74-9101

AYRES, George Elwood, 1942-
AN EVALUATION OF MACHINERY SYSTEMS FOR HARVESTING THE TOTAL CORN PLANT.

Iowa State University, Ph.D., 1973
Engineering, agricultural

An evaluation of machinery systems

for harvesting the total corn plant

by

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A Dissertation Submitted to the

Graduate Faculty in Partial Fulfillment of

The Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1973

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INTRODUCTION AND PURPOSE

Beef cows are gaining popularity in the Corn Belt. From 1966 to 1971, beef cow numbers increased 25 percent in Iowa alone (Iowa Crop and Livestock Reporting Service, 1971a) and 1,842,000 head calved during the first 6 months of 1972, a 13 percent increase from a year earlier (Iowa Crop and Livestock Reporting Service, 1972a). Many factors interact to cause an increase of this magnitude, and two of the most important are the growing demand for locally produced feeder cattle and a growing awareness of abundant and under-utilized feed supplies in the Corn Belt.

Midwestern cattle feeders have traditionally purchased many of their feeder calves from western states. Iowa feeders depend on out-of-state sources more than feeders in any other state, importing over 3 million head per year (Hazel, 1971). Transportation costs from western states, shrink, and losses from stress on cattle shipped long distances have always been penalties for the midwestern buyer. But cattle feeding volume in many of the western states is increasing (Iowa Crop and Livestock Reporting Service, 1971b, 1972b), and midwestern buyers have found increased competition from local cattle feeders in those states. This competition has caused the price of feeder calves to rise and the quality of those available to the midwestern feeder to decline. If this trend continues, he must look elsewhere for his purchases.

An abundant supply of forage is essential for cow herds and yearling programs. The southern states have large areas well-suited for grass production, and a large cow-calf industry is developing there (Fichte et al., 1970). That region is expected to become a major supplier of feeder cattle to the Midwest in the future.

The Midwest also has large forage supplies. Iowa has 9.3 million acres of pasture and hay (Iowa Department of Agriculture, 1972). With present levels of production, Wedin (1970) believes Iowa's pasture and hay acres could support 3.2 million beef cows. If these acres were placed under top management, his estimate is much higher. He obtained a 7-year average annual liveweight gain of 334 pounds of beef per acre on pastures containing birdsfoot trefoil (Wedin, 1971), with annual gains of approximately 125 pounds per acre on unimproved pastures (Wedin, 1970). In well-managed tall grass pastures (tall fescue, reed canarygrass, smooth brome, or orchardgrass), he obtained a 4-year average annual liveweight gain of 559 pounds of beef per acre (Wedin, 1971). When the forage from these grasses was harvested rather than grazed, yields of over 4 tons of dry matter per acre were obtained. At these levels of management, Wedin (1970) believes Iowa's pasture and hay acres could support 7 million beef cows.

Wedin's estimate of beef cow carrying capacity for Iowa appears to have been based on two assumptions: (1) complete adoption of new technology, and (2) all pasture and hay acreage would be used for beef production. As the exposure of new technology increases, and as economic incentives for applying it increase, a larger percentage of farmers will begin using it. But complete adoption of new agricultural technology has seldom, if ever, occurred. This author believes 50 percent adoption of new pasture and forage management practices is a realistic prediction for Iowa.

Iowa's current beef cow population is approximately 60 percent of Wedin's estimate of present carrying capacity. Approximately 40 percent of the pasture and hay acreage is apparently used to support Iowa's dairy cattle and sheep. Dairy and sheep numbers are not increasing in Iowa. Therefore, assuming the same increase in carrying capacity for dairy cattle and sheep with improved management practices, and a 50 percent adoption of those practices, only 24 percent of Iowa's pasture and hay acreage will be needed to support them in the future.

As shown in Table 1, these changes in Wedin's estimates lead to an estimated carrying capacity for Iowa's pasture and forage land of 3.8 million head of beef cows. This is only slightly more than twice the present number of beef cows in Iowa, and well below the number required to supply the 4.5 million head of cattle currently being fed in Iowa each year (Iowa Crop and Livestock Reporting Service, 1972b). The Iowa cattle feeding industry will continue to grow, requiring even more feeder cattle by the time Iowa's beef cow population reaches 3.8 million head.

Another large roughage supply available throughout the Corn Belt is the quantity of plant material remaining in the fields after grain harvest. In 1972, Iowa farmers harvested approximately 10.5 million acres of corn for grain, 6.1 million acres of soybeans, and 51,000 acres of grain sorghum (Iowa Crop and Livestock Reporting Service,

Table 1. Estimated beef cow carrying capacity of Iowa pasture and hay land

	Million head	
Potential carrying capacity (Wedin)	7.0	
Present carrying capacity (Wedin)	3.0	3.0
Potential increase from management	4.0	
Adoption of improved management	0.5	
Predicted increase from management	2.0	2.0
		5.0
Fraction of land available for beef cows		0.76
Estimated carrying capacity		3.8

1973), all producing additional plant material that might be utilized for animal feed. In 1912, Professor W. J. Kennedy, head of the Animal Husbandry Department of Iowa State College, estimated the net feeding value of an acre of cornstalks to be $17. He projected this to a loss of over $100 million to Iowa farmers for not utilizing them (The Threshermen's Review, 1912). He concluded:

> But let us suppose that the cattle that have been running in the fields have utilized half of this feed value - and that is doubtful. We still have from $50,000,000 to $60,000,000 as the annual cornstalk waste in Iowa.

Allowing cattle to graze cornstalk fields during the winter is one of the easiest methods of utilizing part of this large supply of roughage. It is particularly effective with beef cows because they can utilize low quality roughages that are not suitable for many other classes of livestock. Gay and Zmolek (1967) point out that two common mistakes in wintering beef cows are furnishing cows high-quality feeds that are too expensive and giving them too much of these feeds. They report that cornstalks, when properly supplemented, can be used efficiently by wintering cows.

Grazing is also compatible with good soil conservation practices. Hayes (1972) concluded:

> Conservation or mulch tillage with large quantities of crop residues left on the surface is one of the key soil conservation practices that reduce wind and water erosion and sediment in our surface waters while at the same time maintaining or improving crop yields.

Leaving stalk fields for winter grazing precludes any form of fall tillage, leaving all crop residue on the soil surface. Weber (1970) concluded that cows will consume less than 20 percent of the dry matter available in a field of cornstalks while grazing during an open winter. The 80+ percent of the plant material remaining in the field until spring should be comparable to many of the mulch tillage systems recommended for use in the Corn Belt.

Grazing does not require an investment in harvesting and feeding equipment or storage structures except for the cost of maintaining fences. Thus, it may be the only method of utilizing cornstalks that the small farmer with only a few cows can afford.

But grazing has several disadvantages for farmers with larger cow herds that have prompted recent interest in other methods of cornstalk utilization. Cows need easy access to a supply of ice-free water which may not be readily available when stalk fields are located away from the farmstead, particularly for farmers who rent land and whose stalk fields may not be in the same location each year. Weber's (1970) estimate of dry matter consumption was made assuming continuous grazing for a 120-day period. In many areas of the Corn Belt, snow cover during the winter will prevent grazing for part of this period, resulting in an even lower dry matter utilization. Finally, reserve feed supplies are required for periods when cornstalks are inaccessible to grazing animals. These reserve feed supplies must come from mechanically harvested cornstalks or from harvested forage crops grown on other land. Few farmers will voluntarily convert land suited for corn production into forage production.

