	3.98	82.88
	Combine Size = 6-Row					Farm Size = 371.1 Hectares		
Highest	2-75.3	273	1-44.7	470	274.36	17.15	6.25	88.96
Middle	1-85.0	347	1-42.5	493	237.37	14.80	5.31	77.42
Lowest	1-58.9	335	1-46.2	445	233.22	14.01	4.13	74.30
	Combine Size = 8-Row					Farm Size = 446.0 Hectares		
Highest	2-90.2	274	1-53.7	496	277.33	14.55	6.28	87.61
Middle	1-101.4	350	1-52.9	506	243.23	12.48	5.34	76.70
Lowest	1-64.1	348	1-40.3	571	225.36	13.17	4.08	72.45

Table 5.5B Median Completion Dates for Planting and Harvesting in C C S W Rotation.

Tillage intensity level	Total machinery related costs ($/ha)	Planting operations			Harvesting operations		
		Corn	Soybeans	Wheat	Corn	Soybeans	Wheat
		(days after starting date constraint)					
Combine Size = 2-Row					Farm Size = 158.6 Hectares		
Highest	113.99	10.7	4.4	7.8	14.0	7.8	7.4
Middle	106.28	10.8	4.2	7.8	14.0	7.8	7.4
Lowest	101.66	9.2	4.2	9.0	14.0	7.8	7.4
Combine Size = 4-Row					Farm Size = 272.4 Hectares		
Highest	91.53	11.5	4.7	9.1	14.0	9.1	8.7
Middle	85.13	12.4	5.0	9.1	14.0	9.1	8.7
Lowest	82.88	10.1	6.2	10.1	14.0	9.1	8.7
Combine Size = 6-Row					Farm Size = 371.1 Hectares		
Highest	88.96	11.4	4.7	10.4	14.3	10.4	10.0
Middle	77.42	12.2	5.0	10.4	14.3	10.4	10.0
Lowest	74.30	12.8	5.3	10.4	14.3	10.4	10.0
Combine Size = 8-Row					Farm Size = 446.0 Hectares		
Highest	87.61	11.4	4.7	10.8	13.5	10.8	10.4
Middle	76.70	12.0	4.8	10.8	13.5	10.8	10.4
Lowest	72.45	11.9	6.0	11.4	13.5	10.8	10.4

Reduction in the TMRC was not as much for smaller farm sizes because of the higher labor cost associated with smaller tractors. At the LLTI, corn was raised using NTTS, and soybeans and wheat using CHTS. The LLTI reduced the tillage tractor size by as much as 64 percent and the TMRC by about 17 percent. But the reduction was not as much in every case because in some cases selected tractor power could not be fully utilized. There was no sizable difference in median completion dates of planting and harvesting operations among the three levels of tillage intensity, as shown in Table 5.5B.

5.1.6 Corn-corn-field bean-wheat (C C FB W) crop rotation

Table 5.6 shows the effect of tillage intensity for this rotation. The MBTS was used for every crop at the HLTI. At the MLTI, wheat and corn after corn were raised using the CHTS, and the MBTS was used for corn after wheat, and field beans. Tillage tractor power requirements reduced by about 35 percent and thereby TMRC reduced by about 9 percent compared to the HLTI. At the LLTI, corn was grown using the NTTS, wheat using the CHTS and field beans using the MBTS. The use of the LLTI reduced tillage tractor size by about 58 percent and consequently TMRC by about 12 percent.

5.1.7 Corn-wheat-alfalfa-alfalfa (C W A A) crop rotation

Table 5.7 shows the effect of tillage intensity for this rotation. The MBTS was used for each crop at the HLTI. At the MLTI, wheat was

Table 5.6A Effect of Tillage Intensity on Size, Use and Costs of Field Machinery for C C FB W Rotation.

Tillage intensity level	Machinery Size and Use				Initial investment in machinery	Labor costs	Fuel and oil costs	Total machinery related costs
	Tillage tractors		Utility tractors		($/ha)			
	No. & size (PTOkW)	Use (hr)	No. & size (PTOkW)	Use (hr)				
	Combine Size = 2-Row				Farm Size = 158.6 Hectares			
Highest	1-55.9	335	1-24.6	352	358.11	27.92	6.52	115.18
Middle	1-36.5	428	1-22.4	383	329.17	31.80	5.93	112.26
Lowest	1-29.8	363	1-22.4	318	354.62	27.75	4.65	110.46
	Combine Size = 4-Row				Farm Size = 272.4 Hectares			
Highest	1-96.2	334	1-42.5	400	321.76	17.42	6.60	98.77
Middle	1-62.6	429	1-37.3	470	273.00	20.44	6.03	90.17
Lowest	1-41.8	478	1-28.3	462	261.46	21.18	4.72	86.96
	Combine Size = 6-Row				Farm Size = 363.0 Hectares			
Highest	2-64.1	334	1-67.1	444	287.10	18.41	6.75	92.54
Middle	1-82.8	432	1-47.7	485	257.46	15.74	6.03	82.43
Lowest	1-52.9	483	1-38.0	513	249.63	16.83	4.74	80.38
	Combine Size = 8-Row				Farm Size = 450.00 Hectares			
Highest	2-79.0	334	1-67.1	466	278.78	15.22	6.65	87.52
Middle	1-101.4	434	1-59.7	508	256.87	13.07	6.05	80.28
Lowest	1-62.6	490	1-47.7	559	251.55	14.28	4.79	78.80

Table 5.6B Median completion Dates for Planting and Harvesting in C C FB W Rotation.

Tillage intensity level	Total machinery related costs ($/ha)	Planting operations			Harvesting operations		
		Corn	Field beans	Wheat	Corn	Field beans	Wheat
		(days after starting date constraint)					
Combine Size = 2-Row			Farm Size = 158.6 Hectares				
Highest	115.18	10.7	3.7	3.4	14.0	4.9	7.4
Middle	112.26	13.2	4.3	3.4	14.0	4.9	7.4
Lowest	110.46	9.2	3.9	3.4	14.0	4.9	7.4
Combine Size = 4-Row			Farm Size = 272.4 Hectares				
Highest	98.77	10.7	3.7	4.3	14.0	6.2	8.7
Middle	90.17	13.7	4.3	4.3	14.0	6.2	8.7
Lowest	86.96	13.8	5.8	4.3	14.0	6.2	8.7
Combine Size = 6-Row			Farm Size = 363.0 Hectares				
Highest	92.54	11.0	4.0	4.9	14.0	7.0	9.8
Middle	82.43	13.4	4.4	4.3	14.0	7.0	9.8
Lowest	80.38	12.6	5.7	4.3	14.0	7.0	9.8
Combine Size = 8-Row			Farm Size = 450.0 Hectares				
Highest	87.52	11.0	4.0	4.9	13.5	7.1	10.4
Middle	80.28	13.4	4.5	4.9	13.5	7.1	10.4
Lowest	78.80	11.9	5.6	5.3	13.5	7.1	10.4

Table 5.7A Effect of Tillage Intensity on Size, Use and Costs of Field Machinery for C W A A Rotation.

Tillage intensity level	Machinery Size and Use: Tillage Tractors No. & size (PTOkW)	Tillage Tractors Use (hr)	Utility tractors No. & size (PTOkW)	Utility tractors Use (hr)	Alfalfa harvesting: Units of mower-conditioner & baler	Alfalfa harvesting: Units of alfalfa tractors	Initial investment in machinery ($/ha)	Labor costs ($/ha)	Fuel and oil costs ($/ha)	Total machinery related costs ($/ha)
	Combine Size = 2-Row						Farm Size = 234.3 Hectares			
Highest	1-84.3	218	1-36.5	229	4	3	499.25	25.16	6.15	138.13
Middle	1-84.3	197	1-36.5	229	4	3	504.81	24.71	5.91	137.96
Lowest	1-45.5	257	1-22.4	248	4	3	449.98	26.44	5.02	128.72
	Combine Size = 4-Row						Farm Size = 332.7 Hectares			
Highest	2-62.6	263	1-54.4	369	6	3	466.41	24.39	6.42	132.20
Middle	2-62.6	243	1-54.4	369	6	3	469.92	23.80	6.18	131.46
Lowest	2-44.7	219	1-23.9	342	6	4	450.40	25.01	5.04	127.01

Table 5.7B Median Completion Dates for Planting and Harvesting in C W A A Rotation.

Tillage intensity level	Total machinery related costs ($/ha)	Planting operations			Harvesting operations	
		Corn	Wheat	Alfalfa	Corn	Wheat
		----------(days after starting date constraint)-----				
Combine Size = 2-Row				Farm Size = 234.3 Hectares		
Highest	138.13	5.6	9.7	3.4	9.7	10.0
Middle	137.96	5.6	9.7	3.4	9.7	10.0
Lowest	128.72	5.2	9.7	4.7	9.7	10.0
Combine Size = 4-Row				Farm Size = 332.7 Hectares		
Highest	132.20	6.0	8.6	4.0	8.6	10.4
Middle	131.46	6.0	8.6	4.0	8.6	10.4
Lowest	127.01	4.5	10.5	5.1	8.6	10.4

raised using the CHTS and the MBTS was used for corn and alfalfa. The available field work time during the corn planting season determined the size of tractors for this crop rotation. Since the MBTS was used for corn at both the highest and middle level of tillage intensity, machinery size remained the same. At the middle level of tillage intensity, initial investment in machinery increased because an additional chisel plow was required but labor costs and fuel costs decreased because chisel plowing requires less energy compared to moldboard plowing. The TMRC were almost the same at both levels of tillage intensity. At the LLTI the tillage tractor was 46 percent smaller compared to the HLTI but the TMRC were only about 7 percent less than that of the HLTI. The reduction in the size of tillage tractor and in the TMRC for the 332.7 hectare farm size at the LLTI was less compared to the 223.4 hectare farm size because two eight row planters were required for the 332.7 hectare farm size. The planters, in turn, required two 44.7 PTOkW tractors which could not be used to capacity.

5.1.8 Corn-soybean-wheat-alfalfa-alfalfa (C S W A A) crop rotation

The effect of tillage intensity on size, use and costs of field machinery for this rotation is shown in Table 5.8. The MBTS was used for every crop at the HLTI. At the MLTI, soybeans and wheat were raised using the CHTS and the MBTS was used for corn and alfalfa. A 34 percent reduction in tillage tractor size but only a maximum of about 3.5 percent reduction in the TMRC was caused by the MLTI over the

Table 5.8A Effect of Tillage Intensity on Size, Use and Costs of Field Machinery for C S W A A Rotation.

Tillage intensity level	Machinery Size and Use						Initial investment in machinery	Labor costs	Fuel and oil costs	Total machinery related costs
	Tillage tractors		Utility tractors		Alfalfa harvesting		($/ha)			
	No. & size (PTOkW)	Use (hr)	No. & size (PTOkW)	Use (hr)	Units of mower-conditioner & baler	Units of alfalfa tractors				
	Combine Size = 2-Row						Farm Size = 293.4 Hectares			
Highest	1-63.4	428	1-22.4	385	4	3	341.67	27.01	5.98	112.33
Middle	1-41.8	521	1-29.1	317	4	3	330.80	27.43	5.49	108.33
Lowest	1-33.6	498	1-22.4	334	4	3	340.14	27.33	4.82	109.34
	Combine Size = 4-Row						Farm Size = 416.0 Hectares			
Highest	1-89.5	404	1-29.1	437	6	5	341.08	22.36	5.96	106.60
Middle	1-58.9	496	1-42.5	350	6	5	345.40	22.41	5.54	106.50
Lowest	1-47.7	532	1-29.1	397	6	4	327.88	22.61	4.87	101.68

Table 5.8B Median Completion Dates for Planting and Harvesting in C S W A A Rotation.

Tillage intensity level	Total machinery related costs ($/ha)	Planting operations				Harvesting operations		
		Corn	Soybeans	Wheat	Alfalfa	Corn	Soybeans	Wheat
		(days after starting date constraint)						
Combine Size = 2-Row				Farm Size = 293.4 Hectares				
Highest	112.33	8.3	5.7	11.0	4.2	10.4	11.0	10.4
Middle	108.33	10.0	4.6	11.0	5.2	10.4	11.0	10.4
Lowest	109.34	6.7	5.7	11.4	5.7	10.4	11.0	10.4
Combine Size = 4-Row				Farm Size = 416.0 Hectares				
Highest	106.60	8.9	6.2	10.9	4.2	8.7	10.9	10.4
Middle	106.50	10.1	4.5	10.9	5.2	8.7	10.9	10.4
Lowest	101.68	6.7	6.2	11.4	5.7	8.7	10.9	10.4

HLTI. The reduction in the TMRC was small because additional implements - a chisel plow and a stalk shredder - were required for the MLTI. At the LLTI, corn was raised using the NTTS, soybeans and wheat using the CHTS and the MBTS was used for alfalfa. The LLTI reduced tillage tractor power requirements by about 47 percent. But the maximum reduction in the TMRC was only about 4.5 percent because of the necessity of additional implements - no-till planter, chisel plow, and stalk shredder.

5.1.9 Corn-corn-soybean-wheat-alfalfa-alfalfa (C C S W A A) crop rotation

Table 5.9 illustrates the effect of tillage intensity for this rotation. The MBTS was used for each crop at the HLTI. At the MLTI, soybeans, wheat, and corn after corn were raised using the CHTS and the MBTS was used for corn after alfalfa, and alfalfa. The MLTI reduced tillage tractor size by 43 percent but the reduction in the TMRC was very small because of the additional equipment required for the MLTI. The median completion date for corn planting operation was also later for the MLTI compared to the HLTI (Table 5.9B) because of the smaller tillage tractor. At the LLTI, corn was raised using the NTTS, soybeans and wheat using the CHTS, and the MBTS was used for alfalfa. Tillage tractor size reduced by about 49 percent compared to the HLTI but the reduction in the TMRC was very small. The reduction in the TMRC was smaller for the 408.3 hectare farm size compared to the 238.4 hectare farm size because an 8-row planter was required at the MLTI whereas for the HLTI a 4-row planter was adequate.

Table 5.9A Effect of Tillage Intensity on Size, Use and Costs of Field Machinery for C C S W A A Rotation.

Tillage intensity level	Machinery Size and Use: Tillage tractors		Machinery Size and Use: Utility tractors		Machinery Size and Use: Alfalfa harvesting		Initial investment in machinery	Labor costs	Fuel and oil costs	Total machinery related costs
	No. & size (PTOkW)	Use (hr)	No. & size (PTOkW)	Use (hr)	Units of mower-conditioner & baler	Units of alfalfa tractors	($/ha)			
	Combine Size = 2-Row						Farm Size = 238.4 Hectares			
Highest	1-64.1	364	1-22.4	378	3	2	372.26	27.87	6.15	119.43
Middle	1-36.5	484	1-23.9	360	3	2	346.15	30.02	5.51	114.46
Lowest	1-29.8	423	1-22.4	318	3	2	357.19	27.90	4.65	113.00
	Combine Size = 4-Row						Farm Size = 408.3 Hectares			
Highest	1-109.6	350	1-32.8	464	5	4	330.43	20.98	6.15	103.54
Middle	1-62.6	469	1-40.3	404	5	4	325.31	21.70	5.54	102.72
Lowest	1-44.7	468	1-23.9	517	5	4	307.42	23.05	4.65	99.14

Table 5.9B Median Completion Dates for Planting and Harvesting in C C S W A A Rotation.

Tillage intensity level	Total machinery related costs ($/ha)	Planting operations				Harvesting operations		
		Corn	Soybeans	Wheat	Alfalfa	Corn	Soybeans	Wheat
		(days after starting date constraint)						
Combine Size = 2-Row		Farm Size = 238.4 Hectares						
Highest	119.43	10.5	4.5	7.8	2.9	14.0	7.8	7.4
Middle	114.46	13.1	4.1	7.8	3.6	14.0	7.8	7.4
Lowest	113.00	9.2	4.2	9.0	4.0	14.0	7.8	7.4
Combine Size = 4-Row		Farm Size = 408.3 Hectares						
Highest	103.54	11.6	4.7	9.1	3.2	14.0	9.1	8.7
Middle	102.72	13.1	4.1	9.6	3.9	14.0	9.1	8.7
Lowest	99.14	10.2	6.2	10.1	4.7	14.0	9.1	8.7

5.1.10 Corn-corn-field bean-wheat-alfalfa-alfalfa (C C FB W A A) crop rotation

Table 5.10 illustrates the effect of tillage intensity for this rotation. The MBTS was used for every crop at the HLTI. At the MLTI, the CHTS was used for wheat and corn after corn, and the MBTS was used for other crops. The MLTI caused about a 35 percent reduction in tillage tractor power requirements compared to the HLTI. But the change in the TMRC was less than 4 percent because chisel plow and stalk shredder implements were required at the MLTI in addition to the implements required for the HLTI. At the LLTI, the NTTS was used for corn, the CHTS for wheat, and the MBTS for field beans and alfalfa. Tillage tractor power requirements were reduced by about 46 percent but the change in the TMRC was less than 5 percent compared to the HLTI because more implements were required at the LLTI.

5.2 Effect of Crop Rotation

Crop rotation strongly influences the size, use, and costs of field machinery. Both tractor power and harvesting capacity are affected. Machinery size is determined by the amount of work to be done and the field time available to finish the work. Crop rotation influences the amount of work to some extent because tillage requirements of crops vary somewhat. However, the available field time is strongly affected by crop rotation. In a diversified crop rotation the work is distributed over a longer calendar period and therefore smaller machinery is required. If for a given amount of work, available field time could be doubled,

Table 5.10A Effect of Tillage Intensity on Size, Use and Costs of Field Machinery for C C FB W A A Rotation.

Tillage intensity level	Machinery Size and Use						Initial investment in machinery	Labor costs	Fuel and oil costs	Total machinery related costs
	Tillage tractors		Utility tractors		Alfalfa harvesting		($/ha)			
	No. & size (PTOkW)	Use (hr)	No. & size (PTOkW)	Use (hr)	Units of mower-conditioner & baler	Units of alfalfa tractors				
	Combine Size = 2-Row						Farm Size = 238.4 Hectares			
Highest	1-56.7	428	1-24.6	370	3	2	375.30	28.59	6.38	120.19
Middle	1-36.5	541	1-22.4	404	3	3	366.63	32.20	5.96	120.93
Lowest	1-29.8	526	1-22.4	341	3	2	372.36	30.02	5.09	118.36
	Combine Size = 4-Row						Farm Size = 408.3 Hectares			
Highest	1-96.2	418	1-42.5	416	5	4	350.94	20.93	6.40	108.53
Middle	1-62.6	541	1-37.3	487	5	5	324.97	23.40	6.00	104.35
Lowest	1-41.8	646	1-28.3	486	5	5	316.99	24.69	5.14	102.82

Table 5.10B Median Completion Dates for Planting and Harvesting in C C FB W A A Rotation.

