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TILLAGE SYSTEMS FOR MINNESOTA FARMS: ALTERNATIVE TECHNOLOGIES, ECONOMIC CONSIDERATIONS, AND DATA NEEDS

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INTRODUCTION

Selection of a tillage system is an important management decision. Many farmers are reevaluating their tillage system in light of new tillage technologies, increasing machine operating costs, financial considerations, environmental concerns, and other factors. In this paper, alternative tillage systems for Minnesota farms are discussed. An economic analysis of a tillage problem for a Southwestern Minnesota case farm is presented and tillage research needs are addressed.

Of the 10,250,000 acres of row crops produced in Minnesota in 1976, 9,020,000 (88 percent) were tilled with a conventional moldboard plow system [Conservation Tillage Technology Information Center]. However, tillage practices in Minnesota have changed. In 1987 there were 10,260,000 acres of row crops in Minnesota with 69 percent tilled with the conventional moldboard system and 31 percent tilled with other tillage systems. Of the acreage tilled by systems other than the moldboard plow, the mulch-till was used most frequently (2,590,000 acres).[1]

A farmer's choice of tillage practices depends on a variety of technical and economic factors. Many of the alternatives to moldboard plowing use less fuel because fewer operations are performed and/or the tillage operations require less fuel per acre. Thus, expectations regarding energy prices may be influential in determining future tillage practices. The price of machinery will also influence the selection of a tillage system and the timing of the

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[1] Mulch-till includes all conservation tillage systems where the total soil surface is disturbed by tillage prior to planting. Tillage tools such as chisels, field cultivators, discs, sweeps or blades are used [Conservation Tillage Technology Information Center].

investments. As information about the impacts of soil compaction on crop productivity become more widely known and accepted, the use of systems involving lighter equipment and/or fewer operations may increase. Because most alternative tillage systems involve less labor and machine time per acre due to increased field rates and fewer operations, farmers may change from moldboard plow tillage systems to other systems in order to decrease their costs per acre. Lower per acre costs may result in a decrease machinery investment because of the capacity to operate a larger acreage with the same investment in machinery and labor.

Seed germination and seedling vigor problems may occur with tillage practices which leave more residue on the top of the soil, over the row, and in the seed furrow causing the soil to stay wetter and colder in the spring and resulting in poor seed-soil contact. Concerns about environmental quality may have an impact on the tillage system chosen by farmers. Decreased erosion is a benefit of some tillage systems and will increase the likelihood of their adoption by farmers concerned with erosion. The link between tillage practices and pollution (other than soil runoff) is not well defined.

The remainder of this paper discusses alternative tillage methods, economic issues involved in the tillage decision, and the need for further tillage research. In the next section, the techniques and implements used in the alternative tillage systems for Minnesota are described along with technical attribute of each. Pertinent experiments and studies are summarized as are the quantified relationships needed for further analysis. The second section contains a discussion of economic issues related to tillage decisions and an example of an economic analysis for a case farm. The economic issues discussed include shifts in yield response functions of crops and changes in yield variability. Whole farm considerations are also discussed including field operation timeliness, field rates, and available field time. Enterprise budgets for different crops and tillage systems are developed and used in an exemplary linear programming analysis for a case farm. In the final section, tillage research needs are discussed.

ALTERNATIVE TILLAGE SYSTEMS

The most common tillage system on Minnesota crop farms includes moldboard plowing and several secondary tillage operations before planting. This system is commonly referred to as conventional tillage. Systems which leave at least 30 percent of crop residues on the soil surface after planting are commonly referred to as conservation tillage systems [Conservation Tillage Technology Information Center]. Conservation tillage systems range from substituting chisel plowing for moldboard plowing to no-till systems involving the use of special planters.

There is no single best tillage system for all farming situations. The selection of the best tillage system may depend upon soil type, field slope, cropping sequences, machinery costs, operating input prices, product prices, risk preferences, and other factors. The purpose of this section of the paper is to give a technical description of the different tillage systems commonly used in row crop production. The changes in the managerial practices associated with the adoption of conservation tillage are also identified. For this discussion, tillage systems are categorized into two classes: conventional and conservation. The conservation class is divided into full width tillage systems, strip tillage systems, and slot tillage systems.

Conventional Tillage:

The conventional tillage includes either fall or spring moldboard plowing as a primary tillage operation, and at least two secondary tillage operations. Disking, field cultivation, and harrowing are the most commonly used secondary tillage operations. Moldboard plowing incorporates at least 90 percent of the crop residue, and thus leaves the soil relatively bare. Fall moldboard plowing speeds up soil drying and therefore increases spring soil temperatures [Swan, 1972]. This increases the time available in the spring for tillage and planting operations. However, a disadvantage of fall plowing is the potential for soil erosion during the winter because of the lack of protective residue cover. Spring moldboard plowing reduces the erosion hazard during the winter, however, on poorly drained soils it may delay planting and affect soil quality and thus yield [Swan, 1972].

Full Width Conservation Tillage Systems:

Full width tillage systems usually employ a chisel plow, offset disk or tandem disk as a primary tillage tool. Two or more secondary tillage operations usually precede planting. The chisel plow system includes either fall or spring chisel plowing as a primary tillage, and two or more secondary tillage operations similar to those used with the conventional tillage (disking, field cultivation and/or harrowing). The chisel plow produces a rough soil surface and leaves 30 to 60 percent residue on the soil surface. Erosion is decreased up to 60 percent of that expected with conventional tillage. However, using the chisel plow in the spring could delay the planting operations under conditions of wet weather [Timmons, 1982].

With the disk plowing system, either a fall or spring disking operation is performed as the primary tillage. Secondary tillage is done by a field cultivator or disk. The disk could be the implement for primary and secondary tillage alike. The disk plow allows 40 to 70 percent of the crop residue to remain on the soil surface. Fall disk plowing could result in time savings in the spring and hence more timely spring operations. On the other hand, fall disking may increase erosion potential compared to spring disking [Timmons, 1982].

Strip Tillage Systems:

Tillage is normally done by the strip till planter in the row at the time of planting to kill weeds and remove residue from the row. This is a one pass tillage and planting system. The most popular strip tillage systems are the till plant system, commonly known as ridge till, and the rotary till system.

Under the till plant system, a cultivator is used to build ridges in the previous crop to a height of 4 to 6 inches. Planting is carried out by a planter equipped with sweeps or disks to move the top 1 to 2 inches of soil and residue from the top of the ridges into the area between the rows. Residue left in this inter-row zone reduces erosion [Randall, 1982]. However, in steeply sloped fields, if planting is not on the contour, erosion can be as severe as with conventional tillage.