To eliminate the restrictions on the utilization of cornstalks imposed by the weather, and to maximize the feeding value of this large supply of roughage, it appears that some form of mechanical harvesting will be used. Special gathering attachments for forage harvesters, balers, and combines have become available during recent years for harvesting all or part of this forage. Many farmers and researchers have built their own machines. Before any recommendations for their use can be made, many questions must be answered about their performance, the economics of their use, and the nutritional quality of the harvested products. The relationships between cornstalk harvesting, soil organic matter, and soil erosion will also have to be investigated.

The purpose of the research reported in this dissertation was to evaluate several alternative harvesting systems for the corn plant with regard to their feasibility on Corn Belt farms. The author believed that a more thorough study of available harvesting systems should be made before proceeding with the development of new harvesting systems.

REVIEW OF LITERATURE

Harvesting Machinery

The American Indians were the first corn producers, and they harvested only the ears. Early colonists followed the same practice until the importation of livestock caused the rest of the plant to be harvested for feed (Jackson, 1950). Harvesting was done by hand until the first crude machinery began to appear in the last two decades of the 19th century.

> Machinery for the care of the corn crop has been much more difficult to develop than any other line of farm implements. Although there has been considerable progress in methods of harvesting corn, the larger part of the crop is still husked by hand from the standing plant, only the ears being gathered, while the leaves and stalks are almost a total loss. This results in an enormous waste of valuable feed, for it has been demonstrated that when properly harvested corn fodder is as nutritious as good hay, and that the farmer who would receive the full value of his corn crop should secure this fodder with as much care as he gives his hay.

This quotation was the first paragraph of a bulletin written by Zintheo (1907) and, it applies equally well today. Zintheo went on to describe in great detail the historical development of corn harvesting machinery through 1907. Except for the mechanical picker, all early machines were designed to harvest the whole corn plant.

Jackson (1950) credited the full utilization of the corn plant to the silo which was introduced during the last half of the 19th century.

> Before that time farmers had fed some of the stalks as dried fodder from the shock, but much of it had been wasted. By 1890 many of the midwest farmers were coming to realize the feed value of the stover. A series of poor hay crops served to dramatize this.

Sled and platform harvesters, developed during the last two decades of the 19th century, successfully applied horsepower to cut the corn. These harvesters consisted of a platform on which one or two operators stood. The platform was mounted on skids or wheels and had a sharp blade extending out from either one or both sides. As the horse pulled the machine down the row, the corn plants were cut by the blade(s). But the operator(s) still did most of the work, having to catch the cut plants and assemble them into a shock. These machines also worked successfully only when the corn stood straight (Zintheo, 1907). Consequently, the corn binder was generally considered to be the first successful mechanical corn harvester (Jackson, 1950; Tolly, 1918; Zintheo, 1907). The corn binder had a divider on each side of the row to lift lodged stalks, a reciprocating knife to cut the stalks, gathering chains to carry them into the machine, and a twine binder to receive the stalks and bundle them. A bundle carrier was available as an attachment to accumulate a number of bundles for a shock. In later years, a bundle elevator was also made available to elevate the bundles directly to a wagon pulled alongside the binder.

Zintheo (1907) reported that a binder pulled by three horses could cut an average of 7.73 acres of corn per day. Two men were required to follow the machine and assemble the bundles into shocks. The corn binder was rapidly adopted by farmers in all areas of the country who harvested the whole corn plant for either dry fodder or silage.

If the corn was to be stored as silage, the bundles from the binder were immediately gathered and hauled to a stationary ensilage cutter. Woodward et al. (1913) reported that six to ten men, six horses, and three wagons were needed, in addition to the man and three horses operating the binder, to keep a stationary ensilage cutter operating steadily. This included one or two men inside the silo to level and tramp the silage and one man to tend the steam engine if one were used to power the ensilage cutter. A bundle elevator on the binder eliminated the hard work of lifting and loading the bundles, but reduced the harvesting rate of the binder because of stops to allow the hauler to arrange bundles on the wagon and to bring an empty wagon into position.

The binder and stationary ensilage cutter were gradually replaced by the field forage harvester because it required a smaller labor crew. Myers (1934) reported that the average labor crew size on 118 farms with field forage harvesters studied in 1928 and 1929 was 6.8 men, while the average on 47 farms harvesting with a binder was 10.3 men. But the acceptance of the forage harvester was slow on all but large farms because of the investment required (Myers, 1934). Although it was first introduced commercially in 1915 (Jackson, 1950), it continues to be the only widely accepted machine for harvesting the whole corn plant today.

Where dry fodder was desired, the binder was used to harvest the corn and the bundles were gathered and placed in a shock and allowed to dry out in the field. Later, either the ears were husked from the shock by hand and hauled to storage, with the remaining fodder being fed as needed, or the bundles were hauled directly to a stationary husker-shredder. The husker-shredder snapped and husked the ears and either cut or shred the stalk and leaves.

Tolly (1918) reported that three men, one to drive the binder and two to gather and shock the bundles, could harvest 6-7 acres of corn per day, while three men cutting and shocking by hand could harvest 3-4 acres per day. Collier et al. (1928) reported that typical shredding crews consisted of seven to 12 men and eight to 12 horses for loading and hauling fodder, feeding the shredder, and cribbing the corn, depending on the size of the shredder. Husking rates varied from 16 bushels per hour for a 2-roll shredder to 48 bushels per hour for a 10-roll shredder.

Three types of heads were available for husker-shredders. One was equipped with knives similar to those on an ensilage cutter. A second type used whirling blades to shred the stalk and leaves, similar to the hammer mill of today. A third type was a combination of the first two. The shredder head was the preferred type because there were no knives to sharpen, the shredded fodder did not pack so tightly in the mow, and bedding was more absorbent and did not work back in the stall as easily as cut stover (Collier et al., 1928).

The development of the corn picker appears to have been in response to the peculiar needs of farmers in the Corn Belt. Zintheo (1907) wrote:

> In the so-called "corn belt," where corn is the principle crop raised, it has not been possible so far to utilize all the cornstalks. The crop is raised for the ears, which are picked by hand at maturity. To relieve farmers of this somewhat tedious work, for which it is often difficult to get sufficient labor, inventors have been busy for over fifty years trying to build and perfect a machine to pick the corn from the stalks.

Zintheo reports that interest in pickers declined during the first few years after the success of the corn binder, but began again about 1902.

> However, the use of the corn binder and the shocker, while quite extensive, does not solve the corn-harvesting problem in the purely corn-raising regions, where a large share of the corn is still picked by hand from the stalks as they stand in the field.

Corn pickers were introduced commercially around 1902-1904 (Myers, 1933; Shedd and Collins, 1938; Zintheo, 1907), but they were not successful enough for general use until the tractor PTO was used for power (Davidson, 1931; Myers, 1933; Shedd and Collins, 1938). Early machines were ground-driven, and operation was poor in soft or muddy conditions because of the poor traction. The addition of a husking mechanism to these early machines, with its additional power requirement, made operation of the machine even more difficult, and few early machines were equipped with husking mechanisms.

Even after the change to tractor power, adoption of corn pickers was slow on all but large farms. They had higher field losses than hand picking (Davidson, 1931; Louthan, 1933; Paydon, 1941; Shedd and Collins, 1938; Trummel, 1940), and many farmers believed that their corn acreage was not large enough to justify a machine. The depression years of the early 1930's also slowed picker sales (Brodell and Walker, 1953). Corn pickers came into general use, particularly on Corn Belt farms, during and after World War II because of the shortage and high cost of labor (see Table 2).