Tillage intensity level	Total machinery related costs ($/ha)	Planting operations				Harvesting operations		
		Corn	Field beans	Wheat	Alfalfa	Corn	Field beans	Wheat
		(days after starting date constraint)						
Combine Size = 2-Row		Farm Size = 238.4 Hectares						
Highest	120.19	10.6	7.6	3.2	2.9	14.0	4.9	7.4
Middle	120.93	13.2	4.3	3.7	3.6	14.0	4.9	7.4
Lowest	118.36	9.2	9.2	4.2	4.0	14.0	4.9	7.4
Combine Size = 4-Row		Farm Size = 408.3 Hectares						
Highest	108.53	10.7	3.7	3.5	3.1	14.0	6.2	8.7
Middle	104.35	13.7	4.3	3.7	3.9	14.0	6.2	8.7
Lowest	102.82	13.8	5.8	4.9	4.8	14.0	6.2	8.7

the machinery size could be halved; or by keeping machinery size constant, crop land area under cultivation could be doubled.

Ten different crop rotations shown in Table 4.1 involving corn, soybeans, field beans, wheat and alfalfa were studied. Data in Tables 5.1 through 5.10 were rearranged as shown in Tables 5.11 through 5.16 to illustrate the effect of crop rotation on field machinery size, use, and costs at three different levels of tillage intensity. Corn was a dominant crop in crop rotations shown in Tables 5.11 through 5.13 and it largely determined the size of machinery. When corn was the only crop in a crop rotation, machinery requirements per unit area and therefore TMRC were high. By adding other crops to the crop rotation, area under cultivation can be increased without increasing the size of machinery. Crop area harvested by a given size of combine can almost be doubled by following a C C S W rotation in place of a C C rotation, without considerable increase in the size of tractor powered machinery, as can be seen from Tables 5.11 through 5.13. The area under wheat and soybeans did not require additional harvesting capacity but an additional grain header was required. The tillage tractor size increased somewhat, since crop land area doubled, and tillage and planting periods of corn and soybeans overlapped considerably. But power requirements on a per unit area basis were much less. The TMRC reduced to about two-thirds of that of C C rotation.

When soybeans in the C C S W rotation were replaced by field beans, additional equipment for field bean harvesting - field bean puller and pick-up header - were required and therefore initial investment in machinery increased. Planting periods of corn and field beans do not

Table 5.11A Effect of Crop Rotation on Size, Use, and Costs of Field Machinery at the HLTI for those Rotations in which Corn is a Dominant Crop.

Crop rotation	Farm size (ha)	Machinery Size and Use: Combine Use (hr)	Tillage tractor No. & size (PTOkw)	Tillage tractor Use (hr)	Utility tractor No. & size (PTOkW)	Utility tractor Use (hr)	Alfalfa harvesting: Units of mower-conditioner & baler	Alfalfa harvesting: Units of alfalfa tractor	Investment in machinery ($/ha)	Labor costs ($/ha)	Fuel and oil costs ($/ha)	Total machinery related costs ($/ha)
					At Maximum Crop Area that can be Harvested by a 2-Row Combine							
C C	79.3	142	1-55.9	170	1-22.4	231	--	—	581.96	34.03	7.04	166.28
C C S W	158.6	228	1-64.1	274	1-22.4	355	--	--	354.50	26.84	6.20	113.99
C C FB W	158.6	204	1-55.9	335	1-24.6	352	--	--	358.11	27.92	6.52	115.18
C C S W A A	238.4	228	1-64.1	364	1-22.4	378	3	2	372.26	27.87	6.15	119.43
C C FB W A A	238.4	205	1-56.7	428	1-24.6	370	3	2	375.30	28.59	6.38	120.19
					At Maximum Crop Area that can be Harvested by a 4-Row Combine							
C C	136.0	142	1-96.2	170	1-32.8	277	--	--	507.72	21.52	7.07	138.35
C C S W	272.4	245	1-109.6	275	1-32.8	447	--	--	290.99	17.67	6.23	91.53
C C FB W	272.4	221	1-96.2	331	1-42.5	400	—	--	321.76	17.42	6.60	98.77
C C S W A A	408.3	245	1-109.6	350	1-32.8	464	5	4	330.43	20.98	6.15	103.54
C C FB W A A	408.3	220	1-96.2	418	1-42.5	416	5	4	350.94	20.93	6.40	108.53

Total 5.11B Median Completion Dates for Planting and Harvesting at the HLTI for those Rotations in which Corn is a Dominant Crop.

Crop rotation	Total machinery related costs ($/ha)	Planting operations				Harvesting operations		
		Corn	Soybeans or Field beans	Wheat	Alfalfa	Corn	Soybeans or Field beans	Wheat
		-------------(days after starting date constraint)----------						
	At Maximum Crop Area that can be Harvested by a 2-Row Combine							
C C	166.28	11.1				14.0		
C C S W	113.99	10.7	4.4	7.8		14.0	7.8	7.4
C C FB W	115.18	10.7	3.7	3.4		14.0	4.9	7.4
C C S W A A	119.43	10.5	4.5	7.8	2.9	14.0	7.8	7.4
C C FB W A A	120.19	10.6	7.6	3.2	2.9	14.0	4.9	7.4
	At Maximum Crop Area that can be Harvested by a 4-Row Combine							
C C	138.35	11.9				14.0		
C C S W	91.53	11.5	4.7	9.1		14.0	9.1	8.7
C C FB W	98.77	10.7	3.7	4.3		14.0	6.2	8.7
C C S W A A	103.54	11.6	4.7	9.1	3.2	14.0	9.1	8.7
C C FB W A A	108.53	10.7	3.7	3.5	3.1	14.0	6.2	8.7

Table 5.12A Effect of Crop Rotation on Size, Use, and Costs of Field Machinery at the MLTI for those Rotations in which Corn is a Dominant Crop.

Crop rotation	Farm size (ha)	Machinery Size and Use: Combine	Tillage tractor		Utility tractor		Alfalfa harvesting		Investment in machinery	Labor costs	Fuel and oil costs	Total machinery related costs
		Use (hr)	No. & size (PTOkW)	Use (hr)	No. & size (PTOkW)	Use (hr)	Units of mower-conditioner & baler	Units of alfalfa tractor	($/ha)			
At Maximum Crop Area that can be Harvested by a 2-Row Combine												
C C	79.3	142	1-29.8	194	1-22.4	235	--	--	496.21	35.78	5.63	149.42
C C S W	158.6	228	1-36.5	345	1-22.4	359	--	--	314.42	29.21	5.26	106.28
C C FB W	158.6	204	1-36.5	428	1-22.4	383	--	--	329.17	31.80	5.93	112.26
C C S W A A	238.4	228	1-36.5	484	1-23.9	360	3	2	346.15	30.02	5.51	114.46
C C FB W A A	238.4	205	1-36.5	541	1-22.4	404	3	3	366.63	32.20	5.96	120.93
At Maximum Crop Area that can be Harvested by a 4-Row Combine												
C C	136.0	142	1-37.3	266	1-29.1	314	--	--	374.46	26.39	5.66	116.49
C C S W	272.4	245	1-62.6	346	1-30.6	476	--	--	256.52	19.47	5.29	85.13
C C FB W	272.4	221	1-62.6	429	1-37.3	470	--	--	273.00	20.44	6.03	90.17
C C S W A A	408.3	245	1-62.6	469	1-40.3	404	5	4	325.31	21.70	5.54	102.72
C C FB W A A	408.3	220	1-62.6	541	1-37.3	487	5	5	324.97	23.40	6.00	104.35

Table 5.12B Median Completion Dates for Planting and Harvesting at the MLTI for those Rotations in which Corn is a Dominant Crop.

Crop rotation	Total machinery related costs ($/ha)	Planting operations				Harvesting operations		
		Corn	Soybeans or Field beans	Wheat	Alfalfa	Corn	Soybeans or Field beans	Wheat
		(days after starting date constraint)						
At Maximum Crop Area that can be Harvested by a 2-Row Combine								
C C	149.42	10.5				14.0		
C C S W	106.28	10.8	4.2	7.8		14.0	7.8	7.4
C C FB W	112.26	13.2	4.3	3.4		14.0	4.9	7.4
C C S W A A	114.46	13.1	4.1	7.8	3.6	14.0	7.8	7.4
C C FB W A A	120.93	13.2	4.3	3.7	3.6	14.0	4.9	7.4
At Maximum Crop Area that can be Harvested by a 4-Row Combine								
C C	116.49	12.9				14.0		
C C S W	85.13	12.4	5.0	9.1		14.0	9.1	8.7
C C FB W	90.17	13.7	4.3	4.3		14.0	6.2	8.7
C C S W A A	102.72	13.1	4.1	9.6	3.9	14.0	9.1	8.7
C C FB W A A	104.35	13.7	4.3	3.7	3.9	14.0	6.2	8.7

Table 5.13A Effect of Crop Rotation on Size, Use, and Costs of Field Machinery at the LLTI for those Rotations in which Corn is a Dominant Crop.

Crop rotation	Farm size (ha)	Machinery Size and Use: Combine	Tillage tractor		Utility tractor		Alfalfa harvesting		Investment in machinery	Labor Costs	Fuel and oil costs	Total machinery related costs
		Use (hr)	No. & size (PTOkW)	Use (hr)	No. & size (PTOkW)	Use (hr)	Units of mower-conditioner & baler	Units of alfalfa tractor	($/ha)			
At Maximum Crop Area that can be Harvested by a 2-Row Combine												
C C	79.3	142	1-29.8	128	1-22.4	119	--	--	516.72	24.36	3.71	138.08
C C S W	158.6	228	1-29.8	261	1-22.4	295	--	--	327.54	24.56	3.98	101.66
C C FB W	158.6	204	1-29.8	363	1-22.4	318	--	--	354.62	27.75	4.65	110.46
C C S W A A	238.4	228	1-29.8	423	1-22.4	318	3	2	357.19	27.90	4.65	113.00
C C FB W A A	238.4	205	1-29.8	526	1-22.4	341	3	2	372.36	30.02	5.09	118.36
At Maximum Crop Area that can be Harvested by a 4-Row Combine												
C C	136.0	142	1-44.7	146	1-22.4	204	--	--	424.08	17.99	3.71	115.00
C C S W	272.4	245	1-44.7	299	1-23.9	480	--	--	255.61	18.71	3.98	82.88
C C FB W	272.4	221	1-41.8	478	1-28.3	462	--	--	261.46	21.18	4.72	86.96
C C S W A A	408.3	245	1-44.7	468	1-23.9	517	5	4	307.42	23.05	4.65	99.14
C C FB W A A	408.3	220	1-41.8	646	1-28.3	486	5	5	316.99	24.69	5.14	102.82

Table 5.13B Median Completion Dates for Planting and Harvesting at the LLTI for those Rotations in which Corn is a Dominant Crop.

Crop rotation	Total machinery related costs ($/ha)	Planting operations				Harvesting operations		
		Corn	Soybeans or Field beans	Wheat	Alfalfa	Corn	Soybeans or Field beans	Wheat
		(days after starting date constraint)						
	At Maximum Crop Area that can be Harvested by a 2-Row Combine							
C C	138.08	9.2				14.0		
C C S W	101.66	9.2	4.2	9.0		14.0	7.8	7.4
C C FB W	110.46	9.2	3.9	3.4		14.0	4.9	7.4
C C S W A A	113.00	9.2	4.2	9.0	4.0	14.0	7.8	7.4
C C FB W A A	118.36	9.2	9.2	4.2	4.0	14.0	4.9	7.4
	At Maximum Crop Area that can be Harvested by a 4-Row Combine							
C C	115.00	10.2				14.0		
C C S W	82.88	10.1	6.2	10.1		14.0	9.1	8.7
C C FB W	86.96	13.8	5.8	4.3		14.0	6.2	8.7
C C S W A A	99.14	10.2	6.2	10.1	4.7	14.0	9.1	8.7
C C FB W A A	102.82	13.8	5.8	4.9	4.8	14.0	6.2	8.7

overlap and therefore tillage tractor size required remained the same as that for C C rotation even though the crop land area was doubled. Field labor costs and fuel costs were more for C C FB W crop rotation compared to C C S W crop rotation because two discing operations were required for field beans compared to only one for soybeans; and field bean harvesting required an additional operation, field bean pulling.

By adding two years of alfalfa to the C C S W crop rotation, the area under cultivation could be increased to three times that of C C rotation without increasing the size of combine since different harvesting machinery is required for harvesting alfalfa. The planting season for alfalfa does not overlap the tillage season of any other crop, therefore alfalfa could be added to the rotation without increasing the size of tractor(s). Use of the tractor(s) increased. The TMRC were higher than C C S W rotation since the selected harvesting machinery for alfalfa was not utilized to capacity. Again, replacement of soybeans by field beans increased initial investment in machinery and consequently the TMRC slightly.

Tables 5.14 through 5.16 show the effect of those crop rotations in which corn is not a dominant crop. These rotations were also compared with C C rotation. Multicrop rotations reduced machinery requirments on a per unit area basis and the TMRC over that of single crop rotations. The amount of reduction varied with the level of tillage intensity. The reduction was more at the HLTI and was less at the LLTI.

The area of soybeans that a given combine can harvest in one season is less than the area that the same combine can harvest of corn, because field time available for harvesting soybeans is less than that for corn.

Table 5.14A Effect of Crop Rotation on Size, Use, and Costs of Field Machinery at the HETI for those Rotations in which Corn is not a Dominant Crop.

Crop rotation	Farm size (ha)	Machinery Size and Use: Combine Use (hr)	Tillage tractor No. & size (PTOkW)	Tillage tractor Use (hr)	Utility tractor No. & size (PTOkW)	Utility tractor Use (hr)	Alfalfa harvesting: Units of mower-conditioner & baler	Alfalfa harvesting: Units of alfalfa tractor	Investment in machinery ($/ha)	Labor costs ($/ha)	Fuel and oil costs ($/ha)	Total machinery related costs ($/ha)
At Maximum Crop Area that can be Harvested by a 2-Row Combine												
C C	79.3	142	1-55.9	170	1-22.4	231	—	—	581.96	34.03	7.04	166.28
S S	64.3	75	1-29.8	214	1-22.4	131	--	—	558.19	32.44	5.31	150.09
C S	112.5	166	1-48.5	255	1-22.4	278	—	—	423.76	30.86	6.18	130.08
C FB	158.6	188	1-55.9	352	1-29.8	318	--	—	332.11	27.85	6.87	110.83
C W A A	234.3	155	1-84.3	218	1-36.5	229	4	3	499.25	25.16	6.15	138.13
C S W A A	293.4	231	1-63.4	428	1-22.4	385	4	3	341.67	27.01	5.96	112.33
At Maximum Crop Area that can be Harvested by a 4-Row Combine												
C C	136.0	142	1-96.2	170	1-32.8	277	--	--	507.72	21.52	7.07	138.35
S S	91.9	75	1-39.5	231	1-22.4	186	--	—	476.39	26.63	5.34	129.58
C S	173.2	161	1-74.6	255	1-24.6	392	—	—	379.78	23.18	6.20	114.68
C FB	272.4	204	1-96.2	352	1-55.2	369	--	--	305.08	16.88	6.92	95.33
C W A A	332.7	145	2-62.6	263	1-54.4	309	6	3	466.41	24.39	6.42	132.20
C S W A A	416.0	213	1-89.5	404	1-29.1	437	6	5	341.08	22.36	5.96	106.60

Table 5.14B Median Completion Dates for Planting and Harvesting at the HLTI for those Rotations in which Corn is not a Dominant Crop.

Crop rotation	Total machinery related costs ($/ha)	Planting operations: Corn	Planting operations: Soybeans or Field beans	Planting operations: Wheat	Planting operations: Alfalfa	Harvesting operations: Corn	Harvesting operations: Soybeans or Field beans	Harvesting operations: Wheat
		------------(days after starting date constraint)----------						
	At Maximum Crop Area that can be Harvested by a 2-Row Combine							
C C	166.28	11.1				14.0		
S S	150.09		6.4				12.0	
C S	130.08	8.8	7.2			15.5	10.6	
C FB	110.83	10.3	5.9			14.0	8.8	
C W A A	138.13	5.6		9.7	3.4	9.7		10.0
C S W A A	112.33	8.3	5.7	11.0	4.2	10.4	11.0	10.4
	At Maximum Crop Area that can be Harvested by a 4-Row Combine							
C C	138.35	11.9				14.0		
S S	129.58		8.2				12.0	
C S	114.68	10.4	7.5			16.1	11.3	
C FB	95.33	10.1	5.9			14.0	11.5	
C W A A	132.20	6.0		8.6	4.0	8.6		10.4
C S W A A	106.60	8.9	6.2	10.9	4.2	8.7	10.9	10.4

Table 5.15A Effect of Crop Rotation on Size, Use, and Costs of Field Machinery at the MLTI for those Rotations in which Corn is not a Dominant Crop.

Crop rotation	Farm size (ha)	Machinery Size and Use: Combine Use (hr)	Tillage tractor No. & size (PTOkW)	Tillage tractor Use (hr)	Utility tractor No. & size (PTOkW)	Utility tractor Use (hr)	Alfalfa harvesting: Units of mower-conditioner & baler	Alfalfa harvesting: Units of alfalfa tractor	Investment in machinery	Labor costs	Fuel and oil costs	Total machinery related costs
									($/ha)			
At Maximum Crop Area that can be Harvested by a 2-Row Combine												
C C	79.3	142	1-29.8	194	1-22.4	235	--	--	496.21	35.78	5.63	149.42
S S	64.3	75	1-29.8	157	1-22.4	83	--	—	538.61	24.36	4.05	135.61
C S	112.5	166	1-29.8	275	1-22.4	239	--	—	390.50	30.07	4.84	120.69
C FB	158.6	188	1-38.8	454	1-22.4	379	—	--	295.56	32.02	6.20	107.81
C W A A	234.3	155	1-84.3	197	1-36.5	229	4	3	504.81	24.71	5.91	137.96
C S W A A	293.4	231	1-41.8	521	1-29.1	317	4	3	330.80	27.43	5.49	108.33
At Maximum Crop Area that can be Harvested by a 4-Row Combine												
C C	136.0	142	1-37.3	200	1-29.1	314	--	--	374.46	26.39	5.60	116.49
S S	91.9	75	1-29.8	225	1-22.4	119	—	--	436.78	22.63	4.05	115.74
C S	173.2	161	1-29.8	424	1-22.4	368	--	--	300.19	27.35	4.84	102.47
C FB	272.4	204	1-66.4	456	1-40.3	405	—	--	268.75	19.42	6.25	90.89
C W A A	332.7	145	2-62.6	243	1-54.4	369	6	3	469.92	23.80	6.18	131.46
C S W A A	416.0	213	1-58.9	496	1-42.5	350	6	5	345.40	22.41	5.54	106.50

Table 5.15B Median Completion Dates for Planting and Harvesting at the MLTI for those Rotations in which Corn is not a Dominant Crop.

Crop rotation	Total machinery related costs ($/ha)	Planting operations				Harvesting operations		
		Corn	Soybeans or Field beans	Wheat	Alfalfa	Corn	Soybeans or Field beans	Wheat
		(days after starting date constraint)						
	At Maximum Crop Area that can be Harvested by a 2-Row Combine							
C C	149.42	10.5				14.0		
S S	135.61		6.2				12.0	
C S	120.69	8.0	5.6			15.5	10.6	
C FB	107.81	10.5	6.9			14.0	8.8	
C W A A	137.96	5.6		9.7	3.4	9.7		10.0
C S W A A	108.33	10.0	4.6	11.0	5.2	10.4	11.0	10.4
	At Maximum Crop Area that can be Harvested by a 4-Row Combine							
C C	116.49	12.9				14.0		
S S	115.74		8.2				12.0	
C S	102.47	11.2	7.8			16.1	11.3	
C FB	90.89	10.1	6.8			14.0	11.5	
C W A A	131.46	6.0		8.6	4.0	8.6		10.4
C S W A A	106.50	10.1	4.5	10.9	5.2	8.7	10.9	10.4

Table 5.16A Effect of Crop Rotation on Size, Use, and Costs of Field Machinery at the LLTI for those Rotations in which Corn is not a Dominant Crop.