Till planting is well suited to soils that are poorly drained and tend to be cold in the spring. The ridges warm up and dry out faster than the soil between the ridges, thus allowing timely planting and earlier plant growth. A special cultivator is needed with the till plant system to rebuild the ridges for the next year. Ridging is usually done before harvesting when weather and soil conditions permit. Timing of the ridging operation is critical. For best results, corn and soybeans should be ridged when 18-36 inches and 15-24 inches tall, respectively [Randall, 1987].

The rotary till system differs from the till plant system in that it employs a rotary tiller mounted ahead of the planter to till a narrow strip to a depth of about two inches in each row or ridge, instead of sweeps or disks. The rotary till planter, unlike the till planter, provides a means of chemical incorporation but has greater power requirements and higher fuel and labor requirements than the till plant system [Robertson, 1979].

Slot Tillage System:

The slot tillage system, also called no-till or zero till, prepares a 1 to 2 inch wide strip of soil with a fluted or smooth coulter, or angled disks mounted in front of the planter units. Seed is placed in the narrow prepared slots which must be of sufficient width and depth for proper seed coverage and soil contact. Separate tillage operations are eliminated with the slot tillage system. By tilling only a narrow slot in the residue covered soil, less erosion occurs compared to other tillage systems. However, the heavy residue cover allowed by the slot tillage system may result in slow drying and warming of poorly drained soils. Soils that are well drained are best adapted to the slot tillage system [Bauder et al., 1979].

COMPARING TILLAGE SYSTEMS

The conventional moldboard plow tillage system has the highest per acre fuel and labor requirements while the no-till system requires the lowest amount of fuel and labor. Shifting from a conventional tillage system to a full width conservation tillage system has been estimated to reduce fuel consumption by 18 percent with the chisel plow and by 40 percent when the disk plow is used. The use of ridge till and no-till will reduce fuel use by about 50 and 70 percent, respectively, when compared to the conventional tillage system [Shelton, 1987]. The per acre labor requirements of the full width tillage system are 15 percent lower with the chisel plow and 30 percent lower with the disk plow than with the moldboard plow. The adoption of ridge till and no-till systems reduces labor requirements 20 and 35 percent respectively, from the conventional tillage system. Several studies in the U.S. have shown that the yield penalties with the use of conservation tillage systems in crop production is slight [Swan, 1972]. A long term study to evaluate the effect of tillage systems on corn and soybean production was started in 1975 at the University of Minnesota's Southern Experiment Station near Waseca, Minnesota [Randall, 1987]. Yields of corn and soybeans from this study were highest with the moldboard plow and lowest with the no-till system. The average yield of continuous corn with no till was 25 bushels per acre less than the average yield with conventional tillage -- a yield reduction of about 15 percent. The no-till corn yield reduction in this study resulted from excessive weed infestation and a less effective weed control program. However, weed management practices have been altered since the Waseca experiments were begun and conventional and no-till yield levels in recent years have been similar.

Unlike moldboard plow systems which tolerate the most errors in crop management without yield penalties, conservation tillage systems require good management to achieve high profitability. Key areas of management include crop residue, fertilization, weed control and pest control.

Residue Management:

The amount of residue left on the soil surface depends on the type of crop grown, the yield and the tillage system. In addition to reducing erosion, crop residue on the surface of the soil increases water holding capacity and the rate of water infiltration, and decreases the rate of water evaporation [Dickey et al., 1987]. The benefits provided by crop residues are directly related to the percentage of soil surface which is covered. Crop residues are most effective when evenly distributed on the soil surface. Uniform residue distribution will enhance weed control and will allow use of less specialized planters to obtain good crop stands.

The residues of certain crops such as corn are more persistent than that of soybeans and other crops [Rasnake, 1983]. The amount of residue decreases with time as decomposition occurs. The kind of tillage and its intensity also contribute to the reduction of crop residue on the soil surface (Table 1). The percentage of residue remaining with a given tillage system may be estimated by multiplying the percentages in Table 1 for each tillage operation within the selected tillage system. The conventional tillage system buries most of the crop residue and leaves the soil surface almost totally bare (Table 2). About thirty percent of the residue remains on the soil with the full width conservation tillage systems while almost all of the residue could be left on the soil surface with the no-till system.

Table 1: Percent of Residue on the Soil Surface After a Single Operation.

Operation	Following Corn	Following Soybeans
Moldboard Plow	5%	3%
Chisel Plow	55%	35%
Disk	85%	60%
Field Cultivator	70%	50%
Anhydrous Application	80%	45%
Planter	85%	85%
Till planter	80%	60%
No-till planter	95%	85%

Table 2: Estimated Residue Cover and Soil Erosion by Tillage System.

	------ Following Corn ------		---- Following Soybeans ----	
Tillage System[a]	Residue Cover[b]	Soil Erosion[c]	Residue Cover[b]	Soil Erosion[c]
Moldboard Plow	2.0	--	0.6	--
Chisel Plow	21.8	41.0	7.1	75.0
Disk	39.6	16.0	20.2	43.0
Till Plant	76.0	10.0	57.0	7.0
No Till	90.3	2.0	80.8	2.5

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[a] For the moldboard and chisel plow systems, the plowing operation is followed by two disking operations. The disk system uses two diskings.

[b] Percent of total remaining after planting. The initial residue cover is assumed to be 95 percent of the total.

[c] Soil erosion is the percent of that expected when the conventional tillage is used.

Fertilizer management:

For plants to be able to use applied fertilizer, the fertilizer must be in an available form and it must be placed where active roots are present. The shift from conventional tillage to a conservation tillage system may require a change in fertilization practices for the most efficient use of applied plant nutrients. Nitrogen availability with conservation tillage is changed because of changes in soil environment that affects the soil's microbiological activity [Randall, 1982].

Conservation tillage systems involve less tillage and subsequently the soil is less disturbed than with the conventional tillage. Any reduced tillage system that allows some tillage or some incorporation of fertilizers provides a mechanism for fertilizer placement into the soil. Full width tillage is commonly carried out by either a chisel plow or a disk. Both the chisel plow and disk incorporate surface applied fertilizers in the top four inches of the soil. Generally, the use of full width tillage systems requires almost no adjustment in fertilizer management.