Table 2. Number of corn pickers on farms and percent of acreage for grain harvested by corn pickers, from Brodell and Walker (1953)

Year	Number of corn pickers on farms	Percent of acreage grown for grain harvested with corn pickers		
		United States	Corn Belt	Iowa
1910	1,000			
1920	10,000			
1930	61,000			
1938	100,000	12.8	28.0	35.0
1943	146,000	27.1	51.1	63.0
1946	236,000	41.1	64.0	76.0
1951	588,000	68.2	88.9	95.0

Thus, three general corn harvesting methods were used during the years prior to 1950. Farmers whose principal enterprise was livestock production harvested the whole corn plant with a corn binder, and later with a forage harvester. They used either a stationary ensilage cutter to process the whole plant for silage, or shocked the bundles for later feeding as dry roughage. Farmers in the Corn Belt, whose principal enterprise was the production of corn for grain to fatten hogs or cattle, did not need the forage from all the corn they grew. They almost universally adopted the practice of harvesting only the ears.

Collier et al. (1928) reported that shredding was quite popular in the eastern Corn Belt in 1927, but was not widely practiced in states west of Indiana. They reported several reasons for the decline in popularity of shredding from earlier years:

1. Much of the acreage formerly shredded was being put in the silo.
2. The increase in acreage of clover, alfalfa, and other legumes reduced the need for other roughage.
3. A steady decline in horse populations reduced the demand for hay, which lessened the value of shredding on farms where hay was formerly sold.

They reported that shredding was most popular on farms where there was a shortage of hay or straw for roughage or bedding. Shredding was practiced where livestock numbers were too small to make a silo practical, on farms with large dairy herds that required much bedding, and on farms where the grain was wanted separately for hog feeding. In areas where corn was cut to allow planting of winter wheat, shredding was practiced to get the corn husked. They also reported that shredding was an excellent practice for control of the corn borer, and predicted that shredding should increase on farms where the whole plant was being fed directly from the shock.

But the practice of shredding continued to decline because of the large labor crew required. Farmers needing large amounts of forage changed to silage. Silage was more palatable to livestock, and the farm equipment industry failed to continue the development of machinery to process dry roughage.

Most Corn Belt farmers were not interested in the forage produced in their corn fields. Neither were many of the prominent agricultural engineers of the day. Davidson and Collins (1928) reported their research with cornstalk harvesting, but their objective was to bale the cornstalks so that they could be more easily transported to a factory. Barger and Collins (1947) discussed the progress of mechanization in the Corn Belt and mentioned only the corn picker and the forage harvester. During their discussion of the losses with a picker, they wrote:

> It is possible that in the future a different style of picker might be developed that would reduce losses. Obviously the cut-off type which takes the stalk up into the machine would permit the saving of most of the shelled corn. Also it is quite possible that the picking operation could process the cornstalks.

A glimmer of hope immediately shattered as they went on:

> This could be an effective means of killing the corn borer and of preparing the stalks so they could be plowed under more easily.

Their idea eventually took form. Keller (1950) described the development of a picker with its own stalk shredder. But the machine was used to shred the stalks for corn borer control and easier tillage, not for feeding.

Reporting again in 1941 about harvesting cornstalks, Davidson (1941) wrote:

> Cornstalks are looked upon as one of the most promising of the various residues which may be used as a raw material for industrial uses... the stalks, together with the grain left in the field, have a pasturage value of $1.00 to $1.50 per acre... Here we have the extraordinary situation of having a great volume of raw material produced regularly, awaiting utilization when a price can be paid that will interest the grower.

Davidson's prediction may yet come true, with the price coming from the sale of feeder calves.

Renewed interest in harvesting cornstalks occurred with the introduction of the Cornbine in 1951 by the Rosenthal Corn Husker Company (Implement and Tractor, 1951). It was a single-row machine which cut the plants, snapped and husked the ears, and shredded the stalks. The shredded material passed over a shaker to remove any grain shelled during snapping and husking, and the grain was collected in a sack. The husked ears were elevated to a wagon trailed directly behind the machine. The shredded material could be blown back on the ground, either for drying and subsequent baling, or for incorporation by later tillage operations. The shredded material could also be collected in a wagon pulled alongside the machine and hauled to a stack for use as feed or bedding.

The J. I. Case Company designed a snapping and husking attachment for their pull-type forage harvester a few years later, marketing a machine which performed the same functions as the Cornbine. Iowa State College acquired one and used it to harvest material for feeding trials for several years. Jacobs (1955) reported the results of wintering trials with heifers and cows fed chopped stalks from this machine that were ensiled in a trench silo. He reported that the grain contained 32.3 percent moisture at the time of harvesting, and that the yield was 94.02 bushels of 14 percent moisture corn per acre. The yield of chopped cornstalks was 6.42 tons per acre at a moisture content of 66 percent. The protein content of the chopped stalks was 7.21 percent on a dry matter basis.

Even though these machines operated satisfactorily in the field, they were not accepted by many farmers. The major sales area was limited to northern Illinois and southern Wisconsin.[1] Several reasons for their commercial failure have been suggested. They were expensive, and shredded cornstalks were not very valuable in comparison to other forage crops that were readily available. The Cornbine cost approximately $2000, about 80 percent more than a one-row corn-picker which it would replace.[2] Tractor power was limited and the field capacity with these machines was low, even for those days. High moisture ear corn drying was not widely practiced, so operation of the machine was usually delayed until the grain reached a lower moisture content suitable for storage in cribs. The shredded forage was then too dry to ensile and dangerously wet for stacking, causing farmers to worry about spoilage.[2] Beef cow herds in existence at that time were being fed successfully on hay and pasture, and there was little economic

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[1] Norton, Robert A. 1971. Agricultural Engineering Department, Iowa State University, Ames, Iowa. Field observations of the Cornbine. Private communication.

[2] Rosenthal, Henry L. 1972. Oconomowoc, Wisconsin. The development of the Cornbine. Private communication.

pressure to expand the size of beef cow herds in the Corn Belt. Since most farmers could use the forage from only a portion of their crop, these machines had to compete with the machines and labor required for the regular corn harvest. These machines also appeared to have been introduced simply as a machine for performing one operation with little thought having been given to the overall management and production program of the farmers who could use them.[3] The author believes that these machines were introduced 20 years too soon, and that both might be successful if they were available today in two- or four-row sizes.

The introduction of flail-type forage harvesters allowed farmers to use their silage equipment to harvest cornstalks. The grain was harvested with either a picker or combine. After grain harvesting was completed, the cornstalks were collected by a separate harvesting operation with a flail harvester. This had the advantages of permitting the farmer to harvest only the desired quantity of chopped cornstalks, and of spreading the work load so cornstalk harvesting did not compete for labor with grain harvesting. However, the quality of the feed was low. The snapping rolls on the picker or combine broke and crushed the stalks so that they dried out rapidly and left them close to the ground. This made harvesting difficult, and much of the material, particularly the cobs and grain left

[3]Lien, Ray M. 1971. Agricultural Engineering Department, Purdue University, Lafayette, Indiana. Innovations in harvesting equipment and results. Private communication.

by the combine, could not be picked up without gathering soil. The coarse product produced by the flail harvester made subsequent handling and feeding difficult. Even with these disadvantages, many farmers continue to use flail harvesters to obtain part of their roughage from their corn crop because it allows them to use equipment they have available.