Crop rotation	Farm size (ha)	Machinery Size and Use: Combine Use (hr)	Tillage tractor No. & size (PTOkW)	Tillage tractor Use (hr)	Utility tractor No. & size (PTOkW)	Utility tractor Use (hr)	Alfalfa harvesting: Units of mower-conditioner & baler	Alfalfa harvesting: Units of alfalfa tractor	Investment in machinery ($/ha)	Labor costs ($/ha)	Fuel and oil costs ($/ha)	Total machinery related costs ($/ha)
At Maximum Crop Area that can be Harvested by a 2-Row Combine												
C C	79.3	142	1-29.8	128	1-22.4	119	--	--	516.72	24.36	3.71	138.08
C S	112.5	166	1-29.8	185	1-22.4	214	--	--	440.86	25.00	3.88	122.69
C FB	158.6	188	1-38.0	364	1-22.4	344	--	--	338.56	28.10	5.24	109.79
C W A A	234.3	155	1-45.5	257	1-22.4	248	4	3	419.98	26.44	5.02	128.72
C S W A A	293.4	231	1-33.6	498	1-22.4	334	4	3	340.14	27.33	4.82	109.34
At Maximum Crop Area that can be Harvested by a 4-Row Combine												
C C	136.0	142	1-44.7	146	1-22.4	204	--	--	424.08	17.99	3.71	115.00
C S	173.2	161	1-29.8	285	1-22.4	330	--	--	339.79	22.26	3.88	101.59
C FB	272.4	204	1-65.6	367	1-40.3	406	--	--	300.83	17.82	5.34	92.84
C W A A	332.7	145	2-44.7	219	1-23.9	342	6	4	450.40	25.01	5.04	127.01
C S W A A	416.0	213	1-47.7	532	1-29.1	397	6	4	327.88	22.61	4.87	101.68

Table 5.16B Median Completion Dates for Planting and Harvesting at the LLTI for those Rotations in which Corn is not a Dominant Crop.

Crop rotation	Total machinery related costs ($/ha)	Planting operations				Harvesting operations		
		Corn	Soybeans or Field beans	Wheat	Alfalfa	Corn	Soybeans or Field beans	Wheat
		(days after starting date constraint)						
	At Maximum Crop Area that can be Harvested by a 2-Row Combine							
C C	138.08	9.2				14.0		
C S	122.69	7.1	5.6			15.5	10.6	
C FB	109.79	7.6	6.9			14.0	8.8	
C W A A	128.72	5.2		9.7	4.7	9.7		10.0
C S W A A	109.34	6.7	5.7	11.4	5.7	10.4	11.0	10.4
	At Maximum Crop Area that can be Harvested by a 4-Row Combine							
C C	115.00	10.2				14.0		
C S	101.59	9.8	7.8			16.1	11.3	
C FB	92.84	8.1	6.8			14.0	11.5	
C W A A	127.01	4.5		10.5	5.1	8.6		10.4
C S W A A	101.68	6.7	6.2	11.4	5.7	8.7	10.9	10.4

But more field time is available for primary tillage for soybeans compared to corn. Therefore, tillage tractor power requirements were less for S S rotation than for C C rotation. The TMRC were also less for S S rotation compared to C C rotation.

Both planting and harvesting seasons could be enlarged by growing corn and soybean crops in one rotation. A given combine could harvest more crop area in one season but the harvested area could not be doubled because harvesting seasons of these two crops overlap. Tillage tractor power requirements were also reduced but not to half because planting seasons of these two crops also overlap. The TMRC were less for C S rotation compared to both C C and S S rotations.

Crop area harvested by a given combine could be almost doubled over that of C C rotation by following C FB rotation because the harvesting seasons of corn and field beans do not overlap. Tillage tractor power requirements can also be halved over that of C C rotation since planting seasons of these crops also do not overlap. Compared to the C C rotation, the TMRC in C FB rotation were only about two-thirds at the HLTI, three-fourths at the MLTI, and four-fifths at the LLTI.

The C S W A A rotation increased machinery use and decreased TMRC consideralby compared to the C C rotation, but not as much as the C FB rotation. The median completion dates for planting and harvesting operations of corn were also considerably earlier in this crop rotation compared to C C rotation.

The C W A A rotation did not decrease the TMRC as much as other crop rotations. The reason for this was short time available for planting early varieties of corn which are required for this crop rotation. At the middle and the lowest level of tillage intensity, the TMRC for the C W A A rotation were higher compared to C C rotation. It was so because in C W A A rotation at the middle level of tillage intensity corn and alfalfa were raised using the MBTS and at the lowest level of tillage intensity alfalfa was raised using the MBTS and wheat using the CHTS. The requirements of additional equipment for raising different crops using different tillage systems, increased initial investment in machinery and consequently the TMRC.

5.3 Machinery Requirements and Costs

5.3.1 Tillage tractor power requirements

For every crop rotation, there is a calendar period during which tractor power requirements are maximum. The amount of the work and the available field work time during this period determine the size of tractor(s) and thereby the size of tractor powered implements. The spring tillage period was the peak work season for most of the cropping systems considered in this study. As the tillage intensity was decreased, the amount of work to be done during the peak work season also decreased, and consequently the tillage tractor power requirements decreased, as can be seen from Figure 5.1. Since chisel plowing was permitted in fall and moldboard plowing was not permitted, the available field work time during the peak work season was more for the CHTS compared to the MBTS. This also caused considerable decrease in the tillage tractor power requirements for the MLTI and the LLTI.

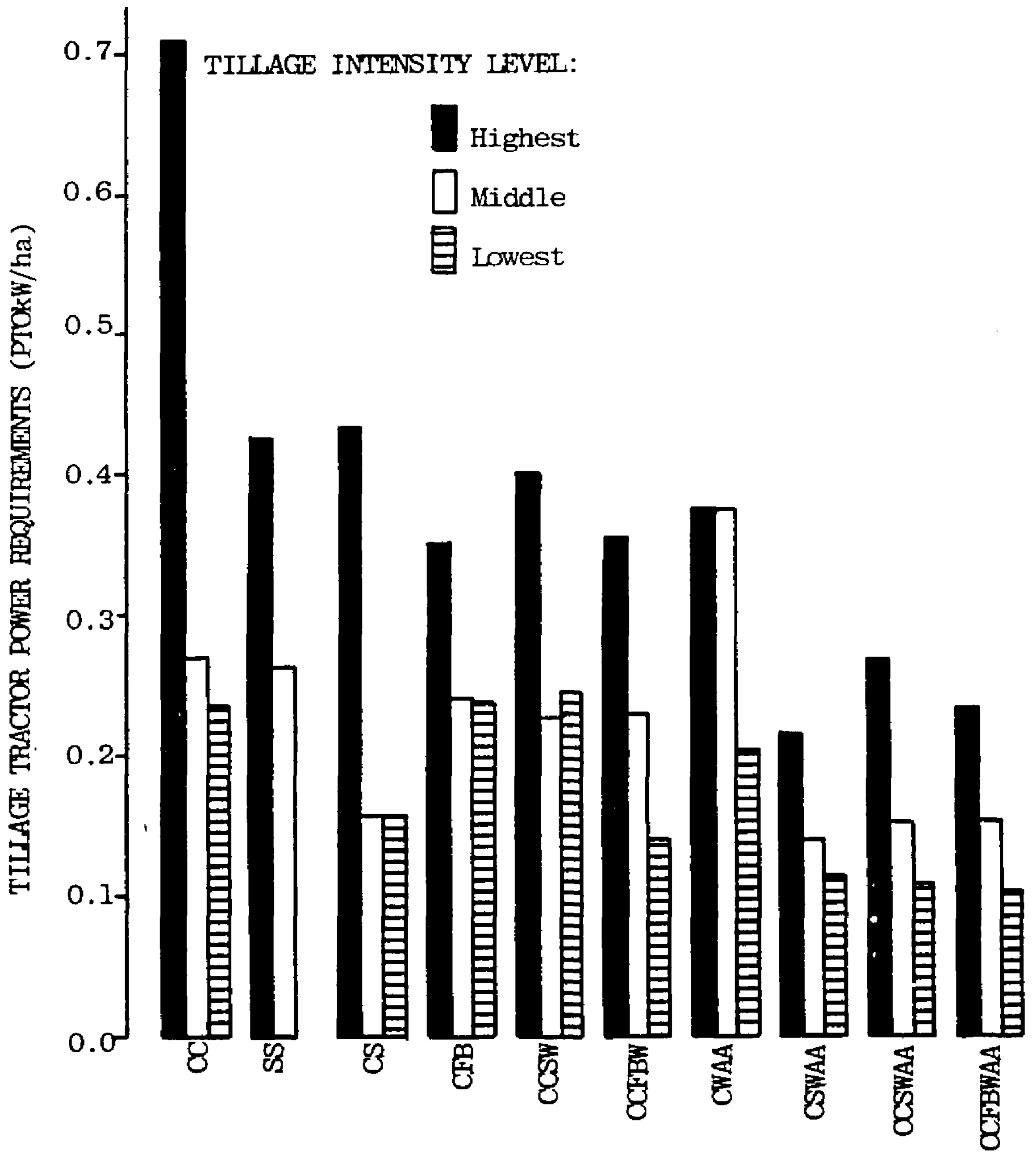


Figure 5.1 Effect of Tillage Intensity Level and Crop Rotation on Tillage Tractor Power Requirements.

Tillage tractor power requirements for the S S rotation were less than for the C C rotation at the HLTI because more time was available for spring tillage for S S rotation, even though the amount of tillage work was the same for both rotations. Available field work time during peak work season and the amount of field work was the same for S S and C S rotations at the HLTI. Therefore, power requirements were also the same for both rotations. The peak work season for C C and C FB rotations at the HLTI was during the spring tillage period of corn. Since only half of the work was required to be finished during this period for C FB rotation compared to C C rotation, tillage tractor power requirements for C FB rotation were also only half of that for C C rotation. Similarly, tillage tractor power requirements for C C FB W rotation were only half, and for C C FB W A A rotation were only one third of that for C C rotation. For crop rotations in which wheat followed soybeans, early varieties of soybeans were required and, therefore, field work time available for soybean planting was less in these crop rotations compared to C S rotation. For this reason tillage tractor power requirements for C C S W, C S W A A, and C C S W A A rotations did not decrease in proportion to the decrease in the amount of work during peak work season. Power requirements were comparatively high for the C W A A crop rotation because of the shorter planting season for short season varieties of corn.

5.3.2 Harvesting machinery

Tillage intensity has no direct influence on size, use, and costs of harvesting machinery. But, crop rotation strongly influences the maximum area that a given combine can harvest during one season (Figure 5.2, and Section 5.2).

Table 5.17 shows harvesting costs (machinery, labor, and fuel) as affected by crop rotation and combine size. Harvesting machinery includes the SP combine and any additional machinery which was required in a given rotation such as corn header, grain header, pick-up header, mower-conditioner, baler, or alfalfa tractors. Whenever utility and/or tillage tractor(s) were used for alfalfa harvesting, their cost, prorated according to the time used, was also included in the harvesting costs.

Harvesting costs were considerably less for multi-crop rotations (not involving alfalfa) than for single-crop rotations. Rotations involving alfalfa also had considerably higher harvesting costs than other rotations. Labor and fuel requirements for three cuttings of alfalfa were higher than for one combining operation for other crops (Table 5.17). Machinery costs were also high for alfalfa harvesting. Combine use was maximized by selecting an appropriate farm size, however machinery selected for alfalfa harvesting could not always be used to capacity. This was one reason for higher machinery costs for alfalfa harvesting.

For the single crop enterprises, harvesting costs for corn decreased with an increase in combine size. However, harvesting costs for soybeans increased with an increase in combine

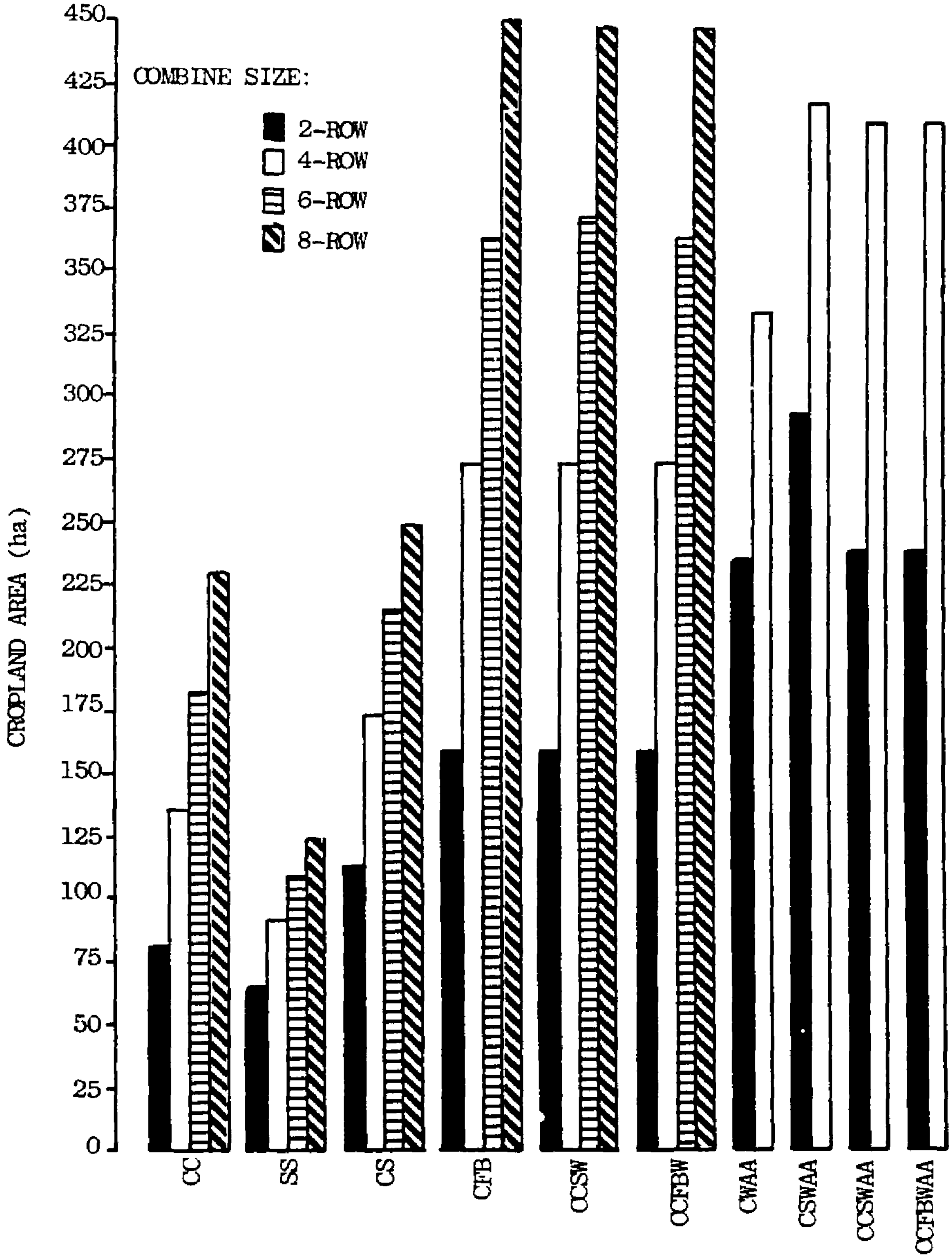


Figure 5.2. Effect of Combine Size and Crop Rotation on the Maximum Cropland Area that a Combine can Harvest in one Season.

Table 5.17 Harvesting Costs ($/ha) as Affected by Crop Rotation and Combine Size.

Crop rotation	Combine Size															
	2-Row				4-Row				6-Row				8-Row			
	Machinery	Labor	Fuel	Total	Machinery	Labor	Fuel	Total	Machinery	Labor	Fuel	Total	Machinery	Labor	Fuel	Total
C C	51.3	8.9	1.8	61.9	44.7	5.2	1.8	51.6	43.9	3.9	1.8	49.6	43.3	3.1	1.8	48.1
S S	55.5	5.8	1.2	62.5	50.5	4.1	1.2	55.7	53.8	3.4	1.2	58.5	57.2	3.0	1.2	61.4
C S	41.6	7.3	1.5	50.4	38.3	4.6	1.5	44.4	39.5	3.7	1.5	44.6	41.6	2.1	1.5	45.2
C FB	31.2	5.9	1.7	38.8	26.3	3.7	1.7	31.7	26.3	2.9	1.7	30.9	26.1	4.7	1.7	32.5
C C S W	31.6	7.1	1.6	40.3	26.8	4.5	1.6	32.9	26.3	3.6	1.6	31.4	26.9	2.9	1.6	31.4
C C FB W	34.9	6.4	1.7	43.0	28.7	4.0	1.7	34.4	28.2	3.2	1.7	33.1	28.1	2.6	1.7	32.3
C W A A	65.3	15.8	3.0	84.1	65.7	14.5	3.0	83.2								
C S W A A	51.4	13.8	2.6	67.8	52.5	12.4	2.6	67.5								
C C S W A A	51.6	13.0	2.5	67.1	48.1	11.2	2.5	61.8								
C C FB W A A	53.6	12.5	2.5	68.6	50.5	10.9	2.5	63.9								

size due to a greater increase in combine purchase price than in harvesting capacity for soybeans. For multicrop enterprises (except C S W A A), harvesting costs considerably decreased when combine size was increased from 2 to 4-row. A further increase in combine size did not change harvesting costs noticeably.

5.3.3 Machinery investment

The effect of tillage intensity and crop rotation on initial machinery investment (IMI) is illustrated in Figure 5.3 for the maximum farm sizes that a 4-row combine can harvest in one season. In general, IMI decreased with a decrease in tillage intensity. This decrease was more pronounced when tillage intensity was reduced for all crops in a rotation (C C, S S, C S), and was less noticeable when tillage intensity was reduced for only a few crops in a rotation (most notably for rotations involving alfalfa).

Crop rotation had a strong effect on IMI. Single-crop enterprises (C C, S S) and C W A A rotation had a higher IMI due mainly to higher harvesting costs. IMI was lowest for C FB, C C S W, and C C FB W rotations because these rotations had a more evenly distributed harvest and tillage work pattern.