Problems arise, however, as tillage is reduced to till plant and zero-tillage systems, which leave a higher level of crop residue on the soil surface. Surface application of nutrients without incorporation generally results in losses and poor utilization of these nutrients. Surface applied nitrogen is subject to losses by immobilization and volatilization, which are affected by high amounts of crop residue [Sander, 1987]. Phosphorus and potassium, which are relatively immobile in soils, will remain on the surface if surface applied, and availability to plants will be minimized. Therefore, the response to applied nutrients in slot-tillage and strip-tillage systems may be improved if the nutrients are placed in the root zone by knifing or banding during planting.

<u>Weed Control</u>:

A primary reason for soil tillage is to control weeds. Prior to the discovery of herbicides, weed control was accomplished by pre-plant tillage operations and cultivation. Weeds compete with crops for available nutrients and soil water and thus cause yield reductions. The adverse effects of uncontrolled weeds can occur regardless of the tillage system used. The common belief that weed problems intensify under conservation tillage might be more properly stated as follows: "weed problems may change under conservation tillage systems" (Fawcett and Nelson, 1982).

The acceptance of conservation tillage systems has been dependent on the development of herbicides for providing suitable weed control. Conservation tillage systems may leave up to 90 percent of the previous year's crop residue on the surface, raising concerns about herbicide performance.

Under the full width tillage systems, the soil is either chisel plowed or disked followed by at least two secondary tillage operations. These systems may leave up to 40 percent of the residue on the soil surface. All herbicide application options (pre-plant incorporated, pre-emergence, and post-emergence) can be effectively used with the full width tillage systems.

With the slot till system, the soil is undisturbed prior to planting. As tillage is eliminated, greater reliance is placed on herbicides for weed control. Success in the slot till system is highly dependent on the weed control program designed. Herbicide applications which are acceptable under conventional tillage may not be adequate for the slot till system. Since no-tillage is performed, the potential for using an incorporated herbicide is eliminated. Broadcast herbicide applications are then required with the no-till system.

There are two methods of chemical weed control in the slot tillage system. One method is a combination of a post-emergence and a residual pre-emergence herbicide at planting time. Another method is to apply the herbicide several days prior to planting [Fawcett et al., 1982]. The early pre-plant approach increases the chances that rainfall will activate the herbicide before weed germination starts.

Intermediate between the full width systems and the slot till is the strip tillage systems. Strip tillage systems remove most crop residue from the row area and improve conditions for herbicide performance in the row. Rotary tillers allow incorporation of herbicides in the row area so all herbicide options can be used with this system. However, with the ridge till system, since row cultivation is usually practiced, a good weed control program should include a band herbicide at planting in the row and timely cultivation [Martin, 1987].

Pest Management:

Weather conditions and certain cultural practices govern to a large degree when pests may be present in a field crop and if they are likely to cause crop losses if no control is used. The major cultural factors affecting pest presence and activity are: crop rotation, date of planting, type and degree of crop residue which is primarily determined by tillage practices [Edwards, 1983].

The moldboard plow provides some control for some pests by burying the crop residue. The elimination of deep plowing and increased residue cover on the surface with conservation tillage practices may permit certain pests to overwinter in greater numbers. Full width tillage equipment such as chisels and disks will make only slight changes in the pest population. Conservation tillage systems that leave heavy surface residue may increase the population of ground insects. A banding application of the insecticide is recommended with these systems [Baxendale, 1987].

Regardless of the tillage system utilized, a good pest management program requires the farmer to be more observant and aware of needed technology to prevent serious pest problems. Insects are not regarded as an unsurmountable problem with conservation tillage systems. Insect stresses are, however, different from those encountered in conventional tillage.

In summary, this section has presented the various alternative technologies available for row-crop tillage. The advantages, disadvantages, and physical management considerations are discussed. In the next section, the economic issues involved in tillage system selection are presented and discussed.

ECONOMIC MODELING OF ALTERNATIVE TILLAGE SYSTEMS

When a farmer changes tillage systems, fundamental relationships pertaining to the crop technology are altered. Therefore, optimal resource allocations change. In this section of the paper, the underlying production economics of a change in tillage systems will be discussed. This will lead up to a presentation and discussion of exemplary enterprise budgets for crops produced under alternative tillage systems. Specifically, the budgets will be for continuous corn, continuous soybeans and a corn-soybean rotation. These crops will be budgeted under two conventional moldboard plow tillage systems and under two ridge tillage systems. Finally, an analysis of the tillage decision using a whole farm linear programming model will be discussed.

Enterprise-Level Considerations:

The yield response to many operating inputs is altered when a change occurs in the tillage system. Therefore, the output of grain per acre associated with various levels of both controlled and uncontrolled inputs is altered. Since conservation tillage systems leave more residue on the surface of the soil than conventional systems, the soil's water holding capacity and the rate of infiltration increase and the rate of evaporation decreases. Thus, a given level of rainfall will tend to imply a greater amount of water available to the crop. The uncontrolled temperature "input" also differs in its yield impact under various tillage systems. Surface residue has an insulating effect on the soil and thus tends to slow the warming of the soil in the spring [Gupta, 1985]. When soil temperature is lower, germination and growth rates are lower -- effectively altering the yield response to seed [Hicks et al., 1978]. The responses to other controlled inputs are similarly altered.

Tillage operations provide a means for applying and incorporating various chemical inputs. For fertilizer use, changes in the means of application and the degree of incorporation among alternative tillage systems changes the yield response to fertilizer. Reduced tillage also implies reduced mechanical control of weeds. In varying degrees, herbicides must be substituted for mechanical weed control under conservation tillage. And because the incorporation and application differs across systems, the efficacy of the herbicide is further altered. Yield loss associated with pest damage (and the yield response to pesticides) is influenced by the level and type of surface residue and thus the tillage system.

Knowledge of crop technologies and the technical differences among tillage systems is a first step in determining how operating input practices should be altered when the tillage system is changed. To determine economically efficient levels of operating inputs, however, it will be necessary to estimate yield response functions which prevail under alternative tillage practices. Thus, indirect effects of the tillage system on operating costs may be estimated. In addition to the average yield response, yield variability is often influenced by the levels of operating inputs. The yield risk associated with various operating input practices is likely also influenced by tillage practices. As implied earlier in the paper, use of nonconventional tillage practices "complicates" crop management in many respects. Intuitively, therefore, one might expect that yield risk would increase.[2] However, conservation tillage may lead to decreases in yield risk associated with variability in rainfall.