Researchers at the University of Illinois began harvesting cornstalks and feeding them to dry pregnant beef cows in 1963 (Albert and Stephens, 1969). A flail-type forage harvester and forage harvesters with either a row-crop gathering unit or a windrow-pickup were used in the early tests. They soon concluded that a machine which harvested both stalks and grain in one operation would be desirable.

Such a machine was built using a combine as t. base unit. A cut-off type two-row corn head was mounted on the front of the combine, and the cutterhead and feed table from a forage harvester were mounted under the rear discharge hood of the combine by extending the combine frame. The whole corn plant was cut and conveyed through the combine, where the grain was separated and elevated to the combine tank. The rest of the plant was discharged into the cutterhead and blown into a trailing wagon. The cutterhead was driven from the combine beater shaft.

The machine was used successfully for several years to harvest forage for feeding trials. The forage was stored in both concrete and gastight upright silos and in a stack on the ground covered with plastic and vacuum sealed. The machine operated successfully at field speeds of 2 to 2.5 miles per hour, and harvesting costs were estimated to be $4.96 per ton of feed for a 70-cow herd.

Several disadvantages of this machine are apparent today. The choice of a combine as the basic harvesting unit precludes its use by farmers with a small acreage of corn who could profitably use the forage from part of their crop for a cow herd. Many of these farmers hire a custom operator to harvest their corn because they cannot afford a combine, and the addition of almost a complete forage harvester (except for the wheels) would make the machine even more expensive. The harvesting capacity of the machine was also reduced because of the large volume of plant material passing through the combine. To avoid overloading the separating portion of the machine, a two-row cut-off head was used on a combine designed for a four-row snapping head. This reduced capacity would be undesirable on larger farms that could afford the machine because harvesting would compete with regular grain harvesting for time.

Researchers at Purdue University also began feeding harvested stalklage to beef cows in the mid-1960's.[4] They developed a harvesting system using equipment already available on many farms. After harvesting the grain, a flail-type mower-conditioner was used to cut and windrow the cornstalks. A conventional forage harvester equipped with a windrow-pickup attachment was used to harvest the

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[4]Lien, Ray M. 1971. Agricultural Engineering Department, Purdue University, Lafayette, Indiana. Innovations in harvesting equipment and results. Private communication.

windrowed stalks in a second operation, and the chopped forage was stored in an upright silo. Harvested yields of stalklage were approximately 2.75 tons of dry matter per acre, and harvesting and storage costs were estimated to be $4.15 per ton of feed.

This harvesting system had the same advantages mentioned earlier for the flail-type forage harvester; harvesting did not compete with grain harvest, no new equipment was required, and only the quantity of stalklage needed was harvested. A major disadvantage of this system was the risk of inclement weather and snow, particularly if grain harvesting was delayed. In 1967, harvesting could not be done at all because grain harvesting was not completed until January. The cobs and grain left by the combine were also lost during the windrowing and harvesting operations, resulting in only partial recovery of the lower quality fractions of available forage.

After their earlier work with a Case combine and several years of harvesting cornstalks with a flail harvester, Iowa State University researchers began the development of a new harvesting machine in 1965. Ferlemann (1966) attached a two-row cornhead and the cutterhead from a forage harvester to the front of a combine. A pair of stripper bars was added to each row of the cornhead above the original gathering belts to remove the ears as the corn plants were pulled between them by the feed rolls of the forage harvester. Gathering chains were attached above the stripper bars and extended back to the combine cylinder to convey the snapped ears into the combine for shelling. The chopped stalks were blown into a wagon pulled alongside the combine and the husks and cobs discharged from the rear of the combine were dropped on the ground.

Functional performance of the machine was unsatisfactory during field tests. The gathering chains did not allow the tops of the plants to lean forward far enough to permit the gathering belts to convey the butt ends of the stalks to the feed rolls. As a consequence, ear removal was unsatisfactory and frequent plugging occurred. The long flights on the gathering chains had a high angular velocity around the idler sprockets at the lower end of the stripper bars. Since the flights contacted the plants at this point, stalks were often dislodged from the lower gathering belt or broken, causing them to remain between the stripper bars until plugging occurred.

Schroeder (1968b) designed a new gathering head for the machine during 1967. Hydraulically driven snapping rolls and new stripper bars were added to one row of Ferlemann's original cornhead. Since the original combine engine was being used, power to operate the forage harvester attachment was limiting, and it was thought that a single row unit would be adequate to test the new design. The ear conveyor was redesigned to reduce the angular velocity of the flight tips and to allow other standard gathering units to be used on the forage harvester attachment. An auger was attached under the rear hood of the combine to collect the cobs and husks and convey them forward to the forage harvester attachment.

Field capacity of the machine, called Beefmaker I, was low because of the one-row head and the limited power available from the combine engine. But functional performance of the new gathering unit was satisfactory, and 75 tons of corn plant silage were harvested during the fall of 1967 and stored for winter feeding trials. Replicated tests were conducted in corn at 17-19 percent moisture content late in the season to measure field losses. Average total harvesting loss was 8.63 bushels per acre; 7.54 bushels per acre of missed ears, and 1.08 bushels per acre of shelled corn. These high losses were considered unsatisfactory and would need to be reduced for an acceptable design.

Beefmaker I was a complete all-crop harvester for the Corn Belt farmer. All standard combine and forage harvester heads could be used with the machine. A grain platform could be used for small grains and soybeans and a conventional cornhead for harvesting corn for grain. With the forage harvester attachment, a direct-cut or windrow pickup head could be used for forage crops and a row-crop head for corn silage. Schroeder's modified cornhead could be used to harvest grain and corn plant silage simultaneously.

Thus, Beefmaker I was both a combine and a self-propelled forage harvester with a common engine and traction system. In theory at least, such a machine should be attractive to the farmer who needs a wide variety of harvesting options. The initial cost of the machine should be lower than the combined cost of a self-propelled forage harvester and a combine. Maintenance costs of one engine and traction unit should also be lower than on two units. But farmers seem to be reluctant to purchase machines of this type. Multiple use machines have been on the market for two decades and have met with only limited success. For whatever reasons, farmers seem to prefer separate machines without the necessity of having to change attachments when going from one crop to another.

Beefmaker I also had the disadvantages of high cost and labor requirements discussed previously for the Illinois machine. But the whole plant did not pass through the combine as it did with the Illinois machine, so the original harvesting capacity of the combine could be maintained if a larger engine were used to furnish the additional power for the forage harvester attachment. It was also a more versatile machine, since it could be used as a self-propelled forage harvester as well as a combine.

With the objective of reducing the initial cost of the machine, Hitzhusen (1969) designed and built a snapping attachment for a pull-type forage harvester. The snapping attachment was mounted between the feed rolls and the row-crop gathering head. A cage-type sheller was mounted above the snapping attachment, and conveying equipment was added to transport the snapped ears to the sheller and the shelled corn to a trailing wagon. The cobs discharged from the sheller were dropped into the path of the stalks behind the snapping rolls. The chopped forage was blown into a wagon pulled alongside the machine.

Field performance of the machine, called Beefmaker II, was satisfactory. It was operated at field speeds of 2-2.5 miles per hour and total harvesting losses were 3.2 bushels per acre. Another

4.8 bushels of corn, shelled by the snapping rolls, passed through the cutterhead into the cornstalk silage. However, it was not completed early enough in the season to be used for harvesting material for feeding trials.