A couple of counter intuitive results appear in Figure 5.3. For C W A A rotation, the IMI at the MLTI was higher than at the HLTI, since additional implements, a chisel plow and a stalk shredder, were required at the MLTI. The IMI was higher at the MLTI as compared to the HLTI for C S W A A rotation also. This happened because a smaller

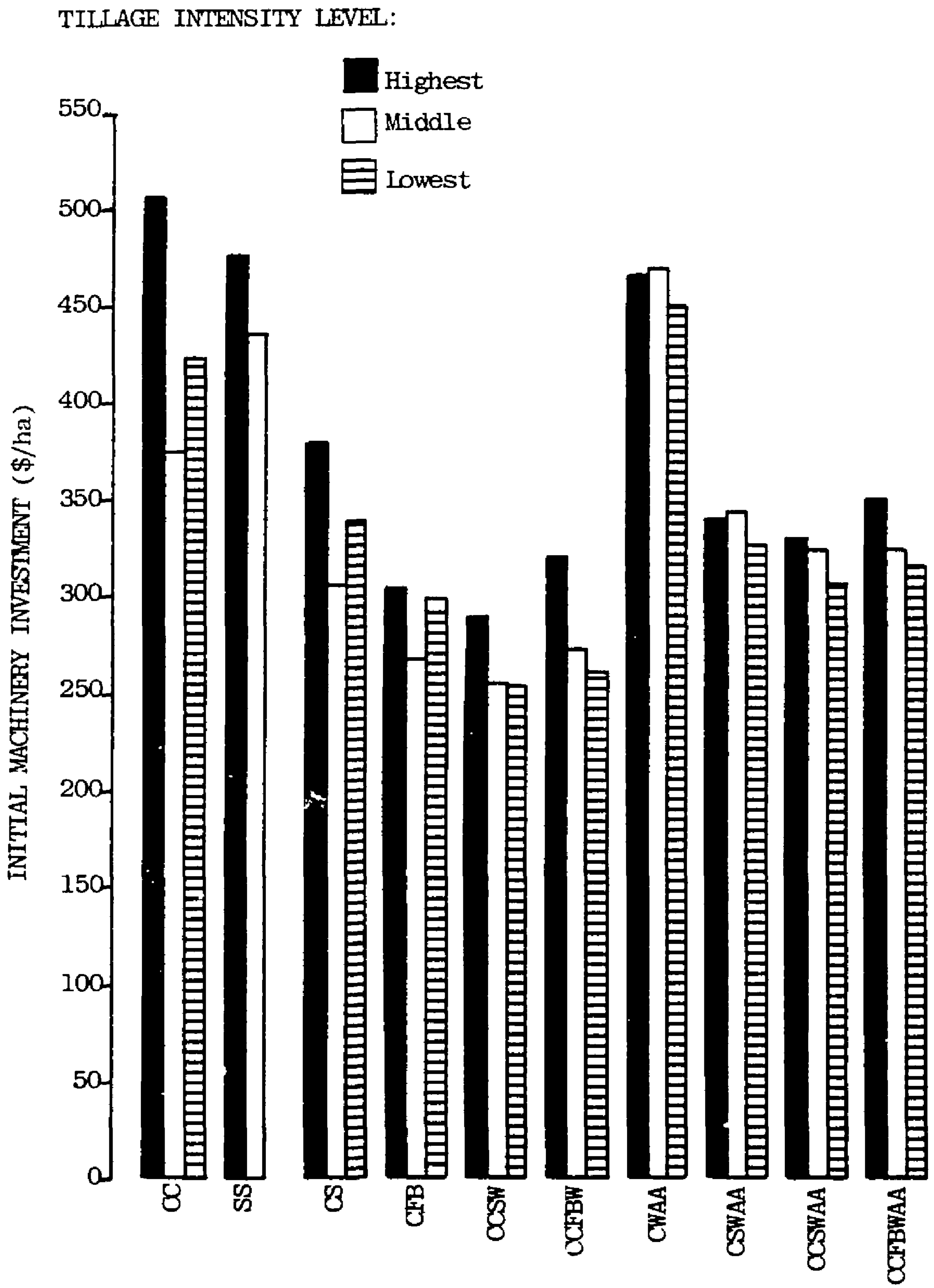


Figure 5.3 Effect of Tillage Intensity Level and Crop Rotation on Initial Machinery Investment for the Maximum Farm Sizes that can be Harvested by a 4-Row Combine.

tillage tractor at the MLTI left less available planting time thereby requiring a bigger, 8-row, planter, whereas the HLTI required only a 4-row planter.

The higher IMI at the LLTI as compared to the MLTI for C C rotation was because an 8-row planter was required at the LLTI (due to the lower maximum speed limit constraint for the no-till planter), whereas a 4-row planter was required at the MLTI. The IMI was higher at the LLTI than at the MLTI for C S and C FB rotations because an additional no-till planter was required at the LLTI.

5.3.4 Total annual machinery related costs

The effect of tilage intensity and crop rotation on total annual machinery related costs (TMRC) is illustrated in Figure 5.4 for the maximum farm sizes that a 4-row combine can harvest in one season. Machinery, labor, and fuel costs were considered. The results for TMRC follow the general pattern of IMI (Figure 5.3). A reduction in tillage intensity reduced TMRC. For most crop rotations, the difference in TMRC was more between the HLTI and the MLTI than between the MLTI and the LLTI. This pattern is similar to that of tillage tractor power requirements (Figure 5.1).

Crop rotations had a stronger influence on TMRC than tillage intensity. The effect of crop rotation on TMRC was generally similar to the effect on IMI, although the variation in the TMRC were slightly less pronounced than in the IMI.

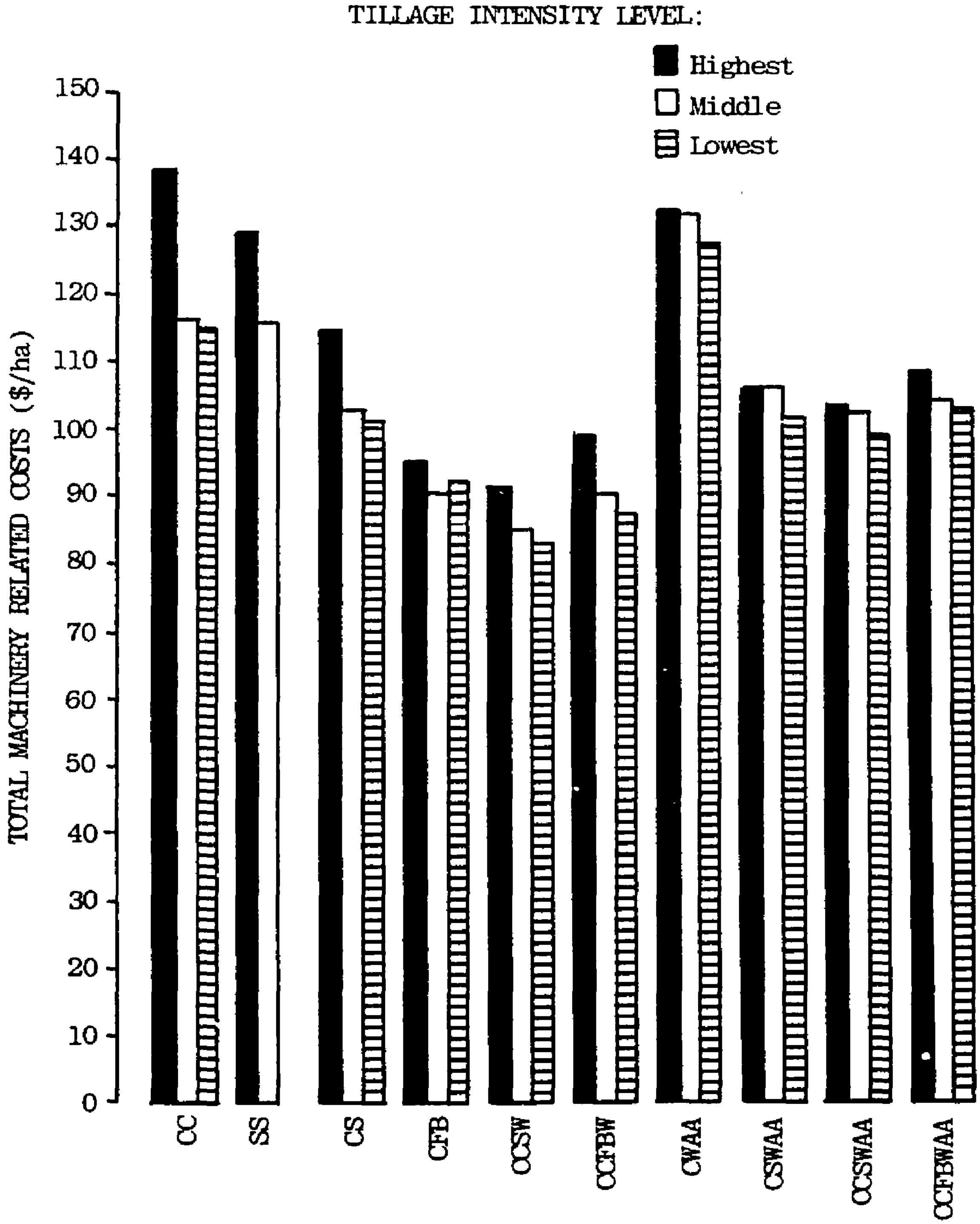


Figure 5.4 Effect of Tillage Intensity Level and Crop Rotation on Total Field Machinery Related Costs for the Maximum Farm Sizes that can be Harvested by a 4-Row Combine.

5.4 Field Labor Requirements

Table 5.18 shows annual field labor requirements in hours per hectare as affected by crop rotation and tillage intensity. Field labor requirements were obtained by dividing the annual sum of field work hours by scheduling efficiency and then adding 30 percent extra labor for repair, off-season maintenance and machine preparation.

The computer program described earlier selects the smallest tractor size that can finish the assigned amount of work within specified calendar date constraints. Since date constraints for field operations of each crop were kept constant across all cropping systems as far as feasible, the labor requirements do not vary much with a change in crop rotation or tillage intensity. However, since fall chisel plowing was permitted and fall moldboard plowing was not, more time was available to complete tillage operations at the MLTI compared to the HLTI. Therefore, in general, labor requirements were higher for the MLTI compared to the HLTI. The difference between the labor requirements at the HLTI and the LLTI was not very large for most of the crop rotations considered. For some crop rotations, the decrease in labor requirements was more for the HLTI than for the LLTI when farm size was increased from the maximum area that can be harvested by a 2-row combine to that corresponding to 4-row. For these rotations at the LLTI, even the smallest permitted tractor size was bigger than actually required for farm sizes corresponding to 2-row combine.

Table 5.19 illustrates field labor distribution for an average (50 percent probability level) year at three different levels of tillage intensity. Multicrop rotations had a more even distribution of labor during the year compared to single-crop rotations. For rotations

Table 5.18. Labor Requirements (h/ha) as Affected by Crop Rotation and Tillage Intensity.

Farm size and tillage intensity	Crop Rotation									
	CC	SS	CS	CFB	CCSW	CCFBW	CWAA	CSWAA	CCSWAA	CCFBWAA
	Combine Size = 2-Row									
Farm size (ha)*	79.3	64.3	112.5	158.6	158.6	158.6	234.3	293.4	238.4	238.4
HLTI	10.5	10.0	9.5	8.5	8.3	8.6	7.7	8.3	8.6	8.8
MLTI	11.0	7.5	9.2	9.9	9.0	9.8	7.6	8.4	9.2	9.9
LLTI	7.5	—	7.7	8.6	7.6	8.5	8.1	8.4	8.6	9.2
	Combine Size = 4-Row									
Farm size (ha)**	136.0	91.9	173.2	272.4	272.4	272.4	332.7	416.0	408.3	408.3
HLTI	6.6	8.2	7.1	5.2	5.4	5.4	7.5	6.9	6.4	6.4
MLTI	8.1	7.0	8.4	6.0	6.0	6.3	7.3	6.9	6.7	7.2
LLTI	5.5	—	6.8	5.5	5.8	6.5	7.7	7.0	7.1	7.6

*Maximum crop area that can be harvested by a 2-row combine.
**Maximum crop area that can be harvested by a 4-row combine.

Table 5.19 Labor (man-week) Distribution during an Average (50 percent probability level) Year at Three Different Levels of Tillage Intensity.*

Crop rotation	April			May					June				July					August				September				October					November		
	10	17	24	01	08	15	22	29	05	12	19	26	03	10	17	24	31	07	14	21	28	04	11	18	25	02	09	16	23	30	06	13	20
Highest Level of Tillage Intensity																																	
C C	1.5	1.0	2.0	2.0	1.8			1.0	1.0	1.0	.3																1.2	1.2	1.2	1.1			
S S	1.0	1.0	1.0	1.0	1.0	2.0	2.0	.5			1.0	.4													1.0	1.0	1.0	.2					
C S	1.3	1.0	2.0	2.0	1.5	2.0	2.0	1.0	1.0	1.0	1.0	.2													1.0	1.0	1.0	1.3	1.3	.6			
C FB	1.5	1.0	2.0	1.4	1.4	1.2	1.2	2.0	1.8	1.0	1.0	.1									1.0	1.0	1.0	.2			1.2	1.2	1.2	1.1			
C C S W	1.5	1.4	2.0	2.0	1.8	2.0	.4	1.0	1.0	1.0	1.0				1.0	1.0	.2							2.1	2.1	.6	1.2	1.2	1.2	1.1			
C C FB W	1.5	1.4	2.0	1.7	1.5	1.2	.6	1.4	1.0	1.0	.8				1.0	1.0	.2				1.7	.8		1.5			1.2	1.2	1.2	1.1			
C W A A	2.3	2.5	2.4	.7				6.0	4.1					4.0	5.2	2.7	3.2			4.4	2.8				3.2	3.2	.5						
C S W A A	1.3	1.5	2.0	2.0	1.1	2.0	.9	5.2	4.5	.3	1.0			4.0	4.1	2.3	2.9			4.0	2.2			2.1	2.1	.7	1.2	1.2	.3				
C C S W A A	1.5	1.4	2.0	2.0	1.8	2.0	.4	5.3	3.8	1.0	1.0			4.0	3.8	2.2	1.4			4.0	1.9			1.9	2.0	.6	1.2	1.2	1.2	1.1			
C C FB W A A	1.5	1.4	2.0	1.7	1.5	1.2	.7	5.8	3.8	1.0	.8			4.0	4.0	2.3	1.4			4.0	3.6	.8		1.2			1.2	1.2	1.2	1.1			
Middle Level of Tillage Intensity																																	
C C	.5		2.0	2.0	2.0	.2		1.0	1.0	.1																	2.4	2.4	2.4	2.3	.9		
S S						2.0	1.9	.5																	2.0	2.0	2.0	.3					
C S	.3		2.0	2.0	1.2	2.0	1.8	1.0	1.0	.1															2.0	2.0	2.0	2.6	2.6	1.7	1.0	.5	
C FB	1.5	1.0	2.0	2.0	1.4	1.4	1.2	2.0	1.8	1.0	1.0	.3									1.6	1.6	1.5	.3			1.3	1.3	1.3	1.2			
C C S W	1.5	1.4	2.0	2.0	2.0	1.7	.5	1.0	1.0	.8					1.0	1.0	.2							2.2	2.2	.7	2.1	2.1	2.1	2.0			
C C FB W	1.5	1.4	2.0	1.5	2.0	1.4	1.2	1.9	1.0	1.0	1.0	.1			1.0	1.0	.2				2.0	1.0		.9			2.1	1.9	1.3	1.2			
C W A A	2.3	2.5	2.4	.7				6.0	4.1					4.0	5.2	2.7	3.2			4.4	2.8				2.8	2.8	.4						
C S W A A	1.3	.5	1.8	1.3	1.3	.9	.4	5.1	4.2					4.0	4.3	2.6	2.9	.5		4.0	2.2			2.1	2.1	1.7	2.0	2.1	.5				
C C S W A A	1.5	1.4	1.9	1.4	2.0	1.7	.2	5.3	3.8	.1				4.0	4.1	2.5	1.7			4.0	1.9			2.1	2.1	.6	2.0	2.0	2.0	1.9			
C C FB W A A	1.5	1.4	2.0	1.5	2.0	1.4	1.2	5.9	3.2	1.0	1.0	.1		4.0	3.0	2.5	1.7			4.0	2.5	.8		1.4			2.1	1.9	1.3	1.2			

Table 5.19 (continued)

Crop rotation	Beginning date of the week																																
	April			May					June				July					August				September				October					November		
	10	17	24	01	08	15	22	29	05	12	19	26	03	10	17	24	31	07	14	21	28	04	11	18	25	02	09	16	23	30	06	13	20
	Lowest Level of Tillage Intensity																																
C C	.5	.8	1.0	1.6	.6			1.0	.4																		1.6	1.6	1.6	1.4			
S S																																	
C S	.3	.5	1.0	1.4	.4	2.0	1.8	1.0	1.0	.1															1.0	1.0	1.1	2.6	2.6	1.7	1.0	.3	
C FB	1.5	1.8	1.0	1.8	1.0	1.4	1.2	2.0	1.8	1.0	1.0	.3									1.0	1.0	1.0	.2			1.3	1.3	1.3	1.2			
C C S W	.5	1.0	1.2	1.6	.6	2.0	.8	1.0	1.0	.6					1.0	1.0	.2							2.4	2.4	1.1	1.5	1.7	2.5	2.4	.1		
C C FB W	1.5	2.0	1.2	1.4	1.3	1.3	1.1	2.0	1.9	1.0	1.0	.2			1.0	1.0	.2				2.0	1.5	.4	.9			1.5	1.5	1.5	1.4			
C W A A	.3	.9	1.8	.5				6.9	3.4					4.0	5.6	2.8	3.7	.3		4.4	2.8			.5	3.5	.6							
C S W A A	.3	.9	1.0	1.0		2.0	1.0	6.0	4.1					4.0	5.6	2.7	2.9	.8		4.4	2.8			2.3	2.3	2.1	2.3	2.3	.6				
C C S W A A	.5	1.0	1.2	1.6	.6	2.0	.8	5.3	3.8	.6				4.0	4.3	2.8	2.1	.2		4.0	1.9			2.4	2.4	1.1	1.5	1.7	2.5	2.4	.1		
C C FB W A A	1.5	2.0	1.2	1.4	1.3	1.3	1.1	6.0	4.0	1.0	1.0	.2		4.0	3.3	2.9	1.9	.3		4.0	2.9	.9		1.7	.2		1.5	1.5	1.5	1.4			

*For maximum farm sizes that can be harvested by a 4-row combine.

involving alfalfa, the labor requirements were very high during three 2-week harvesting seasons of alfalfa. The variation in labor distribution among various crop rotations was more at the LLTI compared to the HLTI.

5.5 Fuel Requirements

Figure 5.5 illustrates the effect of tillage intensity and crop rotation on fuel requirements. Fuel requirements are related to the amount of work. Therefore, as the tillage intensity was decreased for each crop rotation, the fuel requirements also decreased. The fuel requirements also changed with a change in crop rotation because different amounts of work are required to grow different crops. Table 5.20 shows the fuel requirements for each crop under those tillage systems which are used for that crop.

Table 5.20 Fuel Requirements (litres/ha) of the Crops.

Tillage system	Corn	Soybeans	Wheat	Field beans	Alfalfa
Moldboard plow	54.7 (60.3)*	45.6 (51.3)	45.5 (50.0)	(62.6)	71.0+ 32.9++
Chisel plow	43.8 (48.3)	34.7 (39.2)	37.4 (41.9)		
No-till	27.2 (31.7)				

*Numbers within the brackets represent fuel requirements when preceding crop was corn.
+Fuel requirements for planting and harvesting operations of first crop year.
++Fuel requirements for only harvesting operations of second crop year.