A primary objective in estimating optimal input use under conservation tillage is to accurately measure the costs and benefits of alternative systems. The technologies will perform differently on different soil types and in different climates. Estimates of response functions should be representative of the range of conditions faced by Minnesota farmers. The implication of this need is that a thorough analysis of tillage system economics for Minnesota will require extensive data. Because of the cost and time involved in generating additional data, it may be beneficial to augment current information about tillage/crop technologies with simulation techniques.

To this point, the discussion of tillage technologies and economics has focused on private costs and benefits. Social costs and benefits are important considerations in any analysis of tillage practices. The traditional notion of output should be extended to include soil loss and chemical runoff "yields" as well as crop yields.

Whole Farm Considerations:

Several of the specific crop and tillage concerns discussed in the previous section affect timeliness and resource allocation of the whole farm and not just the isolated crop. Timeliness in field operations and fixed

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[2] To a certain extent, the hypothesis that more complex crop management problems imply more yield risk also implied the existence of a learning curve. Once adopted, a manager will gain experience with a new tillage system. So, over time, average yield may increase and yield variability may decline. If management is inherently more complicated under conservation tillage, however, improved management would likely compensate for only part of any average decline in yield or increase in yield risk.

resource allocation need to be considered in the whole farm context to obtain the full impact of different crop choices and tillage systems.

The timeliness issue involves many aspects of the management and technology of the crop and tillage system. In its simplest aspects, timeliness is affected by two variables: machinery field rates and planting date. Some tillage implements can cover ground faster which will leave more time for planting and other operations. Also, some tillage systems require fewer operations to till the soil. With both of these effects, planting could take place earlier and provide an effectively longer growing season. However, these same tillage systems probably leave more trash on the soil which will tend to keep the soil colder and wetter in the spring; thus, planting would be delayed to avoid poor germination and/or low seedling vigor.

The allocation of capital, machinery, and land resources could be affected by the choice of tillage system. And the choice of tillage system could be affected by the interaction with resource allocations and the resulting impact on farm profitability. Several factors are involved in this interaction. Increased speed due to higher field rates and(or) fewer operations may require fewer machinery resources to till current land resources. Fewer machinery resources may allow a reallocation of capital to other aspects of the business, debt reduction, or out of the farm business. If the farm is "under-mechanized" by conventional terms, tillage systems which decrease time commitments, may allow the current land holdings to be tilled in a more timely manner. An additional impact, due to decreased tillage time per acre, can be analyzed only on a whole farm level. This impact is the increase in acres farmed by reallocating (but not the increasing) capital and machinery resources.

ECONOMIC ANALYSIS OF TILLAGE DECISIONS: AN EXAMPLE

To illustrate a whole farm approach to analyzing the economics of alternative tillage systems, a case study of a 600 acre Southwestern Minnesota corn and soybean farm will be reported. Conventional moldboard plow and ridge tillage systems will be considered. Two conventional systems will be analyzed which use a moldboard plow for primary tillage and a disk for secondary tillage. Moldboard Plow-System 1 will use a single 8 row planter for corn and soybeans. Under Moldboard Plow System 2, soybeans will be planted with a grain drill. Also, two alternative ridge tillage systems will be analyzed. Ridge Till System 1 is a "pure" ridge till system with an 8 row minimum tillage planter used along with a ridge cultivator for both corn and soybeans. Paralleling the second conventional system, Ridge Till System 2 will use a grain drill for soybeans requiring soil preparation with a tandem disk. Ownership and operating costs will be estimated for all of the machines used in the various systems. The ownership costs will then be summed to get total ownership costs for the machinery complements associated with each of the four tillage systems. Machine operating cost estimates and other operating input data will be combined with yield data to develop unit budgets for each crop. Corn and soybeans will be budgeted both as continuous and rotated crops. Finally, the unit budget data and other technical data will be used in the construction of an 18 period, annual linear programming model which will be used to determine optimal production practices under each system. The results, together with the machine ownership cost estimates, will provide the basis for comparing the relative profitability of the alternative tillage systems.

<u>Machine Costs</u>:

The machines used in the study are listed in Table 3, which also shows the list and purchase prices, salvage value and assumed level of use. List and purchase prices are as reported in Fuller and McGuire. Salvage values are calculated using remaining value equations from Boehlje and Eidman and annual use levels were estimated based upon typical production practices for the case farm. In Table 4, average annual ownership costs are reported, including capital recovery, taxes, insurance and housing costs. Variable machine costs for field operations include fuel, lubrication, maintenance and repairs. Per hour variable costs are reported by machine in Table 5. Machine ownership and operating costs were computing using the EBMCH1 machine cost worksheet [Apland, 1987]. The machinery complements needed for each tillage system were defined as follows. A machinery set was first defined for a typical 600 acre corn-soybean farm using a conventional moldboard plow tillage system. Then, necessary equipment was added and unneeded equipment deleted from this base set to determine machine complements for each of the other three tillage systems. Each of the four machine complements is described in Table 6. Total average annual ownership costs are $32,745 for moldboard plow system 1 and $34,942 for moldboard plow system 2. For ridge till systems 1 and 2, the average annual ownership costs were $23,358 and $34,037, respectively.

<u>Unit Budgets</u>:

Tillage experiments at the Lamberton Experiment Station in Southwestern Minnesota were used in the derivation of mean yields by crop, rotation and tillage system. A detailed description of these experiments can be found in "A Report on Field Research on Soils, 1985" (pages 263-275) and Moncrief et al. [1988]. Fertilizer, herbicide and insecticide levels were based on

Table 3: Machine Data.

Machine	List Price	Purchase Price[a]	Salvage Value[b]	Annual Use[c]
100 HP Tractor	$43,240	$35,889	$12,772.3	325
140 HP Tractor	54,983	45,636	16,241.1	300
Moldboard Plow 7-16	10,753	9,678	1,901.6	150
Tandem Disk 24 ft	13,783	12,405	2,437.5	110
Planter 8-30	19,140	17,226	3,384.7	100
Min Till Planter 8-30	19,493	17,544	3,447.2	125
Grain Drill 24 ft	17,337	15,603	3,065.8	70
Cultivator 8-30	5,166	4,649	913.5	80
Ridge Cultivator 8-30	8,870	7,983	1,568.6	80
Sprayer 50 ft	4,830	4,347	797.2	55
Mounted Sprayer	2,222	2,000	393.0	40
Medium Truck	36,051	29,922	6,375.2	350
Medium Combine	79,727	66,173	15,038.9	250
Corn Head 4-30	13,074	11,767	2,466.2	150
Soybean Head - Medium	8,230	7,407	1,552.4	100

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[a] Following assumptions made by Fuller and McGuire, purchase price is estimated as 17 percent of list for items with a list price of $30,000 or more and 10 percent of list for items with a list price of less than $30,000.