During 1967 and 1968, Gustafson (1969) designed and built a gathering unit for a combine to harvest broadcast corn. It consisted of a standard grain platform with several modifications. A larger reel was added, and a chain conveyor was mounted above the standard platform to convey the cut plants to two horizontal snapping rolls extending across the back of the platform. The snapping rolls discharged the stalks into a large auger which conveyed them to one side and dropped them in a windrow on the ground.

Gustafson's machine was used to windrow approximately 120 tons of cornstalks in 1968. An auger was attached below the rear discharge hood of the combine to collect the cobs and husks and convey them to the windrow of stalks, and the windrows were harvested with a forage harvester. Although the machine successfully harvested corn of any row width, its use in combination with a forage harvester was not satisfactory for harvesting cornstalks. The cobs and grain sifted down through the windrow and were not picked up by the forage harvester. Dirt pickup by the forage harvester also caused a substantial increase in maintenance of the cutterhead.

The concept of harvesting the entire corn plant appears to be well-accepted in eastern European countries and in Russia. Many machines of differing design are available there to harvest the grain and forage simultaneously. Some are similar in design to Gustafson's cornhead, using a modified grain platform and reel and a pair of horizontal snapping rolls.[5] Others are pull-type units with vertical snapping rolls and individual cutterheads for each row (Hitzhusen, 1969).

Following the limited acceptance of flail-type forage harvesters during the last two decades for harvesting cornstalks, several baler manufacturers introduced flail-type pickup units for balers (Jones, 1970a; Ritchie, 1969; Zimmerman, 1968). These were primarily used by farmers to bale cornstalks for use as bedding for livestock. The higher density of the bales required that the stalks be allowed to dry before baling in order to prevent mold development in storage. The generally cold wet weather late in the season in the Corn Belt makes drying difficult, and the use of these machines has been very limited.

At least one company developed a flail pickup for a conventional forage harvester (Jones, 1970a; Yaw, 1969; Zimmerman, 1969). Since the cornstalks were chopped with a cutterhead fitted with a recutting screen, the fine-cut silage should store and handle better than the material produced by a flail-type forage harvester. However, only part of the plant material can be recovered without picking up dirt,

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[5]Buchele, Wesley F. 1972. Agricultural Engineering Department, Iowa State University, Ames, Iowa. Observations of corn harvesting machinery in eastern Europe and the USSR. Private communication.

and harvesting must immediately follow the combine or picker before the stalks dry out.

For several years, western wheat growers used machines developed by several shortline companies to harvest the chaff and straw from a combine (Deering, 1967; Jones, 1969, 1970a; Zimmerman, 1968). These machines generally consisted of an attachment for the combine to collect the material discharged by the rack and lower sieves and convey it to a trailer pulled behind the machine. When the trailer was filled, the operator of the combine dumped it in the field and continued harvesting. The piles of forage were either picked up later in the season and hauled to a feedlot, or left in the field for grazing animals during the winter. In recent years, these machines have been used by a few farmers in the Corn Belt behind corn combines. Although harvesting is done concurrently with grain harvest, competition for labor is minimal because the forage dumps can be left in the field until the completion of grain harvest.

Animal Performance

Jacobs (1955) included a thorough review of research up to 1955 on the feeding management of beef cows, calves, and yearlings in the Corn Belt. Results of significance to this study will be reported from his review.

An economic study of beef cow breeding herds in southern Iowa during 1932-33 found that the herds with the lowest feed cost per cow were fed the most low quality roughage, like corn stover and straw.

The low cost herds also had higher average calf weaning weights. The high cost herds were fed more corn silage and grain.

Many researchers concluded that cornstalk silage was better feed than either shredded or whole, dry cornstalks. The chopping and ensiling processes broke and softened the stalks, making them more palatable. Waste in the feed bunk was lower and consumption was higher.

Early wintering trials with beef cows by researchers in several states consistently resulted in reduced costs when low quality roughages, such as cornstalks, straw, and prairie hay, were used for a major portion of the ration. Researchers in Utah reported that cows wintered on alfalfa hay fed ad libitum had an average daily gain of 1.58 pounds, but an average weight loss of 16 pounds after 45 days on spring pasture. Similar cows fed 10 pounds of alfalfa hay per day and barley straw ad libitum during the winter, gained only 0.45 pounds per day but had a weight gain of 28 pounds after 45 days on pastures, indicating that cows in better condition at the beginning of the pasture season lose some of the advantage of their larger winter gains.

Researchers in Montana came to a similar conclusion in 1933 after 11 years of research with beef cows. They also concluded that (1) cows will raise calves and gain in weight during the summer with good grass, (2) winter gain or loss in weight should be only enough to maintain cow weight and strength from year to year, (3) gains on grass are cheaper than gains in the feedlot, and (4) there was no significant relationship between winter gains of beef breeding cows and calf weights at birth or at weaning.

Iowa researchers conducted several trials during the early 1950's in which cornstalk silage, chopped cornstalks, or corncobs were fed to yearling steers as an important part of their wintering ration. They concluded that these roughages were satisfactory when properly supplemented, and that early feeding of these low cost roughages followed by finishing on grain would reduce the costs of gains. In several trials, cornstalk silage and either hay or grass silage together produced cheaper gains than grass silage fed alone. In one trial, they reported that cattle fed cornstalks and corncobs produced approximately 50 percent more beef per harvested acre than similar cattle fed ground shelled corn. Similar results had been reported earlier by other researchers for corn silage compared with grain feeding.

Jacobs' own research involved wintering 400-pound heifer calves and dry, pregnant cows with cornstalk silage as the primary ration. The cornstalk silage was harvested with a Case forage harvester equipped with the single-row snapping attachment described earlier. The silage was harvested in September 1954 and stored in a trench silo. The ear corn from the machine was shelled and the cobs were chopped and added to the cornstalk silage in the trench. Preservatives were mixed with the upper one-fourth of the silage in the trench, and the silage was sprinkled with water daily for two weeks after filling.

Jacobs concluded that total wintering costs for the heifers were low relative to costs with other higher quality roughages available, and that gains and condition of the heifers were satisfactory for heifers to be added to a breeding herd for calving at approximately two years of age. The mature cows maintained their weight and condition throughout the experiment, and Jacobs concluded that corn-stalk silage supplemented with a small amount of hay and corn-mineral mix was satisfactory wintering ration.

Weber (1970) reviewed more recent research on wintering beef cows. Many of the experiments he reviewed were concerned with reproductive performance and the influence of energy levels on the length of the breeding season. He reported that researchers at Illinois, using the harvesting systems described earlier, concluded than an acre of corn produced enough roughage to winter two cows for approximately 120 days, and that harvested stalklage was a satisfactory maintenance ration when supplemented with protein. They found that adding the protein during the ensiling operation increased consumption and improved digestibility of the stalklage, and that rechopping of the forage for individual feeding also increased consumption. They also reported a feeding trial with material from one of the combine attachments with a trailing dump wagon. In comparison with cornstalk silage and regular corn silage, the forage from the combine produced an average daily gain of 0.73 pounds when fed at a rate of 30 pounds per day to bred heifers, and the two silages produced average daily gains of 0.11 and 1.24 pounds, respectively.

From 1961 to 1967, Iowa researchers conducted several fall and winter grazing studies with beef cows on solid seeded corn, sudan grass, hybrid forage sorghums, and sudan grass-forage sorghum crosses. With all but the corn, a crop was stacked during the summer and the regrowth was grazed during the fall and winter. The stacked forage was fed during the winter. All the forages were satisfactory when supplemented with protein (Hunsley et al., 1964; Vetter et al., 1965). The solid seeded corn supplied an excess of energy and the cows tended to become overfat. Forage stacking increased the carrying capacity per acre, but did not always reduce feed costs because of the costs of harvesting and stacking.