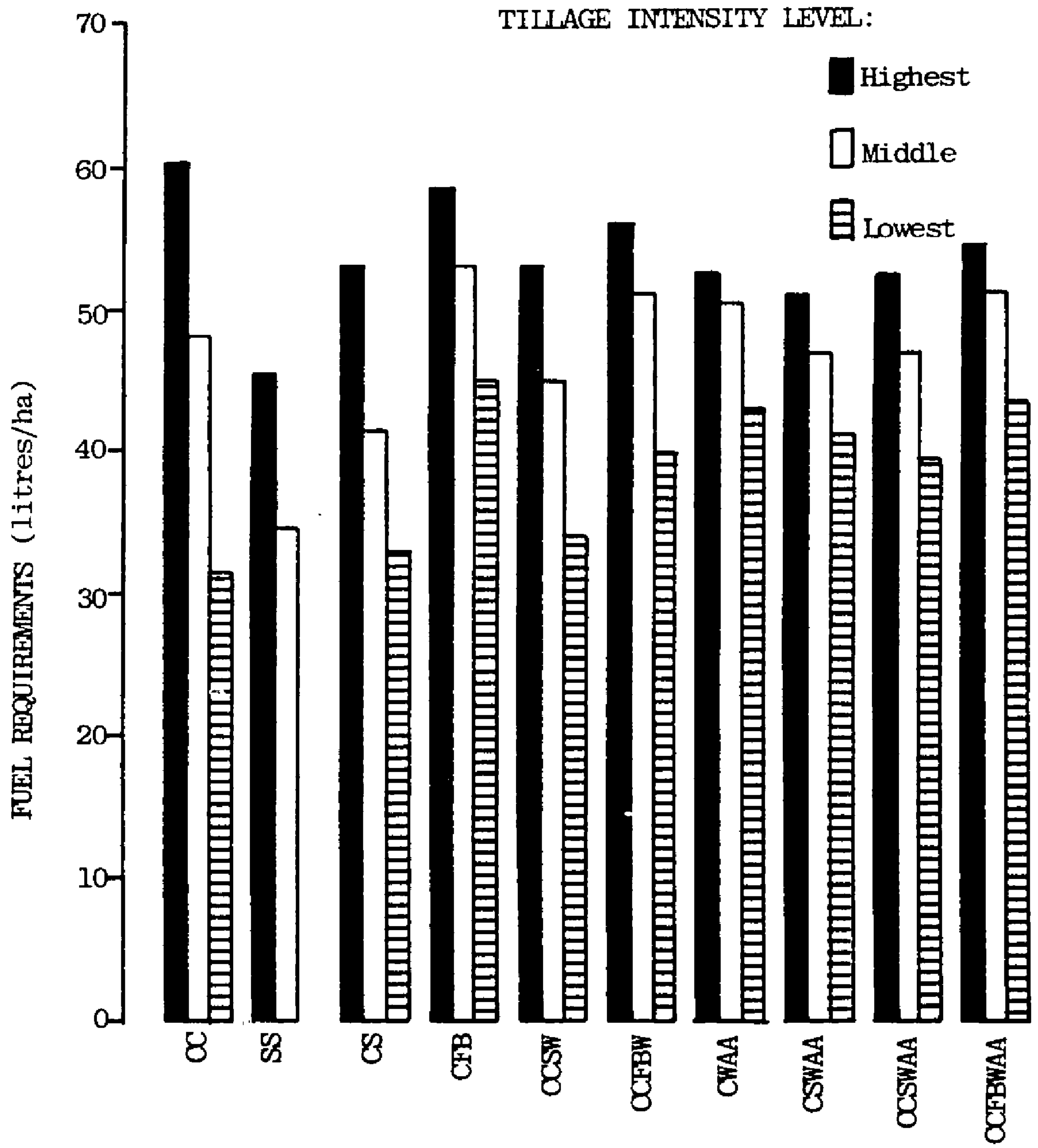


Figure 5.5 Effect of Tillage Intensity Level and Crop Rotation on Fuel Requirements.

5.6 Sensitivity Analysis

The C C S W rotation and the HLTI were selected to illustrate the influence of several important assumptions on field machinery requirements and costs. To study the effect of a design parameter, everything was fixed except the design factor to be studied, and calculations were made for machinery size, use, and costs.

5.6.1 Effect of design probability

Calculations of field machinery size, use, and costs were made for 70, 80, and 90 percent design probabilities. The results are shown in Table 5.21.

As the design probability was increased from 70 to 90 percent, available field work time decreased and therefore, the area that a given size of combine could harvest also decreased. Machinery size on a per unit crop area basis increased and machinery use decreased. Therefore, the initial investment in machinery increased and consequently TMRC also increased. But timeliness costs, as reflected by median completion dates of planting and harvesting operations (Table 5.21B), decreased. Median completion date for corn planting did not decrease when design probability was increased from 80 to 90 percent, because there was no appreciable increase in the size of utility tractor.

Since weekly fractions of calendar days suitable for field work were assumed to be normally distributed, the difference in available field work time between 70 and 80 percent design probability was less than between 80 and 90 percent design probability.

Table 5.21A Effect of Design Probability on Size, Use, and Costs of Field Machinery for C C S W Crop Rotation at the HLTI.

Design probability (percent)	Farm size (ha)*	Machinery Size and Use					Investment in machinery	Labor costs	Total machinery related costs
		Combine	Tillage tractor		Utility tractor				
		Use (hr)	No. & size (PTOkW)	Use (hr)	No. & size (PTOkW)	Use (hr)	($/ha)		
					Combine Size = 2-Row				
70	172.0	247	1-63.4	301	1-22.4	385	326.13	26.93	109.22
80	158.6	228	1-64.1	274	1-22.4	355	354.50	26.84	113.99
90	140.8	202	1-65.6	238	1-22.4	315	401.37	26.64	121.75
					Combine Size = 4-Row				
70	294.2	265	1-108.1	301	1-32.8	480	268.53	17.67	88.17
80	272.4	245	1-109.6	275	1-32.8	447	290.99	17.67	91.53
90	241.2	217	2-56.7	236	1-32.8	401	327.39	22.44	102.62
					Combine Size = 6-Row				
70	394.2	281	2-72.3	302	1-44.0	504	253.13	17.52	86.06
80	371.1	265	2-75.3	273	1-44.7	470	274.36	17.15	88.96
90	339.9	243	2-79.0	238	1-45.5	429	304.63	16.98	93.26
					Combine Size = 8-Row				
70	465.4	274	2-85.8	301	1-52.2	528	256.62	15.00	84.41
80	446.0	263	2-90.2	274	1-53.7	496	277.33	14.55	87.61
90	412.0	243	2-96.2	237	1-55.2	450	308.81	14.09	92.12

*Maximum crop area that can be harvested by the given size of combine.

Table 5.21B Median Completion Dates for Planting and Harvesting Operations at 70, 80, and 90 Percent Design Probability Level for C C S W Rotation at the HLTI.

Design probability (percent)	Total machinery related costs ($/ha)	Planting operations			Harvesting operations		
		Corn	Soybeans	Wheat	Corn	Soybeans	Wheat
		------(days after starting date constraint)-------					
		Combine Size = 2-Row					
70	109.22	11.3	5.8	8.3	15.2	8.3	7.9
80	113.99	10.7	4.4	7.8	14.0	7.8	7.4
90	121.75	11.0	3.9	7.1	12.4	7.1	6.7
		Combine Size = 4-Row					
70	88.17	12.5	5.8	9.8	15.2	9.8	9.4
80	91.53	11.5	4.7	9.1	14.0	9.1	8.7
90	102.62	11.5	4.3	8.2	12.4	8.2	7.8
		Combine Size = 6-Row					
70	86.06	12.7	5.8	10.9	15.3	10.9	10.6
80	88.96	11.4	4.7	10.4	14.3	10.4	10.0
90	93.26	11.6	4.4	9.6	13.1	9.6	9.3
		Combine Size = 8-Row					
70	84.41	12.0	5.8	11.2	14.1	11.2	10.8
80	87.61	11.4	4.7	10.8	13.5	10.8	10.4
90	92.12	11.6	4.4	10.1	12.5	10.1	9.7

5.6.2 Effect of field working hours per day

Field working hours per day (FWH/D) for only tractor powered operations were varied, holding everything else fixed. Table 5.22 shows the results when FWH/D were equal to 8, 10, and 12.

A decrease in the FWH/D caused a proportional increase in the tractor size and consequently a proportional decrease in the tractor use. Whenever an increase in the tractor size was not proportional, it was either because the smallest permitted tractor was selected, or because a bigger tractor was required in order to pull a planter that is matched with combine size and that can complete planting within the specified date constraints. Initial investment in machinery increased with a decrease in the FWH/D due to an increase in the size of tractors and associated machinery. Whenever a decrease in the FWH/D did not cause an increase in the number of tractors, labor costs decreased; otherwise labor costs also increased. In most cases, the decrease in labor costs was not sufficient to offset the increase in annual machinery costs due to a higher initial investment. However, the change in TMRC was sizable only when a decrease in the FWH/D caused an increase in the number of tractors.

5.6.3 Effect of idling tillage tractors during harvest

Some tractors may have to be freed from tillage operations during harvest because labor may not be available for tillage operations or tractors may be engaged in hauling operations (3.1.3). The effect of keeping "n" tillage

Table 5.22. Effect of Field Working Hours per Day on Size, Use, and Costs of Field Machinery for C C S W Rotation at the HLTI.

Field working hours per day	Machinery Size and Use: Tillage tractor No. & size (PTOkW)	Tillage tractor Use (hr)	Utility tractor No. & size (PTOkW)	Utility tractor Use (hr)	Investment in machinery ($/ha)	Labor costs ($/ha)	Total machinery related costs ($/ha)
Combine Size = 2-Row					Farm Size = 158.6 Hectares		
8	1-96.2	183	1-29.1	289	421.02	21.89	119.62
10	1-76.8	229	1-23.1	346	373.97	25.13	115.27
12	1-64.1	274	1-22.4	355	354.50	26.84	113.99
Combine Size = 4-Row					Farm Size = 272.4 Hectares		
8	2-82.8	182	1-47.7	340	365.37	17.35	104.92
10	2-66.4	227	1-40.3	383	335.17	19.77	103.07
12	1-109.6	275	1-32.8	447	290.99	17.67	91.53
Combine Size = 6-Row					Farm Size = 371.1 Hectares		
8	3-75.3	182	2-33.6	291	366.73	18.66	107.32
10	2-90.2	228	1-60.4	424	301.17	15.32	91.90
12	2-75.3	273	1-44.7	470	274.36	17.15	88.96
Combine Size = 8-Row					Farm Size = 446.0 Hectares		
8	3-90.2	182	2-40.3	304	375.85	15.8	106.95
10	2-108.1	234	1-60.4	448	295.64	13.15	88.76
12	2-90.2	274	1-53.7	496	277.33	14.55	87.61

tractors idle (free from tillage) during harvest on machinery size and costs is situation specific. Depending upon the peak work season power requirements and the amount of tillage work that can be scheduled (based on date constraints) during any harvesting season, idling of "n" tillage tractors per operating harvester may necessitate an increase in their size or number; and consequently in TMRC.

In C C S W rotation wheat tillage operations have to be done simultaneously with soybean and corn harvesting. The power requirements for autumn wheat tillage operations were one-half of those for spring corn and soybean tillage operations. A 6 or 8-row combine was used throughout the wheat planting season. The tractors that were idled due to harvesting operations could not be used for the wheat tillage operations. For farm sizes corresponding to 6 and 8-row combines, two tillage tractors were required. In this case, idling of one tractor per operating harvester did not alter the power requirements, since the size of the one tractor was equal to one-half of that of the total tillage tractor power requirements. However, when two tractors were idled for each operating harvester, an additional tractor of equal size was required for autumn wheat tillage operations (Table 5.23). Two and 4-row combines were idle for part of the wheat planting season. Tillage tractors, idled because of the operating harvester, could be used during that period for wheat tillage operations. Thus, for farm sizes corresponding to 2 and 4-row combines, an increase in tillage tractor power requirements coupled with an increase in the number of tillage tractors idled per operating harvester, was not as great as for farm sizes corresponding to 6 and 8-row combines (Table 5.23).

Table 5.23. Effect of Idling Tillage Tractors during Harvest on Size, Use, and Costs of Field Machinery for C C S W Crop Rotation at the HLTI.

Number of tillage tractors idled for each harvester operating in the field	Tillage tractor size & use: No. & size (PTOkW)	Tillage tractor size & use: Use (hr)	Investment in machinery (\$/ha)	Labor costs (\$/ha)	Total machinery related costs (\$/ha)	MCDW*
Combine Size = 2-Row			Farm Size = 158.6 Hectares			
0	1-64.1	274	354.50	26.84	113.99	7.77
1	2-32.1	274	339.65	35.44	118.98	11.79
2	2-91.7	96	525.96	24.27	140.92	16.85
Combine Size = 4-Row			Farm Size = 272.4 Hectares			
0	1-109.6	275	290.99	17.67	91.53	9.14
1	2-55.2	273	276.33	22.61	92.84	11.95
2	3-50.0	201	308.63	23.65	99.56	12.66
Combine Size = 6-Row			Farm Size = 371.1 Hectares			
0	2-75.3	273	274.36	17.15	88.96	10.37
1	2-75.3	273	274.36	17.15	88.96	12.12
2	3-75.3	182	317.01	17.15	96.30	12.44
Combine Size = 8-Row			Farm Size = 446.0 Hectares			
0	2-90.2	274	277.33	14.55	87.61	10.84
1	2-90.2	274	277.35	14.55	87.62	12.28
2	3-90.2	182	318.96	14.55	94.79	12.53

*Median completion date for wheat planting, days after starting date constraint.

Median completion dates of harvesting operations were not affected because no change was made in the harvesting system. Median completion date of corn and soybean planting operations was also not affected because utility tractor size did not change. But median completion date of wheat drilling increased as the number of tractors idled per operating harvester were increased because the idling of tillage tractors occurred during planting season of wheat (Table 5.23).

5.6.4 Sensitivity test of machinery cost factors

The effects of various cost factors used were studied. Assumed cost factors are given in Table A.5. Cost factors were varied, one at a time, and the annual machinery related costs were calculated. The results are shown in Figure 5.6 for a 446-hectare C C S W farm at the HLTI. This figure is presented in the form of a horizontal line nomograph. The effect of varying any one factor on TMRC can be determined by drawing a horizontal line through the new value and reading the percent of the original TMRC on the left-hand scale.

List price variations had the greatest effect on the TMRC. A short obsolescence life also increased the TMRC substantially, but a long obsolescence life did not decrease the TMRC considerably since the total machine use approached wear-out life. Salvage values of the obsolete machines were assumed to be 10 percent of their list price. The trade-in life of machines also significantly affected the TMRC. Actual trade-in values of the machines were estimated from the data given by Hunt, 1977 (Table 4.2). The effect of fuel rate on the TMRC was not sizable.

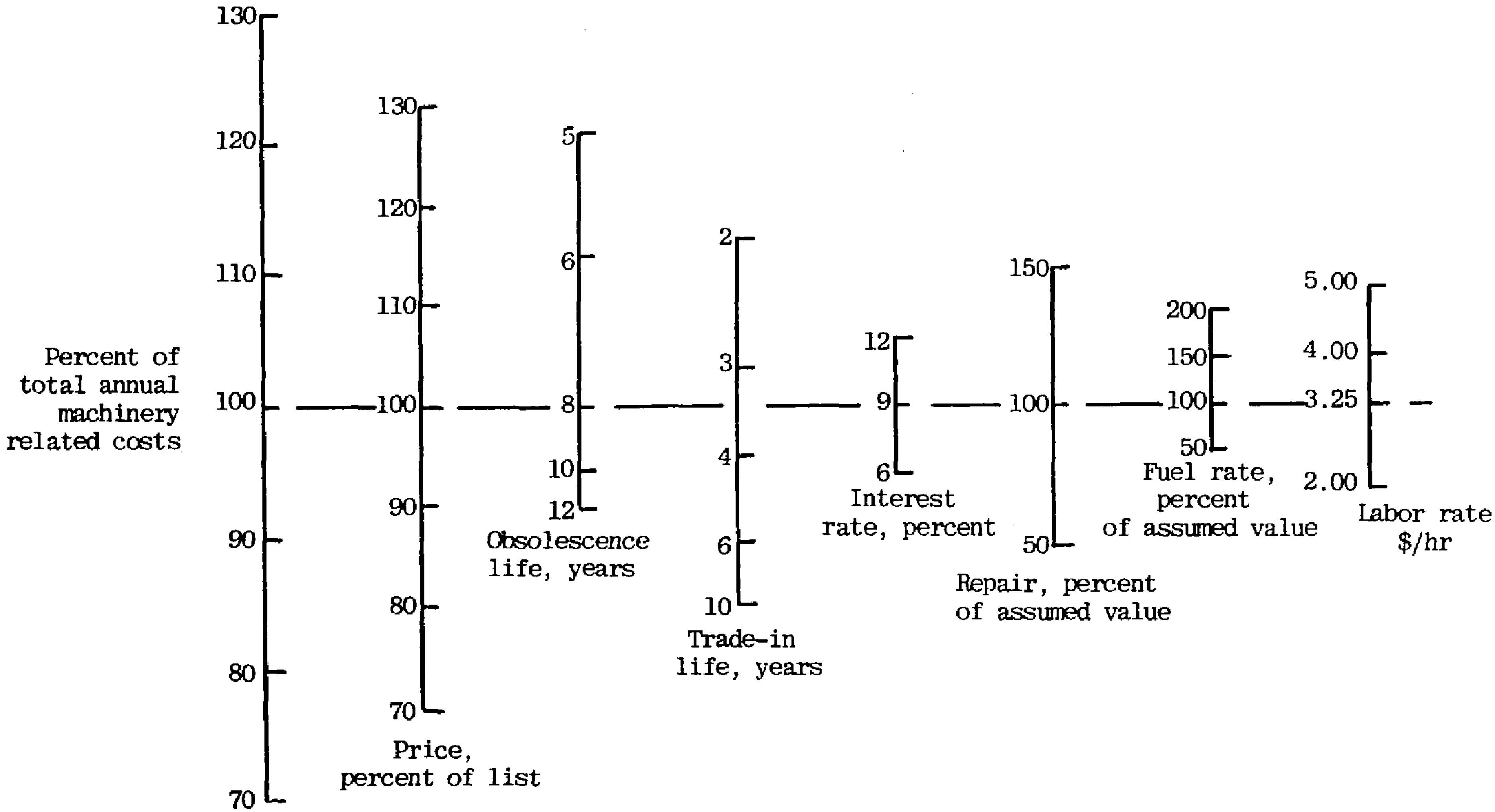


Figure 5.6 Effect of Machinery Cost Factors on Annual Costs for a 446 Hectare C C S W Farm at the HLTI.