[b] Salvage value is estimated using American Society of Agricultural Engineers remaining value equations as reported in Boehlje and Eidman (Page 141).

[c] Hours of annual use is used in the calculation of total accumulated repair cost and repair cost per hour.

Table 4: Average Annual Machine Ownership Costs.

Machine	Capital Recovery[a]	TIH[b]	Total Ownership Cost
100 HP Tractor	4,092.3	277.7	4,370.0
140 HP Tractor	5,203.7	382.0	5,585.7
Moldboard Plow 7-16	1,217.0	149.2	1,366.1
Tandem Disk 24 ft	1,559.9	205.7	1,765.5
Planter 8-30	2,166.1	227.3	2,393.4
Min Till Planter 8-30	2,206.1	228.7	2,434.8
Grain Drill 24 ft	1,962.0	235.0	2,197.0
Cultivator 8-30	584.6	125.9	710.4
Ridge Cultivator 8-30	1,003.8	125.8	1,129.6
Sprayer 50 ft	550.8	169.3	720.1
Mounted Sprayer	251.5	159.0	410.5
Medium Truck	3,726.1	323.6	4,049.7
Medium Combine	8,171.2	604.5	8,775.7
Corn Head 4-30	1,468.3	113.4	1,581.7
Soybean Head - Medium	924.3	92.1	1,016.4

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[a] Annual recovery cost based upon a 10 year useful life, a nominal interest rate of 12 percent and an inflation rate of 5 percent.

[b] Average annual taxes, insurance and housing cost. Property tax rate on machinery assumed to be zero. Insurance is 0.75 percent of average annual investment. Housing cost estimate based upon $0.75 per year per square foot.

Table 5: Per Hour Machine Operating Costs.[a]

Machine	Fuel and Lubrication[b]	Maintenance and Repairs	Total
100 HP Tractor	4.05	2.25	6.30
140 HP Tractor	5.67	2.75	8.42
Moldboard Plow 7-16	--	4.42	4.42
Tandem Disk 24 ft	--	5.16	5.16
Planter 8-30	--	14.88	14.88
Min Till Planter 8-30	--	16.57	16.57
Grain Drill 24 ft	--	11.68	11.68
Cultivator 8-30	--	1.76	1.76
Ridge Cultivator 8-30	--	3.02	3.02
Sprayer 50 ft	--	2.96	2.96
Mounted Sprayer	--	1.20	1.20
Medium Truck	2.31	18.07	20.38
Medium Combine	6.62	26.40	33.02
Corn Head 4-30	--	5.85	5.85
Soybean Head - Medium	--	3.13	3.13

[a] Fuel consumption and per hour repair costs are estimated using American Society of Agricultural Engineers estimating equations and procedures reported in Chapter 4 of Boehlje and Eidman.

[b] Based upon diesel fuel price of $0.80 per gallon. Lubrication costs for machines with engines is assumed to be 15 percent of fuel cost. Lubrication costs for machines without engines is included in the maintenance cost.

Table 6: Machine Sets by Tillage System.

Machine	Moldboard 1	Moldboard 2	Ridge Till 1	Ridge Till 2
100 HP Tractor	X	X	X	X
140 HP Tractor	X	X		X
Moldboard Plow 7-16	X	X		
Tandem Disk 24 ft	X	X		X
Planter 8-30	X	X		
Min Till Planter 8-30			X	X
Grain Drill 24 ft		X		X
Cultivator 8-30	X	X		
Ridge Cultivator 8-30			X	X
Sprayer 50 ft	X	X		X
Mounted Sprayer	X	X		X
Medium Truck	X	X	X	X
Medium Combine	X	X	X	X
Cornhead 4-30	X	X	X	X
Soybean Head - Medium	X	X	X	X

experiment station data and recommendations for each of the systems of production.[3] Per acre labor and fuel use estimates were compiled using results from the EBMCH1 machine cost generator and computations for field operations were completed using the EBCRP1 crop budget generator [Apland, 1987]. Per acre yields, fertilizer levels, labor requirements and fuel use by crop, rotation and tillage system are reported in Table 7. Table 8 provides a summary of the herbicide use.

The summary unit budgets in Table 9 are derived using the technical data in Tables 7 and 8 and 1988 input prices. Long run planning prices of $2.35 for corn and $5.20 for soybeans were assumed.

The Linear Programming Model:

The use of linear programming (LP) in the analysis facilitates a comparison of the profitability of the alternative systems at the farm level. The model will determine the optimal crop mixes for each system, thus allowing the systems to be compared given efficient use of fixed labor, machine and land resources. By defining resource requirements and availability over many production periods in the linear program, the model allows for the effects of timeliness of field operations on crop yields and grain moisture levels to be captured. The linear programming model was constructed using the FS1 farm modeling software [Apland, 1983].

The LP model has 18 production periods. Planting periods are 5 days in length and run from April 23 to June 6 -- a total of 9 periods. Harvest operations may take place from September 15 to November 13 during any of 6 periods 10 days in length. Other production periods accommodate tillage and

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[3] As mentioned earlier, the use of statistically estimated yield response functions for operating inputs, while desirable, was not possible due to data limitations.

Table 7: Yields and Input Use by Enterprise and Tillage System.

Item	Continuous Corn	Continuous Soybeans	Corn After Soybeans	Soybeans After Corn
	--------- Moldboard Plow	Tillage System 1	--------	
Yield, bushels/acre	131	35.7	133	42
Nitrogen, lb/acre	120	0	90	0
Phosphate, lb/acre	30	50	30	50
Potash, lb/acre	20	40	20	40
Labor, hours/acre	1.91	1.67	1.82	1.76
Diesel Fuel, gallons/acre	8.33	6.85	7.80	7.38
	--------- Moldboard Plow	Tillage System 2	--------	
Yield, bushels/acre	131	37.68	133	44.33
Nitrogen, lb/acre	120	0	90	0
Phosphate, lb/acre	30	50	30	50
Potash, lb/acre	20	40	20	40
Labor, hours/acre	1.91	1.50	1.82	1.59
Diesel Fuel, gallons/acre	8.33	6.16	7.80	6.69
	------------- Ridge	Tillage System 1[a]	------------	
Yield, bushels/acre	130	34.56	134	40.66
Nitrogen, lb/acre	120	0	90	0
Phosphate, lb/acre	30	50	30	50
Potash, lb/acre	20	40	20	40
Labor, hours/acre	1.63	1.47	1.63	1.47
Diesel Fuel, gallons/acre	6.42	5.40	6.42	5.40
	------------- Ridge	Tillage System 2[b]	------------	
Yield, bushels/acre	130	37.4	134	44.0
Nitrogen, lb/acre	120	0	90	0
Phosphate, lb/acre	30	50	30	50
Potash, lb/acre	20	40	20	40
Labor, hours/acre	1.63	1.43	1.63	1.43
Diesel Fuel, gallons/acre	6.42	5.71	6.42	5.71

[a] For ridge till system 1, ridge tillage techniques are used for both corn and soybeans. Under system 2, ridge till equipment is used for corn only -- soybean acreage is disked and planted with a drill.