Beginning in 1964, Iowa researchers began a series of winter grazing experiments with beef cows (Hunsley et al., 1966b, 1967b). These early grazing studies were quite successful because of the relatively mild winters without snowcover, and will be discussed later in more detail.

During the winter of 1967-68, the cornstalk silage harvested with the Beefmaker I was fed to pregnant mature cows and compared with regular corn silage and cornstalks (Vetter and Buchele, 1968). The cows did not maintain their body weight until a protein supplement was added, and the coarse cut from Beefmaker I was thought to have limited consumption. Estimated feed cost per cow, however, was lower than the corn silage.

During 1968-69, cornstalk silage harvested from the windrowed cornstalks produced by Gustafson's combine with the gathering unit for broadcast corn was fed with five different rations providing different levels of protein and energy (Gay et al., 1969). As mentioned earlier, this harvesting system was considered only partially satisfactory because of the almost complete loss of cobs and grain when the windrows were harvested. The ration containing protein supplementation was considered satisfactory, even though all cows lost weight. But the two rations containing only shelled corn, vitamins, and minerals were not satisfactory, and weight losses of the cows were too great for good performance. The mature cows performed better than first and second calf heifers, and were better able to utilize the low quality cornstalk silage than the younger animals.

Evaluating Machine Performance

Agricultural machinery management is the art and science of managing men and equipment to achieve some optimum level of agricultural production within a set of constraints for land, labor, and capital. It requires a knowledge of the agricultural sciences, statistics, and economics to quantify the relationships between agricultural production practices and the men and machines required to perform them. It requires the application of modern engineering design techniques to parlay this information into machines and machinery systems capable of performing at this level of production. Finally, it requires the application of proper management techniques to achieve this level of production.

The traditional problem in agricultural machinery management, selecting the proper machine for a given situation, was described by Seferovich (1962) as consisting of the following three steps:

1. Machinery selection of either a new machine or of a replacement machine.
2. Field application of the machine according to its design specifications and the requirements of the job being performed.
3. Integration of the machine with existing units to achieve the best overall performance from the total machinery system.

The engineer has the responsibility of providing the appropriate design specifications for a particular machine, and of communicating these specifications and an evaluation of machine performance to the farmer. The farmer has the responsibility of selecting the proper machine and of applying the proper management so that the potential performance level of the machine is achieved. Together, the engineer and the farmer begin with existing production practices and design a machinery system to optimize some previously selected measure of effectiveness. Techniques for accomplishing this design are well-documented in the literature and in textbooks on agricultural machinery management.

A second, and less well-defined, problem in agricultural machinery management is the design of future machinery systems. This is the problem faced by the engineer in agricultural production research. He must recognize the economic and ecological problems resulting from present production practices, and anticipate or propose changes in production practices and the likelihood of their occurrence. He then develops the specifications for a new system of machinery to implement these practices. These specifications are used to evaluate the feasibility of the proposed system, as design parameters for the new machines required, and as constraints on the adoption of the new production practices. Often these initial design specifications serve as reference points for further research with the new practices or machines.

An essential part of the design of a machinery system is a quantitative description of the performance of each component machine and of the whole machinery system. Barnes (1960) described four types of performance that must be evaluated:

1. Functional performance - how well does the machine perform its intended task.
2. Mechanical performance - how reliable is the machine and how effectively is energy utilized.
3. Capacitive performance - will the machine complete the job within allowable constraints of time.
4. Economic performance - will the machine operate at a profit.

Barnes points out that the values of these performance criteria that are achieved by a particular man-machine combination are affected by both the engineer and the farmer. The engineer provides a potential level of performance in his design specifications, but the actual performance depends of the farmer's ability to select the proper machine, adjust it according to the conditions encountered, and provide the proper maintenance and operating policies for reliable use.

Functional performance of agricultural machines can be evaluated both qualitatively and quantitatively. The fluffiness of a windrow made by a mower-conditioner or the looseness of the soil following a rotary hoe are qualitative measures of performance. A farmer might evaluate a chisel plow by comparing the appearance of the field in which it operated to his standard for acceptable tillage based on his experience. An engineer, on the other hand, might evaluate the same chisel plow by measuring the depth of tillage performed, the size of soil particles or the percentage of crop residue left on the surface, or the quantity of soil eroded from the field (Hayes, 1972). The functional performance of a combine has been evaluated by measuring the quantity of grain left in the field, the quantity of foreign material in the harvested grain, and the mechanical damage inflicted on the grain by the machine (Ayres et al., 1972).

Mechanical performance of a machine may be evaluated by observing the number and frequency of breakdowns and assigning a probability of failure, or by subtracting the probability of failure from one to determine its reliability. (Farmers seem to prefer probability of failure; engineers prefer reliability.) By observing both frequency of failure and duration of downtime, mathematical models may be used to describe a machine's reliability (Frisby and Benedetti, 1971; Gruben, 1963; Olberts et al., 1970; Von Bargen, 1970b).

Economic performance is directly related to the performance levels achieved for the other three criteria. It also depends on the direct costs required to obtain control of the machine, and on any economic penalties incurred for untimely operations (Hunt, 1963). Control of a machine may be acquired through purchase, rental, lease, or custom hire, each with its own combination of costs. These costs may be compared with similar costs for alternative machines to estimate the overall profitability of the machine. True economic performance for purchased machines, however, cannot be measured until they reach the end of their service lives and are salvaged.

The capacitive performance of agricultural machines has usually been evaluated in terms of field area covered per unit of time. This capacity measure, termed effective field capacity, was developed by McKibben (1930), and can be evaluated with the following equation:

$$C = (TC)e = \frac{SWe}{8.25} \qquad (1)$$

where C = effective field capacity, acres per hour

TC = theoretical field capacity, acres per hour

e = field efficiency, decimal

S = field speed, miles per hour

W = machine width, feet

In this equation, field efficiency is the ratio of effective field capacity to theoretical field capacity, and includes the effects of time lost in the field and failure to utilize the full width of the machine. Representative field efficiencies for many machines have been tabulated for easy reference (American Society of Agricultural

Engineers, 1972; Hunt, 1973).

Time lost during field operations results from many causes. Time for turning and travel across headlands is related to field geometry. McKibben (1930) developed a relationship between idle travel time and the dimensions of a rectangular field when operating back and forth parallel to one boundary. Hunt (1973) developed equations relating field efficiency to field dimensions for several common operational patterns. Bainer et al. (1955) point out that turning, idle travel, and machine adjustment time tend to be proportional to operating time, while other delays, such as stopping to fill seed and fertilizer boxes, interruptions caused by poor field or crop conditions, and stopping to unload harvested crops tend to be proportional to area. They developed the following expression for field efficiency:

$$e = \frac{100(TO)}{TE + TA + TH} \tag{2}$$

where e = field efficiency, decimal

TO = theoretical operating time

TE = effective operating time = TO/k

k = fraction of machine width utilized, decimal

TA = time lost proportional to area

TH = time lost proportional to TO

Barnes et al. (1959) showed that this equation could be used to predict field efficiencies of large corn planters and cultivators if the field efficiencies of smaller machines were known.