6. CONCLUSIONS

In the course of conducting this study, the following items were accomplished:

1. A computer model to design a field machinery system for cash crop farms was developed. The computer model designs a machinery system based upon field work specifications, field operation calendar date constraints, machinery capacity relations, and field work conditions for a farm growing a mix of field crops. The model specifies the size and number of each component, prepares a detailed week-by-week work schedule, gives the distribution of labor needs for operating machines, calculates fuel requirements for each operation, and makes detailed cost analysis of the selected machinery set.
2. Field machinery requirements for 29 major cash crop production systems of southern Michigan were calculated over a range of farm sizes.
3. The influence of tillage intensity and crop rotation on costs and requirements of machinery, labor, and fuel for field work was evaluated.
4. A sensitivity analysis was made to measure the effect of system design parameters on machinery requirements and costs.

On the basis of this study, the following can be said:

1. Given reasonably accurate input data, the computer model is able to select (in a completely automatic manner) a reasonable machinery set for a farm growing a mix of field crops.
2. As farm size increases, annual machinery related costs decrease at a decreasing rate. Maximum reduction occurs when farm size is increased from the maximum area that a 2-row combine can harvest to that corresponding to a 4-row combine.
3. The computer model was used to evaluate the influence of tillage intensity and crop rotation on costs and requirements of field machinery. However, the results of the model are only as reliable as the input data. Assuming that the input data were fairly accurate, the following conclusions can be made regarding the influence of tillage intensity and crop rotation for Michigan conditions:
   a. The crop area that can be harvested in one season by a given size of combine is greater for multicrop rotations than it is for single-crop rotations. For Michigan conditions, the area harvested by a given size of combine in one season can be almost doubled by following C FB, C C S W, or C C FB W rotation rather than continuous corn rotation; and by adding two years of alfalfa to C C S W, C C FB W, or C S W rotation, the crop area can be almost tripled over that of continuous corn rotation.
   b. Tractor power requirements for continuous corn rotation at the HLTI are very high in comparison to other cash crop production systems studied. Tractor power requirements for

rotations involving alfalfa are less than other rotations.

The difference in tractor power requirements, on a unit area basis, between the HLTI and the MLTI is substantial for all rotations studied, except C W A A; but the difference between the MLTI and the LLTI is not very large.

c. Harvesting costs per unit area are highest for rotations involving alfalfa, and are lowest for C FB, C C S W, and C C FB W rotations. Single-crop rotations have lower harvesting costs than rotations involving alfalfa, but higher than other multicrop rotations.

d. The harvesting costs are highest for maximum farm sizes that can be harvested by a 2-row combine. Increasing combine size from 2 to 4-row, decreases harvesting costs in every crop rotation. But, further increase in combine size does not significantly change harvesting costs. However, the harvesting costs decrease slightly for a continuous corn rotation, and increase slightly for a continuous soybean rotation, when combine size is increased beyond a 4-row size.

e. In general, the use of each piece of machinery increases as the number of crops in a crop rotation increases.

f. Multicrop rotations have a more even distribution of labor during the year compared to single-crop rotations. However, the annual labor requirements, on a unit area basis (h/ha), are not considerably affected by the crop rotation. For rotations involving alfalfa, the labor requirements are very high during three 2-week harvesting seasons of alfalfa. The variation in labor distribution among various crop rotations was more at the LLTI compared to the HLTI.

g. Fuel requirements decrease with a decrease in tillage intensity for every crop rotation. But the variation in fuel requirements among crop rotations is not sizable.

h. The level of tillage intensity does not have a sizable influence on the TMRC for rotations involving alfalfa. For other rotations, the difference in the TMRC between the HLTI and the MLTI is greater than the difference between the MLTI and the LLTI. Comparing the MLTI with the LLTI for multicrop rotations shows small cost advantages for the LLTI.

i. The TMRC are highest for single-crop rotations (C C, S S) and for a C W A A rotation; and are lowest for C FB, C C S W, and C C FB W rotations. Rotations involving alfalfa, except C W A A, and C S rotation have TMRC lower than single-crop rotations but higher than C FB, C C S W, and C C FB W rotations.

4. The following conclusions can be drawn from the sensitivity analysis:

   a. With an increase in the design probability, machinery size, machinery investment and consequently annual machinery related costs increase, but machinery use and timeliness costs decrease.

b. A decrease in the field working hours per day for tractor powered operations causes a proportional increase in the size of tractors and related implements, and a proportional decrease in the use of tractors and tractor powered machinery. Machinery investment and thereby annual machinery related costs increase, but labor costs decrease if the number of tractors does not increase. In most cases, a decrease in labor costs is not sufficient to offset the increase in annual machinery related costs due to higher machinery investment. However, the change in annual machinery related costs is sizable only when a decrease in field working hours per day results in an increase in the number of tractors.

c. The effect of keeping "n" tillage tractors idle (free from tillage) during harvest on machinery size and costs is situation specific. Depending upon the peak work season power requirements and the amount of tillage work that can be scheduled (based on date constraints) during any harvesting season, idling of "n" tillage tractors per operating harvester may necessitate an increase in their size or number; and consequently in annual machinery related costs.

d. The machinery cost factors can be placed in the following order based on their influence on annual machinery related costs: list price, obsolescence or trade-in life (whichever is used for computing depreciation), repair costs, labor rate, interest rate and fuel rate.

7. SUGGESTIONS FOR FURTHER STUDY

It is suggested that this study be expanded in the following ways:

1. Enlarge the model by including transportation, drying, storage, and marketing components, to make the tradeoff analysis more complete.
2. Include other material resources - seed, fertilizer, pesticide, and supplemental irrigation; capital requirements for land, and short-run operating expenses; as well as revenue from the sale of crops; to make a complete economic analysis of each crop production system.
3. Include soil loss and organic matter effects of each crop production system, to get a more complete picture of the tradeoffs among the selected cropping systems.
4. Include other important Michigan crops, like sugarbeets and oats; and necessary field operations for those crops.

It is also suggested that the model be improved by:

1. Explicitly including timeliness costs in the cost analysis. This will simplify the comparison of different crop production systems.
2. Increasing the accuracy of the tractive efficiency values for various field operations. This will improve the estimation of productivity of the field operations.
3. Including the constraints on availability of labor.

4. Including four-wheel drive tractors as a category of tractors.
5. Allowing the substitution of custom operations as an alternative to ownership of certain pieces of equipment.
6. Introducing a trade-off analysis between the size and number of tillage tractors and utility tractors.

Better data are required in the following areas to increase the accuracy of the results:

1. Harvesting capacity of different sizes of combine for each crop.
2. Available field work time for harvesting operations at different probability levels.
3. Available field work time for tillage operations under different soil conditions.
4. Fuel requirements for harvesting operations.
5. Data for calculation of machine productivity and machinery costs.
6. Timeliness cost data for planting and harvesting operations of different crops.

APPENDICES

APPENDIX A

INPUT DATA

Table A.1 Assumed Field Operations and Calendar Date Constraints.

Field operation	Moldboard Plow Tillage System					Chisel Plow Tillage System			NITS[1]
	Corn	Soybeans	Field Beans	Wheat	Alfalfa	Corn	Soybeans	Wheat	Corn
Harvesting	$(\frac{10}{09}-\frac{11}{13})$[2,3]	$(\frac{09}{25}-\frac{10}{23})$[10]	$(\frac{08}{28}-\frac{10}{02})$[13]	$(\frac{07}{17}-\frac{08}{07})$		$(\frac{10}{09}-\frac{11}{13})$	$(\frac{09}{25}-\frac{10}{23})$[10]	$(\frac{07}{17}-\frac{08}{07})$	$(\frac{10}{09}-\frac{11}{13})$[3]
Corn stalk shredding	[4,5]					[4]			[4]
Discing[22]	[4,6]								
Chisel plowing[22]						([16] $-\frac{05}{22}$)	([16] $-\frac{06}{05}$)[11]	([16] $-\frac{10}{16}$)[17]	
Fertilizer spreading	$(\frac{04}{10}-\frac{05}{22})$[7]					$(\frac{04}{10}-\frac{05}{22})$			$(\frac{04}{10}-\frac{05}{22})$[7]
Alfalfa cutting #1					$(\frac{05}{29}-\frac{06}{12})$[19]				
Alfalfa cutting #2					$(\frac{07}{10}-\frac{07}{24})$[19]				
Baling wheat straw					$(\frac{07}{17}-\frac{08}{14})$				
Moldboard plowing	$(\frac{04}{10}-\frac{05}{22})$[7]	$(\frac{04}{10}-\frac{06}{05})$[11]	$(\frac{04}{10}-\frac{06}{19})$	([16] $-\frac{10}{16}$)[17]	$(\frac{07}{17}-\frac{08}{28})$				
Apply herbicide			$(\frac{05}{15}-\frac{06}{19})$[15]						$(\frac{04}{17}-\frac{05}{22})$[7]
Disc harrowing	$(\frac{04}{24}-\frac{05}{22})$[7]	$(\frac{05}{15}-\frac{06}{05})$[11]	$(\frac{05}{15}-\frac{06}{19})$[15]			$(\frac{04}{24}-\frac{05}{22})$	$(\frac{05}{15}-\frac{06}{05})$[11]	([18] $-\frac{10}{18}$)[17]	
Disc-drag				([18] $-\frac{10}{16}$)[17]	$(\frac{07}{17}-\frac{08}{28})$				
Seed drilling				([18] $-\frac{10}{18}$)[17]	$(\frac{07}{31}\ \frac{08}{28})$			([18] $-\frac{10}{16}$)[17]	

Table A.1 (continued)

Field operation	Moldboard Plow Tillage System Corn	Soybeans	Field Beans	Wheat	Alfalfa	Chisel Plow Tillage System Corn	Soybeans	Wheat	NTTS[1] Corn
Planting	(04/24 - 05/22)[7,8]	(05/15 - 06/05)[11,12]	(05/29 - 06/19)[12]			(04/24 - 05/22)[8]	(05/15 - 06/05)[11,12]		
No-till planting									(04/24 - 05/22)[7]
Topdress nitrogen				(03/06 - 04/03)				(03/06 - 04/03)	
Apply herbicide		(05/15 - 06/12)[11]		(04/17 - 05/08)			(05/15 - 06/12)[11]	(04/17 - 05/08)	(05/01 - 05/29)[21]
Anhydrous ammonia application	(05/29 - 06/26)[9]					(05/29 - 06/26)			(05/29 - 06/26)[9]
Row cultivate	(06/05 - 06/26)[9]	(06/19 - 07/10)[11]	(06/19 - 07/10)						
Alfalfa cutting #3					(08/21 - 09/04)[19]				

[1]No-till tillage system.
[2]Figures within brackets represent starting and ending date constraints of the operation (month/date - month/date).
[3]Starting and ending date constraints for corn before wheat are September 25 and October 16, respectively.
[4]Starting date constraint = starting date constraint of corn harvesting, ending date constraint = ending date constraint of planting operation for the following crop.
[5]Corn stalks are shredded only if following crop is wheat.
[6]Discing is not done when the following crop is wheat.
[7]Ending date constraint for corn before wheat is May 08.
[8]Herbicides are applied during the planting operation.
[9]Ending date constraint for corn before wheat is June 19.
[10]Starting and ending date constraints for soybeans before wheat are September 18 and October 16, respectively.
[11]Ending date constraint for soybeans before wheat is one week early.
[12]Fertilizer is applied during the planting operation.
[13]Includes the field bean pulling operation.
[14]Herbicides are sprayed before the disc harrowing operation.
[15]Disc harrowing is done twice.
[16]Starting date constraint of the harvesting operation for the preceding crop.
[17]Ending date constraint for wheat after field beans is October 9.
[18]September 25 for wheat after corn, and September 18 for wheat after soybeans and wheat after field beans.
[19]Mowing-conditioning and baling.
[20]Chisel tillage system is used for corn in Michigan only when corn follows corn, or soybeans, or field beans.
[21]Ending date constraint for corn before wheat is May 15.
[22]If the operation was not finished during the fall, it was discontinued on November 26 and was resumed on April 10 in the following spring.

Table A.2A Field Working Hours per Day Assumed for Various Field Operations.

Field operation	Field work hours per day
Corn harvesting	9
Soybean harvesting	8
Field bean harvesting	7
Wheat harvesting	6
Alfalfa harvesting	9
Other operations	12

Table A.2B Mean and Standard Deviation of Fraction of Calendar Days Suitable for Non-Harvesting Field Operations.

Beginning date of the week	Tillage, planting, cultivation and ammonia application operations		Stalk shredding, fertilizer spreading and spraying operations*	
Mo/Day	Mean	Standard deviation	Mean	Standard deviation
1/02	.0000	.0000	.3262	.4610
1/09	.0000	.0000	.4032	.4787
1/16	.0000	.0000	.4984	.4793
1/23	.0000	.0000	.6032	.4688
1/30	.0000	.0000	.6817	.4587
2/06	.0000	.0000	.7413	.4335
2/13	.0000	.0000	.7920	.3810
2/20	.0000	.0000	.8316	.3262
2/27	.0000	.0000	.8071	.3056
3/06	.0000	.0000	.6834	.3458
3/13	.0000	.0000	.5135	.3893
3/20	.0000	.0000	.3754	.3979
3/27	.0000	.0000	.4510	.3653
4/03	.0000	.0000	.5092	.3265
4/10	.2874**	.2626**	.6152	.2999
4/17	.2715	.2819	.7112	.2737
4/24	.3699	.3029	.6222	.2566
5/01	.4786	.3139	.6841	.2437
5/08	.5508	.3140	.7175	.2340
5/15	.6167	.3139	.7476	.2180
5/22	.6619	.2965	.7675	.2046
5/29	.6897	.2876	.7817	.2004
6/05	.6936	.2829	.7817	.2096
6/12	.6802	.2791	.7714	.2135
6/19	.6905	.2658	.7818	.2031

Table A.2B (continued)

Mo/Day	Mean	Standard deviation	Mean	Standard deviation
6/26	.7127	.2509	.7976	.1849
7/03	.7437	.2498	.8206	.1740
7/10	.7508	.2574	.8222	.1754
7/17	.7468	.2526	.8143	.1741
7/24	.7341	.2409	.8048	.1710
7/31	.7357	.2301	.8087	.1686
8/07	.7381	.2410	.8175	.1737
8/14	.7349	.2658	.8190	.1876
8/21	.7215	.2878	.8119	.1984
8/28	.7064	.3058	.8079	.2048
9/04	.6817	.3074	.7952	.2063
9/11	.6357	.3231	.7738	.2174
9/18	.5976	.3349	.7492	.2385
9/25	.5889	.3564	.7436	.2595
10/02	.6088	.3691	.7531	.2671
10/09	.5929	.3870	.7452	.2699
10/16	.5397	.4004	.7111	.2792
10/23	.4516	.4013	.6540	.3001
10/30	.3786	.3895	.5873	.3254
11/06	.2889	.3353	.5079	.3314
11/13	.1968	.2504	.3952	.3265
11/20	.0936	.1342	.2659	.2792
11/27	.0000	.0000	.1492	.2339
12/04	.0000	.0000	.0889	.1993
12/11	.0000	.0000	.1016	.2425
12/18	.0000	.0000	.1683	.3227
12/25	.0000	.0000	.2516	.4103

*These operations were assumed to be feasible on frozen soil irrespective of snow cover.
**Includes fractions of previous two weeks.

Table A.2C Mean and Standard Deviation of Suitable Work Days for Harvesting Operations.

Harvesting operation	Beginning date of the week, Mo/Day	Mean	Standard deviation
Corn harvesting	10/09	0.75	0.27
	10/16	0.71	0.28
	10/23	0.65	0.30
	10/30	0.59	0.32
	11/06	0.51	0.33
Soybean harvesting	9/18	0.50	0.20
	9/25	0.50	0.20
	10/02	0.50	0.20
	10/09	0.50	0.20
	10/16	0.40	0.20
Field bean harvesting	8/28	0.50	0.25
	9/04	0.50	0.25
	9/11	0.40	0.20
	9/18	0.40	0.20
	9/25	0.35	0.20
	10/02	0.35	0.20
Wheat harvesting	7/17	0.60	0.13
	7/24	0.60	0.13
	7/31	0.60	0.13
Alfalfa harvesting	5/29	0.60	0.15
	6/05	0.60	0.15
	7/10	0.65	0.13
	7/17	0.60	0.13
	8/21	0.60	0.15
	8/28	0.60	0.15

Table A.3A Assumed Productivity Data for Self-Propelled Combines.

Operation	Size	Speed (Km/h)	Field efficiency (percent)	Field capacity (ha/h)
Corn harvesting	2-ROW*	5.23 (3.25)+	70	0.56 (1.38)++
	4-ROW	4.83 (3.00)	65	0.96 (2.36)
	6-ROW	4.43 (2.75)	63	1.28 (3.15)
	8-ROW	4.43 (2.75)	60	1.62 (4.00)
Soybean harvesting	3.05 m** (10-FT)	4.02 (2.50)	70	0.86 (2.12)
	3.96 m (13-FT)	4.43 (2.75)	70	1.23 (3.03)
	3.96 m (13-FT)	5.23 (3.25)	70	1.45 (3.58)
	4.88 m (16-FT)	5.23 (3.25)	65	1.66 (4.10)
Wheat harvesting	3.05 m** (10-FT)	4.43 (2.75)	75	1.01 (2.50)
	3.96 m (13-FT)	4.83 (3.00)	75	1.43 (3.55)
	3.96 m (13-FT)	5.63 (3.50)	75	1.67 (4.14)
	4.88 m (16-FT)	5.63 (3.50)	70	1.92 (4.75)
Field bean harvesting	8-ROW***	4.02 (2.50)	70	1.72 (4.24)
	12-ROW	3.62 (2.25)	67	2.22 (5.48)
	16-ROW	3.22 (2.00)	65	2.55 (6.30)
	16-ROW	4.02 (2.50)	63	3.09 (7.64)

*Size of corn header
**Size of grain header
***Number of rows that combine picks up
+Speed in mph
++Field capacity in acres/hour

Table A.3B Assumed Productivity Data for Tractor Powered Field Machines.

Machine	Draft (N/m)	Field efficiency (percent)	Tractive efficiency (fraction)	Operating speed Minimum (Km/h)	Operating speed Maximum (Km/h)
Moldboard plow	11675 (800)+	80	0.75	5.63 (3.5)++	8.05 (5.0)++
Disc-harrow	4086 (280)	85	0.60	4.83 (3.0)	8.05 (5.0)
Disc	3648 (250)	85	0.75	6.76 (4.20)	11.27 (7.0)
Chisel plow	7297 (500)	80	0.75	5.63 (3.5)	8.05 (5.0)
Disc harrow + drag	4670 (320)	85	0.60	4.22 (2.63)	7.04 (4.38)
Grain drill	1678 (115)	75	0.60	4.02 (2.5)	8.05 (5.0)
Row cultivator	2189 (150)	80	0.60	4.83 (3.0)	8.05 (5.0)
Mower-conditioner	3940 (270)	80	0.75	5.63 (3.5)	8.05 (5.0)
Planter	1713* (385)	60	0.60	4.83 (3.0)	8.05 (5.0)

Table A.3B (continued)

Planter, no-till	2402* (540)	60	0.75	4.83 (3.0)	6.44 (4.0)
Ammonia applicator	1868* (420)	65	0.60	4.83 (3.0)	8.05 (5.0)
Baler**	5838 (400)	75	1.0	4.83 (3.0)	8.05 (5.0)
Baler***	3648 (250)	75	1.0	4.83 (3.0)	8.05 (5.0)
Rotary stalk chopper	2919 (200)	80	0.75	4.83 (3.0)	9.66 (6.0)
Fertilizer spreader	438 (30)	70	0.75	8.05 (5.0)	8.05 (5.0)
Sprayer	584 (40)	60	0.75	9.65 (6.0)	9.65 (6.0)
Field bean puller	1668* (375)	75	0.75	6.44 (4.0)	6.44 (4.0)

*per row not per meter of width
**when crop yield is 2 ton/acre
***when crop yield is 1 ton/acre
+draft in lb/ft
++speed in mph

Table A.4A Assumed Size and Price Data for Tractor Powered Field Machines.