[b] Corn yields and input levels are the same as under ridge till system 1.

Table 8: Herbicide Use Per Acre by Enterprise and Tillage System.

Continuous Corn	Continuous Soybeans	Corn After Soybeans	Soybeans After Corn
----------------- Moldboard Plow Tillage Systems 1 and 2 -----------------			
Lasso, 2.5lb	Treflan, 1.0lb	Lasso, 2.5lb	Treflan, 1.0lb
Bladex, 2.5lb	Basagran, 0.75lb	Bladex, 2.5lb	Basagran, 0.75lb
	Crop Oil, 1.0qt		Crop Oil, 1.0qt
------------------------ Ridge Tillage System 1 ------------------------			
Lasso, 2.5lb	Lasso, 2.5lb	Lasso, 2.5lb	Lasso, 2.5lb
Bladex, 2.5lb	Roundup, 0.5lb	Bladex, 2.5lb	Roundup, 0.5lb
Roundup, 0.5lb	Basagran, 0.75lb		Basagran, 0.75lb
	Crop Oil, 1.0qt		Crop Oil, 1.0qt
------------------------ Ridge Tillage System 2 ------------------------			
Lasso, 2.5lb	Treflan, 1.0lb	Lasso, 2.5lb	Treflan, 1.0lb
Bladex, 2.5lb	Basagran, 0.75lb	Bladex, 2.5lb	Basagran, 0.75lb
Roundup, 0.5lb	Crop Oil, 1.0qt		Crop Oil, 1.0qt

Table 9: Receipts and Operating Costs by Enterprise and Tillage System.[a]

Item	Continuous Corn	Continuous Soybeans	Corn After Soybeans	Soybeans After Corn
	--------- Moldboard Plow	Tillage System 1	--------	
Receipts, $/acre --------	307.85	185.64	312.55	218.40
Operating Costs, $/acre:				
Seed	18.00	9.00	18.00	9.00
Fertilizer	32.54	15.80	28.94	15.80
Herbicide	23.50	16.45	23.50	16.45
Insecticide	12.79	0	0	0
Machine	38.09	31.00	36.92	32.16
Other	29.65	21.01	27.62	22.66
Total Operating Cost	154.56	93.25	134.98	96.07
Receipts Minus Oper. Cost	153.29	92.39	177.57	122.33
	--------- Moldboard Plow	Tillage System 2	--------	
Receipts, $/acre --------	307.85	195.94	312.55	230.52
Operating Costs, $/acre:				
Seed	18.00	9.00	18.00	9.00
Fertilizer	32.54	15.80	28.94	15.80
Herbicide	23.50	16.45	23.50	16.45
Insecticide	12.79	0	0	0
Machine	38.09	29.07	36.92	30.23
Other	29.65	20.00	27.62	21.69
Total Operating Cost	154.56	90.31	134.98	93.18
Receipts Minus Oper. Cost	153.29	105.63	177.57	137.34
	------------- Ridge	Tillage System 1	-------------	
Receipts, $/acre --------	305.50	179.71	314.90	211.43
Operating Costs, $/acre:				
Seed	18.00	9.00	18.00	9.00
Fertilizer	32.54	15.80	28.94	15.80
Herbicide	18.56	18.81	11.76	18.81
Insecticide	12.79	0	0	0
Machine	35.29	29.08	35.29	29.08
Other	25.92	18.97	25.04	19.77
Total Operating Cost	143.10	91.66	119.03	92.45
Receipts Minus Oper. Cost	162.40	88.06	195.87	119.98
	------------- Ridge	Tillage System 2	-------------	
Receipts, $/acre --------	305.50	194.48	314.90	228.80
Operating Costs, $/acre:				
Seed	18.00	9.00	18.00	9.00
Fertilizer	32.54	15.80	28.94	15.80
Herbicide	18.56	16.45	11.76	16.45
Insecticide	12.79	0	0	0
Machine	35.29	28.25	35.29	28.25
Other	25.92	19.14	24.04	20.04
Total Operating Cost	143.10	88.64	119.03	89.55
Receipts Minus Oper. Cost	162.40	105.84	195.87	139.25

[a] Unit prices for corn and soybeans are $2.35 and $5.20 respectively.

post-plant activities beyond those which may take place in planting or harvest periods. Details of the calender of production operations are provided in Tables 10, 11 and 12. Sequencing constraints require that field operations occur in the designated order. The optimal solution to the LP model may be thought of as an intermediate run equilibrium. That is, given the fixed machine, labor and land resources of the farm firm, the solution represents an expected profit maximizing production plan which could be repeated year after year.

Land, labor and machine time constrain the production activities in the model. Land is constrained at 600 acres which are assumed to be of homogeneous quality. Two full time workers are assumed available for field operations -- labor availability in each of the 18 production periods is restricted. Hours of labor available in a particular period are calculated as follows:

Number of Workers x Hours Per Day x Number of Field Days

Hours per day is set at the number of hours of daylight (rounded down to the nearest whole hour) or 12, whichever is smaller. Ten years of field days data from Lamberton where used to complete the calculation. Means and standard deviations were calculated for each period. Then, assuming a normal distribution, field days were set at levels which would be exceeded with a probability of 0.6.[4] Similar constraints were imposed on machine resources. Available tractor, planter, harvester and tillage services were constrained in the appropriate periods and by machine type and size.

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[4] Previous studies have suggested that the use of mean filed days overstates fixed resource availability in planning models [Apland, 1988].

Table 10: Calender of Field Operations for Moldboard Plow Tillage Systems.