Renoll (1969, 1970a, 1970b) defined a field machine index to describe the relationship between field geometry and capacitive performance of machinery. The field machine index was the ratio of productive field time to productive plus turn time, as expressed in the following equation:

$$FMI = \frac{(T - TU - TT)100}{T - TU} \quad (3)$$

where FMI = field machine, index, percent

T = total field time

TU = unproductive field time not including turning time

TT = turning time

Renoll showed that the specific machine operation had very little influence on the magnitude of the index. If a field had a high field machine index for one machine, it would have high index values for other machines as well. By measuring values of field machine index for all fields with a common machine, a manager could predict field capacities for other machines without conducting tests with each machine.

As the number of concurrent functions being performed by agricultural machines and machinery systems increased, more detailed descriptions of the causes of poor capacitive performance were needed. An operations analysis has become a valuable tool for evaluating the performance of modern machinery systems.

Von Bargen and Cunney (1972) define an operations analysis of agricultural machinery systems as follows:

> An operations analysis is an evaluation of the effects of the many activities performed by man-machine combinations in carrying out field operations. The objective of this analysis is a reliable prediction of the performance of a machine in a specific situation.

Renoll (1970c) states that an operations analysis involves three basic parts. The first is to obtain accurate time records of all activities relating to a specific machine operation in the field. The second is to divide these records into primary function time and support function times. The last is to study the records in detail for activities with excessive times.

Barnes et al. (1959) made an operations analysis of corn planting and cultivating machinery. Marley (1960) conducted an operations analysis of all field activities for one year on a farm in northwest Iowa. Frisby (1963) made an operations analysis of a large corn harvesting and drying system and concluded that such a study was the only way in which the importance of the many small delays could be ascertained.

Von Bargen (1966, 1967, 1968) conducted an extensive operations analysis of hay harvesting systems in Nebraska. He proposed that the classification of activities for agricultural field machines be standardized in a manner similar to the ASME classification for processing and materials-handling evaluation. His division of activities for agricultural machines is shown in Table 3 and Figure 1. In an operations analysis, times for each support function would be measured separately and delay activity would be subdivided into its components to ascertain where corrective action was needed.

Table 3. Activity classification for agricultural field machines

Activity	Description
Operate:	Machine performs its primary function or a necessary support function: (a) Primary function - windrowing, baling, loading, transport, etc. (b) Support function - required but nonproductive jobs. Turning, filling a hopper, adding baling wire, etc.
Delay:	Undesirable interruption of operating activity, including minor field repairs.
Travel:	Movement of the machine while not operating.
Service:	Machine is being attended. Major repairs, lubrication, refueling, preventative maintenance, etc.
Idle:	Not classified in a category above: (a) Operable (b) Awaiting repair parts

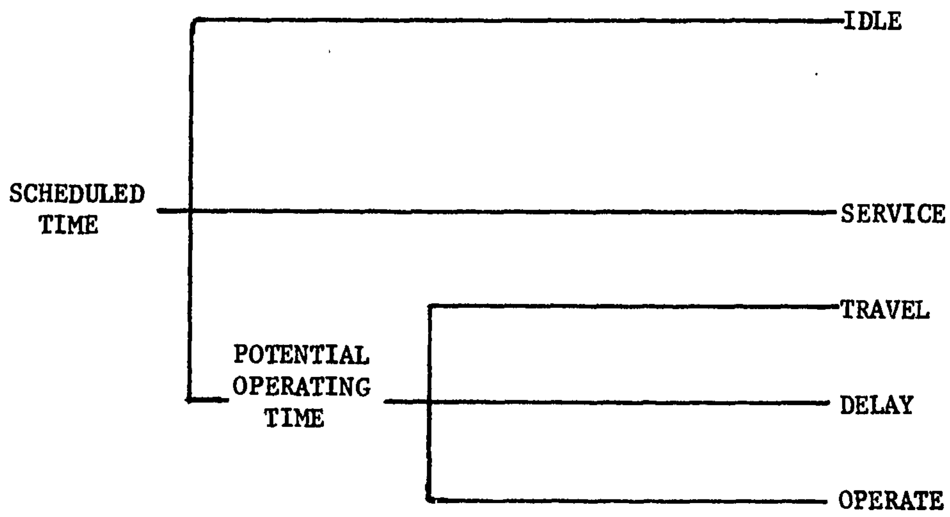


Figure 1. Activity division for agricultural field machines

Von Bargen (1967, 1968) defined man-machine activity, or functional activity, as the ratio of the operate activity time to potential operating time, expressed as a percent. Man-machine activity is a random variable, and Von Bargen used cumulative frequency curves to define activities. He found that the man-machine activity distribution for a self-propelled windrower was normal for a poor operator, and was skewed to the left for a good operator. He also concluded that good activity performance should exceed 65 percent. In a later study, Von Bargen (1970a) used the same division of activities in an operations analysis of large corn planting machinery in Indiana.

Von Bargen and Cunney (1972) concluded that the foregoing procedures were inadequate to determine the effects of small changes in specific activities during operations analysis. They developed the following activity ratios to relate specific activity times to total field time and capacitive performance.

$$e = \frac{TP}{TP + TI} \tag{4}$$

where e = field efficiency, decimal

TP = primary activity time

TI = sum of Ti, i = 1,...,n

Ti = ith activity time

Dividing by TP,

$$e = \frac{1}{1 + RI} = \frac{1}{R} \tag{5}$$

where RI = sum of Ri, i = 1,..., n activities

Ri = ith activity ratio = Ti/TP

$R = 1 + RI$ = composite activity ratio

Therefore,

$$C = \frac{SW}{8.25R} \tag{6}$$

where C = effective field capacity, acres per hour

S = field speed, miles per hour

W = machine width, feet

To include nonfield activities, the composite system activity ratio, R, was defined as

$$R = 1 + RI + RJ \tag{7}$$

where RI = sum of Ri, $i = 1, \ldots, n$ field activities

RJ = sum of Rj, $j = 1, \ldots, m$ nonfield activities

Activity ratios were also defined for the additional time caused by failure to utilize the full width of the machine, and for the random component of primary activity time resulting from random fluctuations in field speed caused by uneven engine loading and tractive conditions.

Operations Research and Systems Analysis

The techniques discussed in the last section belong to a broad family of mathematical techniques used to study the behavior of systems. Bonder (1967) offered the following definitions for distinguishing between two important classes of systems studies:

1. Operations research - an analysis to increase the efficiency of existing man-machine systems.
2. Systems analysis - a systematic approach to the comparison of alternative systems for carrying out some specified task

or tasks. If differences in cost are considered, it is referred to as "cost-effectiveness" analysis.

Hillier and Lieberman (1967) summarize an operations research study in the following six steps:

1. Formulating the problem.
2. Constructing a mathematical model to represent the system under study.
3. Deriving a solution from the model.
4. Testing the model and the solution derived from it.
5. Establishing controls over the solution.
6. Putting the solution to work: implementation.

They also discuss several advantages of using mathematical models to study the performance of a system. A mathematical model describes a problem concisely, tending to make the over-all structure of the problem more comprehensible and revealing important cause-and-effect relationships. It allows a consideration of all interrelationships simultaneously, and forms a bridge to the use of high-powered mathematical techniques and computers. On the other hand, mathematical models are necessarily abstract idealizations of real problems, requiring approximations and simplifying assumptions. The researcher must take care to insure that the model remains a valid representation of the problem. Hillier and Lieberman state that it is not necessary that the absolute magnitude of the measures of effectiveness be approximately correct for various alternatives as long as their relative values are sufficiently precise. All that is required is a high correlation between the model prediction and what would actually happen in the real world.