Moldboard plow	Size, no. of bottoms*	2	3	4	5	6	7	8	
	Price ($)	681	1006	2561	2987	3490	4317	5083	
Disc-harrow	Size, m	2.00	2.44	2.87	3.48	3.91	4.34	5.21	5.64
	(ft)	(6.58)	(8.00)	(9.42)	(11.42)	(12.83)	(14.25)	(17.08)	(18.50)
	Price ($)	850	932	1105	2636	2825	2937	5469	5601
Chisel plow	Size, m	1.22	1.83	2.44	3.05	3.66	4.27	4.88	5.49
	(ft)	(4.0)	(6.0)	(8.0)	(10.0)	(12.0)	(14.0)	(16.0)	(18.0)
	Price($)	700	900	1161	1245	1456	1560	1654	2236
Grain drill	Size, m	2.44	3.05	3.66	3.96				
	(ft)	(8.0)	(10.0)	(12.0)	(13.0)				
	Price ($)	2361	2984	3631	3746				
Row cultivator	Size, no. of rows**	4	6	8	12				
	Price ($)	1277	1715	2913	3911				
Mower-conditioner	Size, m	2.74							
	(ft)	(9.0)							
	Price ($)	4710							
Planter	Size, no. of rows**	4	6	8	12				
	Price ($)	4410	6460	8840	14165				
Planter, no-till	Size, no. of rows**	4	6	8					
	Price ($)	5667	7877	10044					
Ammonia applicator	Size, no. of rows**	3	4	5	6	7	8		
	Price ($)	2400	2700	3000	3300	3600	3900		
Baler	Size, m+	2.74							
	(ft)	(9.0)							
	Price ($)	4132							
Rotary stalk chopper	Size, m	1.52	2.13	2.74	3.66	4.12			
	(ft)	(5.0)	(7.0)	(9.0)	(12.0)	(13.5)			
	Price ($)	816	1996	2021	2140	2474			
Fertilizer spreader	Size, m+	12.19							
	(ft)	(40.0)							
	Price ($)	1749							
Sprayer	Size, m+	6.10							
	(ft)	(20.0)							
	Price ($)	1620							
Field bean puller	Size, no. of rows**	4	6	8					
	Price ($)	1352	1698	2252					

*0.41 m (1.33 ft) bottoms, **0.76 m (2.5 ft) rows, +Field width covered in one run

Table A.4B Tractor Power and Price Data Used for Developing Regression Equation 6.

Power group	Power range, PTO kW (PTO HP)	Make of the tractor	Model of the tractor	Power, PTO kW (HP)	Price, ($)
1	22.4–29.8 (30–40)	Ford	BA 113C	23.86 (32.00)	6436
		Deutz	D 3006	23.86 (32.00)	5813
		MF*	MF-230	25.75 (34.53)	6058
		IH**	364	26.85 (36.00)	6700
2	29.8–37.3 (40–50)	Ford	CA 113C	29.83 (40.00)	7200
		David Brown	885	32.21 (43.20)	7116
		IH	464	33.12 (44.42)	8005
		White	2-50	34.30 (46.00)	9118
3	37.3–44.7 (50–60)	John Deere	2240	37.56 (50.37)	8565
		Deutz	D 5206	38.78 (52.00)	8878
		IH	574	39.19 (52.55)	9335
		White	2-60	44.00 (59.00)	10685
4	44.7–52.2 (60–70)	Ford	LA 114C	44.74 (60.00)	10463
		Leyland	272	46.23 (62.00)	9769
		David Brown	1210	49.20 (65.98)	11032
		MF	MF-275	50.28 (67.43)	10254
5	52.2–59.7 (70–80)	John Deere	2640	52.47 (70.37)	11234
		White	2-70	52.65 (70.60)	11861
		Long	900	54.35 (72.88)	10147
		Allis-Chalmers	185	55.83 (74.87)	12225
6	59.7–67.1 (80–90)	David Brown	1410	60.25 (80.80)	12557
		MF	MF-285	61.12 (81.96)	12142
		Ford	FA 115M	62.64 (84.00)	13323
		Deutz	D 8006	63.76 (85.50)	14009
7	67.1–74.6 (90–100)	Long	1100	68.60 (92.00)	11239
		J. I. Case	970	69.66 (93.41)	14183
		Long	R 9500	72.85 (97.70)	12888
		John Deere	4230	74.81 (100.32)	15309
8	74.6–82.0 (100–110)	MF	MF-1105	75.11 (100.72)	16266
		J. I. Case	1070	75.11 (100.73)	15288
		IH	966	75.17 (100.80)	18084
		Deutz	D 10006	78.33 (105.04)	16183

Table A.4B (continued)

9	82.0-89.5	White	2-105	78.75 (105.61)	15863
	(110-120)	Allis-Chalmers	7000	79.37 (106.44)	18533
		Ford	G2615 M	82.54 (110.69)	15166
		MF	MF-1135	90.11 (120.84)	17642
10	89.5-96.9	J. I. Case	1175	92.32 (123.80)	17127
	(120-130)	IH	1066	93.72 (125.68)	21081
		Deutz	D 13006	93.79 (125.77)	19406
		John Deere	4430	93.87 (125.88)	17755
11	96.9-104.4	J. I. Case	1270	100.96 (135.39)	23638
	(130-140)	Ford	H 2615M	101.01 (135.46)	17340
		Allis-Chalmers	7040	101.78 (136.49)	22054
12	104.4-111.9	MF	MF-1155	105.12 (140.97)	20553
	(140-150)	IH	1466	108.70 (145.77)	23640
		White	2-150	109.98 (147.49	21240
		John Deere	4630	112.35 (150.66)	21736

*Massey-Ferguson
**International Harvester

Table A.4C Combine Price Data.

Make		Size: 2-ROW	4-ROW	6-ROW	8-ROW
John Deere	Model	3300 SP	4400 SP	6600 SP	7700 SP Corn-Grain-Soybean
	Price ($)	16655	20839	25624	31888
Allis-Chalmers/ Gleaner	Model	KKS	FKS	MKS	LKS Corn-Soybean
	Price ($)	15244	19564	26037	32420
International Harvester	Model	--	715 SP	815 SP	915 SP Corn-Soybean
	Price ($)	--	21763	30853	36068
Massey-Ferguson	Model	300 SP	510 SP	750 SP	760 SP
	Price ($)	14349	20403	25092	32037
Average price ($)		15416	20642	26902	33103

Table A.4D Corn Head Price Data.

Make	Size: 2-ROW	4-ROW	6-ROW	8-ROW
	Price ($)			
John Deere	2994	6574	8890	11552
Allis-Chalmers/ Gleaner	3135	6673	8959	11668
International Harvester	3340	7025	9440	12270
Massey-Ferguson	3039	6774	8763	11523
Average price	3127	6762	9013	11753

Table A.4E Grain Head Price Data.

Make	Size 3.05 m (10-ft)	3.96 m (13-ft)	4.88 m (16-ft)
	Price ($)		
Allis-Chalmers/ Gleaner	2952	3192 (3212)*	3452

*For 3.96 m grain head attached to 6-row combine

Table A.4F Price Data for Pick-Up Head and Attachments for Field Beans.

Make	Size 2-ROW	4-ROW	6-ROW	8-ROW
	Price ($)			
Allis-Chalmers/ Gleaner	2169	2266	3349	3324

Table A.5 Assumed Machinery Cost Factors.

Machinery cost factor	Assumed value, and method of calculation
Depreciation	Straight line method assuming a 10 percent salvage value, maximum useful life = 8 years
Interest	9 percent annual interest on average investment
Annual housing	0.75 percent of initial price
Annual insurance	0.25 percent of initial price
Tax	0.0, no tax on field machinery in Michigan
Repair	A fixed percentage of the purchase price over the wear-out life of a machine, prorated according to annual machine use
Labor	$3.25 per hour
Diesel fuel	10.17¢/litre (38.5¢/gallon)
Oil and filter	15 percent of total fuel cost

APPENDIX B

THE PROCEDURE FOR CALCULATING MEDIAN COMPLETION DATE FOR PLANTING AND HARVESTING OPERATIONS

APPENDIX B

THE PROCEDURE FOR CALCUALTING MEDIAN COMPLETION DATE FOR PLANTING AND HARVESTING OPERATIONS

The median completion date for a planting or harvesting operation is defined as follows:

$$\text{Median completion date} = \frac{\text{hectare-days delay}}{\text{total crop hectares}}$$

where

hectare-days = $\sum_{i=1}^{N}$ hectare planted (or harvested) on day i x calendar days elapsed from the starting date constraint to day i

i = 1 on the starting date constraint, and = N on actual completion date

The weekly operations schedule provides total area planted (or harvested) of a crop in a week. To calculate daily planting (or harvesting) rate, the fraction of the week during which the operation was performed needs to be determined.

The fraction of the week (≤ 1.0) during which planting rate of a crop was assumed to be uniform was the maximum of the following four fractions:

1. The fraction of the week for which total utility tractor time was used for planting the crop

    If the cumulative area finished of the planting operation is equal to the cumulative area finished of any preplant tillage operation of the crop,

2. The fraction of the week for which total tillage tractor time was used for preplant tillage operations of the crop,

3. The biggest fraction of the week for which total available time of any implement was used for a preplant tillage operation of the crop,

   If planting of the crop immediately follows the harvesting of a previous crop, and the cumulative area planted is equal to the cumulative area harvested of the preceding crop,

4. The fraction of the week for which total harvesting capacity was used for harvesting preceding crop.

The fraction of the week (≤ 1.0) during which harvesting rate of a crop was assumed to be uniform was the fraction of the week for which total harvesting capacity was used for harvesting the crop.

It was also assumed that the latter part of the week is used for planting (or harvesting). However, if the operation was completed during a week, it was assumed that the first part of the week is used for planting (or harvesting). Sunday was assumed to be the first day of a week and no work was performed on Sunday.

The daily planting (or harvesting) rate (ACREPD) was calculated by dividing the total area planted (or harvested) in the week by 6 times the fraction of the week used for planting (or harvesting). The hectare-days of delay for the area planted (or harvested) during a week were calculated using the following equation:

$$\text{hectare-days delay} = \sum_{J=k}^{M} (7 * (I-L) + J)\ \text{ACREP}$$

where

K = 2, when first part of the week is used, and

= 7, when latter part of the week is used

M = 6 * fraction of the week used for planting (or harvesting),

+ 1, when first part of the week is used

= 7 - [6 * fraction of the week used for planting (or harvesting)],

when latter part of the week is used

I = sequence number of the week

L = sequence number of the starting date week constraint

ACREP = Min^{m} (ACREPD, ACREL)

ACREL = Total area to be planted (or harvested) during the week

- the area planted (or harvested) before day J.

APPENDIX C

FIELD MACHINERY REQUIREMENTS FOR THE SELECTED MICHIGAN CASH CROP PRODUCTION SYSTEMS

Table C.1 Field Machinery Requirements for the Selected Michigan Cash Crop Production Systems.[†]

Farm size (ha)	SP combine[1] (no. of rows)**	Tillage tractor (PTOkW)	Utility tractor (PTOkW)	Alfalfa tractor[2] (no. of units)	Moldboard plow (no. of 0.41 m bottoms)	Disc-harrow (m)	Chisel plow (m)	Grain drill (m)	Row-cultivator (no. of rows)	Mower-conditioner[3] (no. of units)	Planter[*] (no. of rows)	No-till planter (no. of rows)	Ammonia applicator (no. of rows)	Baler[5] (no. of units)	Rotary cutter (m)	Fertilizer spreader[6] (no. of units)	Sprayer[7] (no. of units)	Field bean puller (no. of rows)
C CROTATION												HIGHEST LEVEL OF TILLAGE INTENSITY						
79.3	2	55.9	22.4		4	2.9			4		4		3			1		
136.0	4	98.2	32.8		6	5.2			4		4		4			1		
181.3	6	64.1*	43.3		4*	3.5			6		6		5			1		
230.3	8	81.3*	55.2		5*	4.3			8		8		7			1		
C C ROTATION												MIDDLE LEVEL OF TILLAGE INTENSITY						
79.3	2	29.8	22.4			2.0	1.2				4		3		2.1	1		
136.0	4	37.3	29.1			2.0	1.8				4		4		2.7	1		
181.3	6	49.2	38.8			2.9	1.8				6		5		3.7	1		
230.3	8	62.6	48.5			3.5	2.4				8		6		3.7	1		
C C ROTATION												LOWEST LEVEL OF TILLAGE INTENSITY						
79.3	2	29.8	22.4									4	4		2.1	1	1	
136.0	4	44.7	22.4									8	5		2.1	1	1	
181.3	6	43.3	22.4									6	5		2.1	1	1	
230.3	8	54.4	22.4									8	7		2.1	1	1	
S S ROTATION												HIGHEST LEVEL OF TILLAGE INTENSITY						
61.3	2	29.8	22.4		2	2.0			4		4						1	
91.9	4	39.5	22.4		3	2.0			4		4						1	
106.9	6	47.0	30.6		3	2.4			6		6						1	
124.2	8	53.7	40.3		3	2.9			8		8						1	

Table C.1 (continued)

Farm size (ha)	SP combine[1] (no. of rows)**	Tillage tractor (PTOkW)	Utility tractor (PTOkW)	Alfalfa tractor[2] (no. of units)	Moldboard plow (no. of 0.41 m bottoms)	Disc-harrow (m)	Chisel plow (m)	Grain drill (m)	Row-cultivator (no. of rows)	Mower-conditioner[3] (no. of units)	Planter[4] (no. of rows)	No-till planter (no. of rows)	Ammonia applicator (no. of rows)	Baler[5] (no. of units)	Rotary cutter (m)	Fertilizer spreader[6] (no. of units)	Sprayer[7] (no. of units)	Field bean puller (no. of rows)
S S ROTATION											MIDDLE LEVEL OF TILLAGE INTENSITY							
64.3	2	29.8	22.4			2.0	1.2				4						1	
91.9	4	29.8	22.4			2.0	1.2				4						1	
108.9	6	29.8	30.6			2.0	1.2				6						1	
124.2	8	32.8	40.3			2.0	1.2				8						1	
C S ROTATION											HIGHEST LEVEL OF TILLAGE INTENSITY							
112.5	2	48.5	22.4		3	2.9			4		4		3			1	1	
173.2	4	74.6	24.6		5	3.9			4		4		3			1	1	
214.1	6	92.5	30.6		6	5.2			6		6		4			1	1	
248.9	8	107.4	40.3		6	5.6			8		8		5			1	1	
C S ROTATION											MIDDLE LEVEL OF TILLAGE INTENSITY							
112.5	2	29.8	22.4			2.0	1.2				4		3		2.1	1	1	
173.2	4	29.8	22.4			2.0	1.2				4		3		2.1	1	1	
214.1	6	33.6	30.6			2.0	1.2				6		4		2.7	1	1	
218.9	8	38.8	40.3			2.0	1.8				8		5		3.7	1	1	
C S ROTATION											LOWEST LEVEL OF TILLAGE INTENSITY							
112.5	2	29.8	22.4			2.0	1.2				4	4	3		2.1	1	1	
173.2	4	29.8	22.4			2.0	1.2				4	4	3		2.1	1	1	
214.1	6	33.6	30.6			2.0	1.2				6	6	4		2.7	1	1	
248.9	8	44.7	40.3			2.4	1.8				8	8	5		3.7	1	1	

Table C.1 (continued)

Farm size (ha)	SP combine[1] (no. of rows)**	Tillage tractor (PTOkW)	Utility tractor (PTOkW)	Alfalfa tractor[2] (no. of units)	Moldboard plow (no. of 0.41 m bottoms)	Disc-harrow (m)	Chisel plow (m)	Grain drill (m)	Row-cultivator (no. of rows)	Mower-conditioner[3] (no. of units)	Planter[4] (no. of rows)	No-till planter (no. of rows)	Ammonia applicator (no. of rows)	Baler[5] (no. of units)	Rotary cutter (m)	Fertilizer spreader[6] (no. of units)	Sprayer[7] (no. of units)	Field bean puller (no. of rows)
C FB ROTATION — HIGHEST LEVEL OF TILLAGE INTENSITY																		
158.6	2	55.9	30.6		4	2.9			6		6		4			1	1	4
272.4	4	96.2	55.2		6	5.2			8		8		7			1	1	4
363.0	6	64.1*	67.1		4*	3.5			6*		6		8			1	1	6
450.0	8	79.8*	67.1		5*	4.3			8		8		8*			1	1	8
C FB ROTATION — MIDDLE LEVEL OF TILLAGE INTENSITY																		
158.6	2	38.8	22.4		3	2.0	1.8		4		4		3			1	1	4
272.4	4	66.4	40.3		4	3.5	2.4		8		8		5			1	1	4
363.0	6	88.0	55.2		5	5.2	3.7		6		6		7			1	1	6
450.0	8	108.9	68.4		6	5.6	4.3		8		8		8			1	1	8
C FB ROTATION — LOWEST LEVEL OF TILLAGE INTENSITY																		
158.6	2	38.0	22.4		3	2.0			4		4	6	3			1	1	4
272.4	4	65.6	40.3		4	3.5			8		8	8	5			1	1	4
363.0	6	105.1	58.9		6	5.6			6		6	6	7			1	1	6
450.0	8	53.7*	65.6		3*	2.9*			8		8	8	8			1	1	8
C C S W ROTATION — HIGHEST LEVEL OF TILLAGE INTENSITY																		
158.6	2	64	22.4		4	3.5		2.4	4		4		3			1	1	
272.4	4	109.6	32.8		6	5.6		3.0	4		4		4			1	1	
371.1	6	75.3*	44.7		5*	3.9		4.0	6		6		5			1	1	
446.0	8	90.2*	53.7		5*	5.2		4.0	8		8		6			1	1	

Table C.1 (continued)