---- Period ----	Disk 1[a]	Plow	Disk 2[b]	---- Corn -----			--- Soybeans ---		
				Plant	Cult	Harv	Plant	Cult[c]	Harv
1 07-Apr 22-Apr									
2 23-Apr 27-Apr			X	X					
3 28-May 02-May			X	X					
4 03-May 07-May			X	X	X		X		
5 08-May 12-May			X	X	X		X		
6 13-May 17-May			X	X	X		X	X	
7 18-May 22-May			X	X	X		X	X	
8 23-May 27-May			X	X	X		X	X	
9 28-May 01-Jun			X	X	X		X	X	
10 02-Jun 06-Jun			X		X		X	X	
11 07-Jun 26 Jun					X				X
12 15-Sep 24-Sep	X	X							X
13 25-Sep 04-Oct	X	X							X
14 05-Oct 14-Oct	X	X				X			X
15 15-Oct 24-Oct	X	X				X			X
16 25-Oct 03-Nov	X	X				X			
17 04-Nov 13-Nov	X	X				X			
18 14-Nov 30-Nov	X	X							

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[a] After corn only.

[b] Concurrent with planting. When preceding soybeans, includes herbicide application.

[c] Moldboard plow system 1 only.

Table 11: Calender of Field Operations for Ridge Tillage System 1.

	---------- Corn ----------			-------- Soybeans --------		
---- Period ----	Plant	Ridge Cult	Harvest	Plant	Ridge Cult	Harvest
1 07-Apr 22-Apr						
2 23-Apr 27-Apr	X					
3 28-May 02-May	X					
4 03-May 07-May	X	X		X		
5 08-May 12-May	X	X		X		
6 13-May 17-May	X	X		X	X	
7 18-May 22-May	X	X		X	X	
8 23-May 27-May	X	X		X	X	
9 28-May 01-Jun	X	X		X	X	
10 02-Jun 06-Jun		X		X	X	
11 07-Jun 26 Jun		X			X	
12 15-Sep 24-Sep						X
13 25-Sep 04-Oct						X
14 05-Oct 14-Oct			X			X
15 15-Oct 24-Oct			X			X
16 25-Oct 03-Nov			X			
17 04-Nov 13-Nov			X			
18 14-Nov 30-Nov						

Table 12: Calender of Field Operations for Ridge Tillage System 2.

---- Period ----			Disk 1[a]	Disk 2[b]	Disk 3[c]	----- Corn ------			-- Soybeans --	
						Plant	Cult[d]	Harv	Plant	Harvest
1	07-Apr	22-Apr	X	X						
2	23-Apr	27-Apr	X	X		X				
3	28-May	02-May	X	X		X				
4	03-May	07-May	X	X	X	X	X		X	
5	08-May	12-May	X	X	X	X	X		X	
6	13-May	17-May	X	X	X	X	X		X	
7	18-May	22-May	X	X	X	X	X		X	
8	23-May	27-May	X	X	X	X	X		X	
9	28-May	01-Jun	X	X	X	X	X		X	
10	02-Jun	06-Jun	X	X	X		X		X	
11	07-Jun	26 Jun					X			
12	15-Sep	24-Sep	X							X
13	25-Sep	04-Oct	X							X
14	05-Oct	14-Oct	X					X		X
15	15-Oct	24-Oct	X					X		X
16	25-Oct	03-Nov	X					X		
17	04-Nov	13-Nov	X					X		
18	14-Nov	30-Nov	X							

[a] Preceding soybeans only.

[b] Preceding soybeans only. Includes herbicide application.

[c] Preceding soybeans only. Concurrent with planting.

[d] Ridge cultivation.

Yield coefficients for corn and soybeans were used to adjust yields by planting and harvest periods. The same coefficients were used for each tillage system and regardless of rotation. The base yields used in the unit budgets (Table 9) were adjusted with the yield coefficients to reflect the timing of the production activities. Grain moisture levels were similarly adjusted based on the periods of planting and harvest.

After optimal solutions are derived for each tillage system, sensitivity analyses will be performed to examine the effects of changes in total crop acreage on the relative profitability of the systems. Because each system has a unique set of field operations with varying field rates, differences will be expected in economic efficiency for different farm sizes. To examine this, optimal solutions will be derived for total crop acreages of 200, 300, 400, 600, 800 and 1000.

The Linear Programming Results:

The base solutions for the 600 acre farm are provided in Table 13. For purposes of comparing tillage systems, expected profit is calculated as total revenue minus total variable cost and machine ownership cost. Other fixed costs are assumed constant across systems. For purposes of discussion, the results for moldboard plow system 1 will be compared to each of the other tillage systems. Under all of the tillage systems, the optimal crop mix included 300 acres of corn and 300 acres of soybeans -- the two year rotation. With moldboard plow system 1, the average corn yield was 132.04 bushels per acre and the soybean yield was 35.14 bushels per acre. Expected net revenue was $85,602 and with annual fixed machinery costs of $32,745, the expected profit was $52,857.

Table 13: Summary of Linear Programming Solutions by Tillage System.

	Moldboard 1	Moldboard 2	Ridge Till 1	Ridge Till 2
Acres Corn Produced	300.0	300.0	300.0	300.0
Acres Soybeans Produced	300.0	300.0	300.0	300.0
Corn Yield (bu/ac)	130.33	132.12	130.86	132.46
Soybean Yield (bu/ac)	42.13	44.45	40.48	44.17
Expected Net Revenue	$86,522	$91,622	$89,171	$96,202
Annualized Machinery Cost[a]	$32,745	$34,942	$23,358	$34,037
Expected Profit[b]	$53,777	$56,680	$65,813	$62,165

[a] Total average annual ownership costs for each machinery complement includes annual capital recovery and average annual taxes, insurance and housing.

[b] Expected net revenue less machine ownership costs.

Moldboard plow system 2 involves the addition of a grain drill to the machine set for planting soybeans. The added annual fixed machine cost of $2197 is more than offset by the $5,491 increase in expected net revenue. The net revenue increase is attributable to the increased expected soybean yield when the grain drill is used. Further, the addition of a second planter and the elimination of soybean cultivation allowed for improvements in the timeliness of corn production activities and thus a slight improvement in corn yields.

With ridge till system 1, a minimum tillage planter replaces the corn planter and a ridge cultivator replaces the conventional cultivator. The 140 horsepower tractor, the moldboard plow, the tandem disk and the sprayers are eliminated. Although soybean yields are 3.9% lower than under moldboard system 1, expected net revenue increases by $2,649 due to the lower operating costs of ridge till system 1. And due to the substantially lower machinery costs, expected profit is increased by $12,036.