Farm size (ha)	SP combine[1] (no. of rows)**	Tillage tractor (PTOkW)	Utility tractor (PTOkW)	Alfalfa tractor[2] (no. of units)	Moldboard plow (no. of 0.41 m bottoms)	Disc-harrow (m)	Chisel plow (m)	Grain drill (m)	Row-cultivator (no. of rows)	Mower-conditioner[3] (no. of units)	Planter[4] (no. of rows)	No-till planter (no. of rows)	Ammonia applicator (no. of rows)	Baler[5] (no. of units)	Rotary cutter (m)	Fertilizer spreader[6] (no. of units)	Sprayer[7] (no. of units)	Field bean puller (no. of rows)
C C S W ROTATION — MIDDLE LEVEL OF TILLAGE INTENSITY																		
158.6	2	36.5	22.4		2	2.0	1.8	2.4	4		4		3		2.1	1	1	
272.4	4	62.6	30.6		4	3.5	2.4	3.0	4		4		4		2.7	1	1	
371.1	6	85.0	42.5		5	4.3	3.1	4.0	6		6		5		3.7	1	1	
446.0	8	101.4	52.9		6	5.2	3.7	4.0	8		8		6		4.1	1	1	
C C S W ROTATION — LOWEST LEVEL OF TILLAGE INTENSITY																		
158.6	2	29.8	22.4			2.0	1.2	2.4			4	4	3		2.1	1	1	
272.4	4	41.7	23.9			2.4	1.8	3.0			4	8	3		2.1	1	1	
371.1	6	58.9	46.2			3.5	2.4	4.0			6	6	6		3.7	1	1	
450.0	8	64.1	40.3			3.5	2.4	4.0			8	8	5		3.7	1	1	
C C FB W ROTATION — HIGHEST LEVEL OF TILLAGE INTENSITY																		
158.6	2	55.9	24.6		4	2.9		2.4	4		4		3			1	1	4
272.4	4	96.2	42.5		6	5.2		3.0	8		8		5			1	1	4
363.0	6	64.1*	67.1		4*	3.5		4.0	6		6		8			1	1	6
450.0	8	79.0*	67.1		5*	4.3		4.0	8		8		8			1	1	8
C C FB W ROTATION — MIDDLE LEVEL OF TILLAGE INTENSITY																		
158.6	2	36.5	22.4		2	2.0	1.8	2.4	4		4		3		1.5	1	1	4
272.4	4	62.6	37.3		4	3.5	2.4	3.0	4		4		5		2.7	1	1	4
363.0	6	82.8	47.7		5	4.3	3.0	4.0	6		6		6		3.7	1	1	6
450.0	8	101.4	50.7		6	5.2	3.7	4.0	8		8		7		3.7	1	1	8

Table C.1 (continued)

Farm size (ha)	SP combine[1] (no. of rows)**	Tillage tractor (PTOkW)	Utility tractor (PTOkW)	Alfalfa tractor[2] (no. of units)	Moldboard plow (no. of 0.41 m bottoms)	Disc-harrow (m)	Chisel plow (m)	Grain drill (m)	Row-cultivator (no. of rows)	Mower-conditioner[3] (no. of units)	Planter[4] (no. of rows)	No-till planter (no. of rows)	Ammonia applicator (no. of rows)	Baler[5] (no. of units)	Rotary cutter (m)	Fertilizer spreader[6] (no. of units)	Sprayer[7] (no. of units)	Field bean puller (no. of rows)
C C FB W ROTATION												LOWEST LEVEL OF TILLAGE INTENSITY						
158.6	2	29.8	22.4		2	2.0	1.2	2.4	4		4	4	3		1.5	1	1	4
272.4	4	41.8	28.3		3	2.4	1.8	3.0	4		4	4	4		2.1	1	1	4
363.0	6	52.9	38.0		3	2.9	2.4	4.0	6		6	6	5		3.7	1	1	6
450.0	8	62.6	47.7		4	3.5	2.4	4.0	8		8	8	6		3.7	1	1	8
C W A A ROTATION												HIGHEST LEVEL OF TILLAGE INTENSITY						
228.9	2	84.3	36.5	3	5	4.3		4.0	6	4	6		4	4	2.1	1	1	
332.7	4	62.6*	54.4	3	4*	3.5		4.0	8	6	8		6	6	2.7	1	1	
C W A A ROTATION												MIDDLE LEVEL OF TILLAGE INTENSITY						
228.9	2	84.3	36.5	3	5	4.3	3.0	4.0	6	4	6		4	4	2.1	1	1	
332.7	4	62.6*	54.4	3	4*	3.5	2.4	4.0	8	6	8		6	6	2.7	1	1	
C W A A ROTATION												LOWEST LEVEL OF TILLAGE INTENSITY						
228.9	2	45.5	22.4	3	3	2.4	1.8	3.0		4		8	3	4	2.1	1	1	
332.7	4	44.7	24.0	4	3	2.4	1.8	3.0		6		8	3	6	2.1	1	1	
C S W A A ROTATION												HIGHEST LEVEL OF TILLAGE INTENSITY						
293.0	2	63.4	22.4	3	4	3.5		3.0	4	4	4		3	4		1	1	
416.0	4	89.5	29.1	5	5	5.2		3.7	4	6	4		4	6		1	1	

Table C.1 (continued)

Farm size (ha)	SP combine[1] (no. of rows)**	Tillage tractor (PTOkW)	Utility tractor (PTOkW)	Alfalfa tractor[2] (no. of units)	Moldboard plow (no. of 0.41 m bottoms)	Disc-harrow (m)	Chisel plow (m)	Grain drill (m)	Row-cultivator (no. of rows)	Mower-conditioner[3] (no. of units)	Planter[4] (no. of rows)	No-till planter (no. of rows)	Ammonia applicator (no. of rows)	Baler[5] (no. of units)	Rotary cutter (m)	Fertilizer spreader[6] (no. of units)	Sprayer[7] (no. of units)	Field bean puller (no. of rows)
C S W A A ROTATION												MIDDLE LEVEL OF TILLAGE INTENSITY						
293.0	2	41.8	29.1	3	3	2.4	1.8	3.7	4	4	4		4	4	2.1	1	1	
416.0	4	58.9	42.5	5	4	3.5	2.4	4.0	8	6	8		5	6	2.7	1	1	
C S W A A ROTATION												LOWEST LEVEL OF TILLAGE INTENSITY						
293.0	2	33.6	22.4	3	2	2.0	1.2	3.0		4	4	6	3	4	2.1	1	1	
416.0	4	47.7	29.1	4	3	2.4	1.8	3.7		6	4	8	4	6	2.7	1	1	
C C S W A A ROTATION												HIGHEST LEVEL OF TILLAGE INTENSITY						
238.4	2	64.1	22.4	2	4	3.5		3.0	4	3	4		3	3		1	1	
408.3	4	109.6	32.8	4	6	5.6		4.0	4	5	4		4	5		1	1	
C C S W A A ROTATION												MIDDLE LEVEL OF TILLAGE INTENSITY						
238.4	2	36.5	24.0	2	2	2.0	1.8	3.0	4	3	4		3	3	2.1	1	1	
408.3	4	62.6	40.3	4	4	3.5	2.4	4.0	8	5	8		5	5	3.7	1	1	
C C S W A A ROTATION												LOWEST LEVEL OF TILLAGE INTENSITY						
238.4	2	29.8	22.4	2	2	2.0	1.2	3.0		3	4	4	3	3	2.1	1	1	
408.3	4	44.7	23.9	4	3	2.4	1.8	3.0		5	4	8	3	5	2.1	1	1	

Table C.1 (continued)

Farm size (ha)	SP combine[1] (no. of rows)**	Tillage tractor (PTOkW)	Utility tractor (PTOkW)	Alfalfa tractor[2] (no. of units)	Moldboard plow (no. of 0.41 m bottoms)	Disc harrow (m)	Chisel plow (m)	Grain drill (m)	Row-cultivator (no. of rows)	Mower-conditioner[3] (no. of units)	Planter[4] (no. of rows)	No-till planter (no. of rows)	Ammonia applicator (no. of rows)	Baler[5] (no. of units)	Rotary cutter (m)	Fertilizer spreader[6] (no. of units)	Sprayer[7] (no. of units)	Field bean puller (no. of rows)
C C FB W A A ROTATION												HIGHEST LEVEL OF TILLAGE INTENSITY						
238.4	2	56.7	24.6	2	4	2.9		3.0	4	3	4		3	3		1	1	4
408.3	4	96.2	42.5	4	6	5.2		4.0	8	5	8		5	5		1	1	4
C C FB W A A ROTATION												MIDDLE LEVEL OF TILLAGE INTENSITY						
238.4	2	36.5	22.4	3	2	2.0	1.8	3.0	4	3	4		3	3	1.5	1	1	4
408.3	4	62.6	37.3	5	4	3.5	2.4	4.0	4	5	4		5	5	2.7	1	1	4
C C FB W A A ROTATION												LOWEST LEVEL OF TILLAGE INTENSITY						
238.4	2	29.8	22.4	2	2	2.0	1.2	3.0	4	3	4	4	3	3	1.5	1	1	4
408.3	4	41.8	28.3	5	3	2.4	1.8	3.7	4	5	4	4	4	5	2.1	1	1	4

*Two units of this size were required

**A 76 cm row width was assumed

†Field machinery requirements were calculated using the computer model described in Chapter 3 and input data of Appendix A. Design probability was fixed at 80 percent. Sufficient additional labor and machinery was assumed to be available to transport harvested crop to the farmstead. Therefore, no tillage tractor was kept idle when a harvester was operating in the field.

[1]Necessary attachments - a corn head of corresponding size, if a crop rotation involved corn, a grain head (3 m for 2-row combine, 4 m for 4 or 6-row combine, and 4.9 m for 8-row combine), if a crop rotation involved soybeans or wheat, and a pick-up head of corresponding size, if a crop rotation involved field beans.

[2]Each tractor was of 29.8 PTOkW size.

[3]Each mower-conditioner was 2.75 m wide (John Deere 1209 mower-conditioner).

[4]Planter with dry fertilizer and herbicide attachments was assumed.

[5]John Deere 336 wire baler with pick-up.

[6]John Deere 602 spin spreader (1.73 m^3 capacity)

[7]John Deere 220 tractor mounted sprayer with 6 m belly mounted boom.

LIST OF REFERENCES

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Adams, W. 1975. Personal communication. Crop and Soil Sci. Dept., Michigan State University, East Lansing, MI.

ASAE D230.1. 1969. Farm machinery costs and use. Agricultural Engineers Yearbook. ASAE, St. Joseph, MI, p 278-283.

ASAE D230.2. 1977. Agricultural machinery management data. Agricultural Engineers Yearbook. ASAE, St. Joseph, MI, p 326-333.

Ayres, G. E. 1975. A simulation for predicting days suitable for corn harvesting. ASAE Paper No. 75-1502. ASAE, St. Joseph, MI.

Ayres, G. E. 1976. Fuel requirements for field operations. Coop. Ext. Service, Iowa State University, Ames, IA.

Baier, W. and G. Robertson. 1966. A new versatile soil moisture budget. Can. J. Plant Sci. 46:299-315.

Bolton, Bill, J. B. Penn, F. T. Cooke, Jr., and A. M. Heagler. 1968. Days suitable for field work - Mississippi River Delta cotton area. Dept. Agr. Econ. Res. Rep. No. 384. Dept. Agr. Econ. & Agribusiness, Louisiana State University, Baton Rouge, LA.

Bowers, Wendell. 1970. Modern concepts of farm machinery management. Stipes Publishing Co., Champaign, IL.

Bowers, W. 1975. Selection of machinery for a 50,000 hectare farming operation in Yugoslavia. ASAE Paper No. 75-1006. ASAE, St. Joseph, MI.

Burrows, W. C. and J. C. Siemens. 1974. Determination of optimum machinery for corn-soybean farms. Transaction of the ASAE 17(6):1130-1135.

Carpenter, M. L. and D. B. Brooker. 1970. Minimum cost machinery systems for harvesting, drying and storing shelled corn. ASAE Paper No. 70-322. ASAE, St. Joseph, MI.

Census of Agriculture. 1969. Volume 1, part 13, section 1. U. S. Government Printing Office, Washington, DC.

Committee on Agricultural Production Efficiency. 1975. Agricultural Production Efficiency. National Academy of Sciences, Washington, DC.

Connor, L. J. 1976. Personal communication. Dept. Agr. Econ., Michigan State University, East Lansing, MI.

Deere and Company. 1975. Agricultural Whole Goods Price List. Revision 6. Moline, IL.

Eidsvig, D. H. and C. E. Olson. 1969. Determining least-cost machinery combinations. Bull. 479. Dept. Agr. Econ., Agr. Exp. Sta., North Dakota State University of Agr. and Applied Science, Fargo, ND.

Elliott, R. L., W. D. Lembke and D. R. Hunt. 1977. A simulation model for predicting available days for soil tillage. Transactions of the ASAE 29(1):4-8.

Fairbanks, G. E., G. H. Larson and Do-Sup Chung. 1971. Cost of using farm machinery. Transaction of the ASAE 14(1):98-101.

Fridley, R. B. and J. B. Holtman. 1972. Simulation of soil freezing, soil thawing, and soil temperature for use in systems analysis of corn production. Agr. Eng. Preprint Series No. 3. Agr. Eng. Dept., Michigan State University, East Lansing, MI.

Frisby, J. C. and C. W. Bockhop. 1968. Weather and economics determine corn-production machinery systems. Transactions of the ASAE 11(1):61-64.

Frisby, J. C. 1970. Estimation of good working days available for tillage in central Missouri. Transactions of the ASAE 13(3):641-643.

Fulton, C. V. and G. E. Ayres. 1976. Expected number of days suitable for field work in Iowa. Transactions of the ASAE 19(6):1045-1047.

Hassan, A. E. and R. S. Broughton. 1975. Soil moisture criteria for tractability. Can. Agr. Eng. 17(2):124-129.

Heichel, G. H. 1973. Comparative efficiency of energy use in crop production. Conn. Agr. Exp. Sta. Bull. 739.

Holtman, J. B., L. K. Pickett, D. L. Armstrong and L. J. Connor. 1973. A systematic approach to simulating corn production systems. Transactions of the ASAE 16(1):19-23.

Holtman, J. B., and L. J. Connor. 1976. Resource productivities for Michigan crop production systems. Project outline. Mich. Agr. Exp. Sta. Project Number 3197. Michigan State University, East Lansing, MI.

Holtman, J. B., et al. 1976. Material-energy requirements in alternative dairy farm systems. Proceedings of Conference on Energy and Agriculture, CBNS, Washington University Press.

Hunt, D. 1963. Efficient field machinery selection. Agr. Eng. 44(2)78-79, 88.

Hunt, D. 1966. A FORTRAN program for selecting farm equipment. ASAE Paper No. 66-154. ASAE, St. Joseph, MI.

Hunt, D. 1972. Selecting an economic power level for the big tractor. Transactions of the ASAE 15(3):414-415.

Hunt, D. 1974. Eight years of farm machinery cost monitoring. ASAE Paper No. 74-1544. ASAE, St. Joseph, MI.

Hunt, D. R. 1977. Farm power and machinery management. Iowa State University Press, Ames, IA.

Hughes, H. A. and J. B. Holtman. 1974. Machinery complement selection based on time constraints. ASAE Paper No. 74-1541. ASAE, St. Joseph, MI.

Implement & Tractor, Red Book. 1977. Intertec Publishing Corp., Kansas City, MO.

Kish, A. J. and C. V. Privette. 1974. Number of fieldworking days available for tillage in South Carolina. ASAE Paper No. 74-1019. ASAE, St. Joseph, MI.

Link, D. A. 1962. Weather probabilities affecting machine system capabilities. Unpublished Ph.D. dissertation. Library, Iowa State University, Ames, IA.

Link, D. A. 1968. Research needs for farm machinery scheduling. Computers and farm machinery management proceedings. ASAE Publication PROC-468:28-32, St. Joseph, MI.

Link, D. A. and C. W. Bockhop. 1964. Mathematical approach to farm machine scheduling. Transactions of the ASAE 7(1):8-13, 16.

Lucas, R. E. 1976. Personal communication. Crop and Soil Sci. Dept., Michigan State University, East Lansing, MI.

MacHardy, F. V. 1966a. Programming for minimum-cost machinery combinations. Can. Agr. Eng. 8(1):22-25.

MacHardy. F. V. 1966b. A method for sizing farm machines for weather dependent operations. Can. Agr. Eng. 8(1):26-28.

Millier, W. F. and G. E. Rehkugler. 1972. A simulation — The effect of harvest starting date, harvesting rate, and weather on the value of forage for dairy cows. Transactions of the ASAE 15(2):409-413.

Morey, R. V., G. L. Zachariah and R. M. Peart. 1971. Optimum policies for corn harvesting. Transactions of the ASAE 13(4):787-792.

Morey, R. V., R. M. Peart and D. L. Deason. 1972. A corn-growth harvesting and handling simulator. Transactions of the ASAE 14(2):326-328.

National Farm and Power Equipment Dealers Association. Spring 1976. Official Guide to Tractors and Farm Equipment, St. Louis, MO.

Pavelis, G. A. 1973. Energy, natural resources, and research in agriculture. Effects on economic growth and productivity for the United States. ERS, USDA.

Peterson, Mark and J. C. Frisby. 1969. A wind tunnel to simulate weather conditions. Transactions of the ASAE 12(3):456-495, 462.

Pimentel, D., L. E. Hurd, A. C. Bellotti, M. J. Forster, I. N. Oka, O. D. Sholes and R. J. Whitman. 1973. Food production and energy crisis, Science 182:443-449.

Robertson, L. S. 1977. Personal Communication. Crop and Soil Sci. Dept., Michigan State University, East Lansing, MI.

Rutledge, P. L. and F. V. McHardy. 1968. The influence of the weather on field tractability in Alberta. Can. Agr. Eng. 10(2);70-73.

Scarborough, J. N. and D. R. Hunt. 1973. Replacement and scheduling effects on a least-cost machinery system model. ASAE Paper No. 73-147. ASAE, St. Joseph, MI.

Sebrio, I. S. and W. M. Brown. 1972. Estimation of spring workdays from climatological records. Can. Agr. Eng. 14(2):79-81.

Shaw, R. H. 1963. Estimation of soil moisture under corn. Res. Bull. 520. Iowa Agr. Exp. Sta., Ames, IA.

Shaw, R. H. 1965a. Estimation of field working days in the spring from meteorological data. Iowa State J. Sci. 39(4):393-402.

Shaw, R. H. 1965b. The prediction of soil moisture for the winter period in Iowa. Iowa State J. Sci. 39(4):327-344.

Singh, Devindar and L. J. Connor. 1978. A FORTRAN program for multicrop farms to determine operations schedule, field machinery requirements and costs. Agr. Econ. Rep. No. 331, Dept. Agr. Econ., Michigan State University, East Lansing, MI.

Stapleton, H. N. and W. W. Hinz. 1974. Increase farm profits through better machinery selection. Bull. A-78. Agr. Exp. Sta. and Coop. Ext. Service, University of Arizona, Tucson, AZ.

Tulu, M. Y. 1973. Simulation of timeliness and tractability conditions for corn production systems. Unpublished Ph.D. dissertation. Agr. Eng. Dept., Michigan State University, East Lansing, MI.

Tulu, M. Y., J. B. Holtman, R. B. Fridley and S. D. Parsons. 1974. Timeliness costs and available working days - shelled corn. Transactions of the ASAE 17(4):798-800, 804.

Waters, W. K. and D. R. Daum. Undated. Farm machinery management guide. Special circular 192, Agr. Ext. Service, Pennsylvania State University, University Park, PA.

White, R. G. 1975a. Where does the horsepower go? Agr. Eng. FACTS, No. 38, File 18.48. Agr. Eng. Dept., Michigan State University, East Lansing, MI.

White, R. G. 1975b. Effect of speed on power requirements for selected farming operations. Agr. Eng. FACTS, No. 41, File 18.4. Agr. Eng. Dept., Michigan State University, East Lansing, MI.

Zoz, F. M. 1972. Predicting tractor field performance. Transactions of the ASAE 15(2):249-255.