Under ridge till system 2, only the moldboard plow is eliminated form the conventional machinery set. A grain drill is added and the minimum till planter and ridge cultivator replace the corn planter and conventional cultivator. Due to increased soybean yields resulting from planting with a grain drill, and improved timeliness in corn production, expected net revenue increases by $9,680 to $96,202. The increase in expected profit is $8,388 -- a smaller increase since machine ownership costs go up by $1,292 annually.

<u>Results of the Capacity Analysis</u>

Since the various production systems studied here involve different operations with different field rates, it might be expected that the acreage capacity of each system would differ. The LP model was used to analyze the capacity question. To do this, the available acreage was increased from 200 to 1400 in increments of 200 acres. The optimal solutions for each system at each acreage level are summarized in Table 14. The results listed include the optimal values of the land constraint dual variable, corn acreage, soybean acreage, net revenue and profit. The dual of the land constraint represents the marginal implicit value of land in terms of expected net revenue.

The maximum total acres of corn and soybeans were 1,091, 1,228, 866, and 1,250 for moldboard plow systems 1 and 2, and ridge till systems 1 and 2, respectively. Maximum profit for each of the machine sets, at the acreage maximums, was $107,957, $132,554, $95,802 and $143,889, respectively. While ridge tillage system 1 is the most profitable of the four machine sets from 200 through 800 acres, the other systems are more profitable when the acreage is increased beyond the capacity of ridge till 1.

For both the moldboard and ridge tillage systems, addition of the second planter (the grain drill for soybeans) freed up machine and labor resources and enabled the economical production of larger crop acreages. The dual variables on the land constraints provide further evidence of the increased capacity and improved timeliness afforded by the addition of a grain drill. For each acreage, the duals are greater for the systems using the grain drills under both the moldboard and ridge till systems.

With the moldboard plow, profit is higher for the system with the grain drill for all but the 200 acre case. The change in profit associated with the addition of the drill increases from $554 at 400 acres to $6193 at 1000 acres. The difference in annual machine costs for the two ridge tillage systems is more significant -- $10,679 versus $2197 with the moldboard plow. As acreage is increased from 200, the profit advantage of $8651 of ridge till system 1 over system 2 narrows to $464 at 800 acres. However, system two has

Table 14: Summary of the Capacity Analysis.

Crop Land Available		Moldboard 1	Moldboard 2	Ridge Till 1	Ridge Till 2
200 Acres	Land Dual[a]	$161.99	$170.70	$165.62	$175.76
	Corn Ac.	106.0	100.0	100.0	100.0
	Soybean Ac.	94.0	100.0	100.0	100.0
	Net Revenue	$32,755	$34,140	$33,660	$35,688
	Profit[b]	$10	($802)	$10,302	$1,651
400 Acres	Land Dual[a]	$137.52	$146.36	$133.10	$150.94
	Corn Ac.	200.0	200.0	200.0	200.0
	Soybean Ac.	200.0	200.0	200.0	200.0
	Net Revenue	$61,132	$63,883	$62,857	$67,087
	Profit[b]	$28,387	$28,941	$39,499	$33,050
600 Acres	Land Dual[a]	$119.45	$128.76	$126.36	$137.49
	Corn Ac.	300.0	300.0	300.0	300.0
	Soybean Ac.	300.0	300.0	300.0	300.0
	Net Revenue	$86,522	$91,622	$89,171	$96,202
	Profit[b]	$53,777	$56,680	$65,813	$62,165
800 Acres	Land Dual[a]	$119.32	$128.68	$88.42	$137.46
	Corn Ac.	400.0	400.0	400.0	400.0
	Soybean Ac.	400.0	400.0	400.0	400.0
	Net Revenue	$110,401	$117,370	$113,482	$123,697
	Profit[b]	$77,656	$82,428	$90,124	$89,660
1000 Acres	Land Dual[a]	$114.36	$118.51	$0	$120.79
	Corn Ac.	500.0	500.0	447.3	500.0
	Soybean Ac.	500.0	500.0	419.1	500.0
	Net Revenue	$133,884	$142,274	$119,160	$149,443
	Profit[b]	$101,139	$107,332	$95,802	$115,406
1200 Acres	Land Dual[a]	$0	$104.31	$0	$106.36
	Corn Ac.	669.7	600.0	447.3	600.0
	Soybean Ac.	421.7	600.0	419.1	600.0
	Net Revenue	$140,702	$164,544	$119,160	$172,719
	Profit[b]	$107,957	$129,602	$95,802	$138,682
1400 Acres	Land Dual[a]	$0	$0	$0	$0
	Corn Ac.	669.7	614.2	447.3	625.1
	Soybean Ac.	421.7	614.2	419.1	625.1
	Net Revenue	$140,702	$167,496	$119,160	$177,926
	Profit[b]	$107,957	$132,554	$95,802	$143,889

[a] The dual of the land constraint represents the marginal value of land to the firm measured in expected net revenue.

[b] Expected net revenue less machine ownership costs.

the capacity for up 1250 acres and thus becomes more profitable as the machine costs are spread over more land.

SUMMARY

The choice of a tillage system involves a variety of technical and economic considerations. While much research has been completed, continued research involving experimental trials and economic analysis is needed. Changes in tillage systems involve fundamental changes in the output response to operating inputs, especially herbicides, insecticides and fertilizer. Analyses which focus on the yield response to operating inputs should consider the impacts of tillage techniques and alternative input levels on both average yields as well as yield variability. The fundamental changes in the impacts of "uncontrolled" inputs such as rainfall and temperature which are associated with tillage practices suggest this need to develop probability distributions of yields.

Economic analyses should consider both the private and social costs and benefits of tillage practices. Alternatives to conventional tillage systems reduce soil loss by leaving more crop residue on the soil surface. The long term private and social benefits which result must be estimated. To the extent possible, estimates of the impacts should be comprehensive, including considerations of surface and groundwater pollution as well as soil loss.

Because of changes in the number and type of field operations, the allocation of fixed labor and machine resources to alternative crops is influenced by tillage practices. The linear programming analysis presented in this paper suggested that differences in timeliness and capacity make optimal machine size an important consideration related to the choice of a tillage system. Further work is needed to determine how available field time and field rates are influenced by tillage practices. A related need exists for finding an appropriate measure of field time for use in models which focus on tillage decisions.

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