After constructing a mathematical model for an operations research or systems analysis study, a mathematical technique must be selected to derive a solution. Reeser (1972) classified these techniques as shown in Table 4. He also classified them as being either algorithmic, of which linear programming is an example, or heuristic, examples being the various simulation techniques.

Table 4. Classification of mathematical techniques

State of nature	Form of technique	Specific techniques
Relative certainty	Deterministic	Linear programming Break-even analysis Equipment replacement analysis
Known risk	Objective probabilistic	Queing theory CPM, PERT Simulation
Relative uncertainty	Subjective probabilistic	Decision theory Game theory Bayesian statistics

Simulation

Rockwell (1967) stated that "to simulate means to duplicate the essence of a system without actually attaining reality." Link and Splinter (1970) stated, "One simulates the behavior of the prototype by manipulating the model, observing its behavior, and thus predicting the behavior of the prototype."

Simulation is useful for many reasons. Analytic formulation of many complex systems is unmanageable. Experimentation with some prototype systems is impossible or very costly. Simulation experiments may provide sufficient indication of how the variables in these systems interact so that analytic formulation can be developed. Time scales, non-linearities, irregular distributions, and discontinuities can be designed into simulation models. Random values for probabilistic inputs can be generated. Since simulation is basically a descriptive process, it forces the researcher to explicitly describe the system processes and required data, often leading to a more complete understanding of the system.

A methodology for implementing simulation experiments is illustrated in Figure 2. It was modified slightly from the diagram in Nieswand and Mears (1971). They point out that the decision to proceed with mathematical modeling should be made only after the problem has been completely defined. Furthermore, simulation should be selected only after initial modeling and evaluation of other techniques available for problem solution. Simulation experiments should be designed with the same statistical considerations that would be needed for experiments with the real system. Special simulation languages should also be considered when developing computer models (Huang, 1970; Lambert, 1971; Nieswand and Mears, 1971; Sanders and Lalor, 1971). These special languages allow the researcher to concentrate on the system rather than on mathematical manipulation and programming.

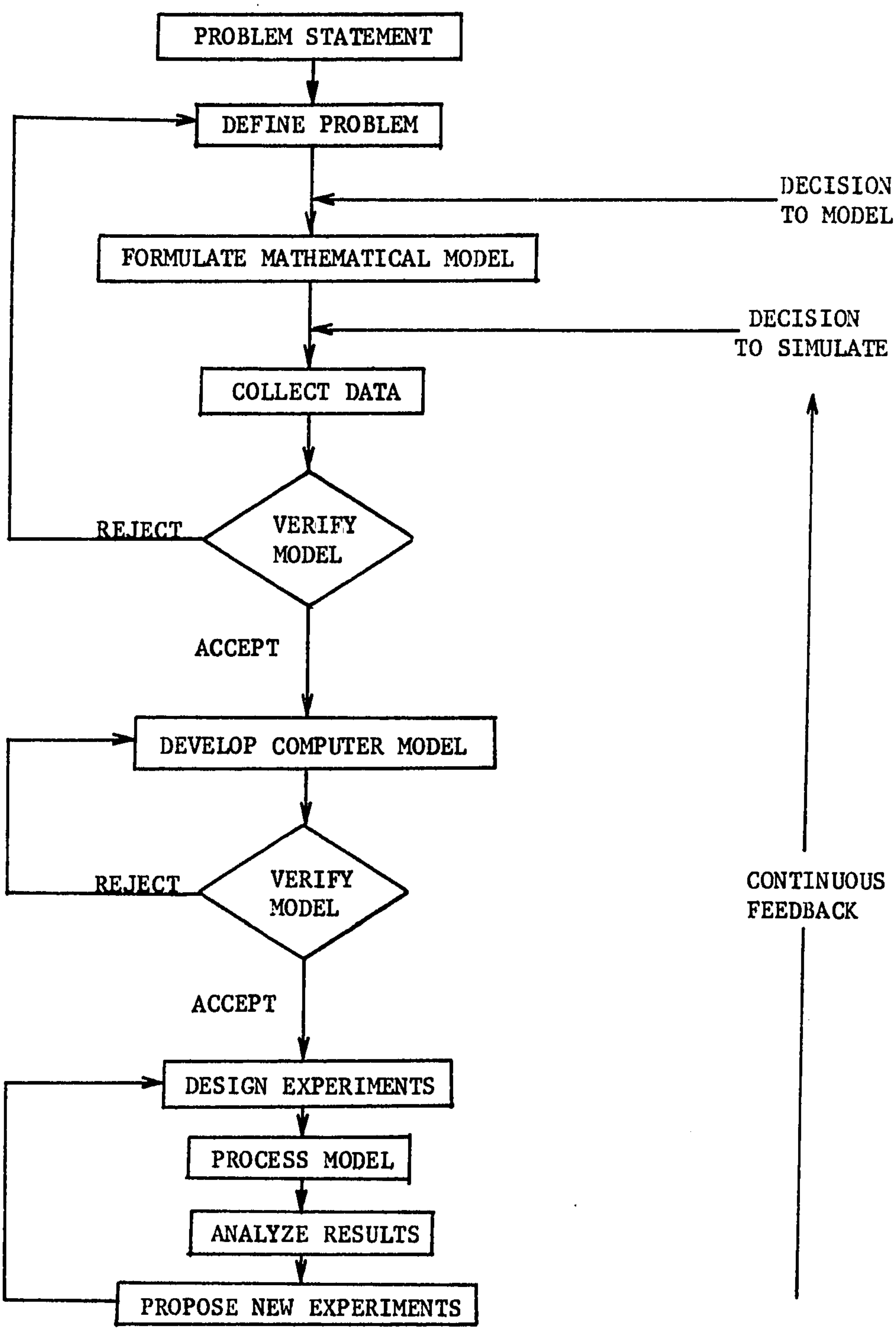


Figure 2. Methodology for implementing simulation experiments

TERMINOLOGY

Many of the companies that have introduced equipment for harvesting all or part of the corn plant, and many of the farmers who have developed their own harvesting systems, have coined new terms for the products harvested. In order to avoid confusion over product names, and to prevent having to describe the products each time they are mentioned, the following definitions will be used throughout the remainder of this dissertation:

1. Corn refuse: the forage produced by harvesting the whole corn plant and removing the shelled grain.
2. Cornstalks: the corn plant material left in the field by a combine or corn picker.
3. Corn stalklage: the forage produced by harvesting cornstalks.
4. Corn husklage: the forage produced by collecting the material discharged from the rear of a combine harvesting shelled corn. A special combine attachment is required to collect the husklage before it is dropped on the ground.

HARVESTING STUDIES

The objectives of the harvesting studies were:

1. To measure the yield per acre, moisture content, and composition of each harvested product.
2. To observe the functional and mechanical performance of the harvesting machines.
3. To measure the capacitive performance of the harvesting and handling machines.
4. To harvest a sufficient quantity of each product so that its nutritional value could be studied in animal feeding trials.

Several harvesting machines were selected for study during 1969, 1970, 1971, and 1972. Machine selection was based primarily on a desire to obtain a wide variety of harvested products. All harvesting studies were conducted on the Beef Nutrition Farm in cooperation with the Animal Science Department, and on several nearby farms operated by the University Farm Service Department. All harvested products except for some of the shelled corn were stored on the Beef Nutrition Farm for use in feeding trials.

Machinery

Corn silage was harvested each year and stored in one of the upright silos on the farm. It was harvested with a conventional pull-type forage harvester by personnel from the Farm Service Department.

The Beefmaker II (Figures 3, 4, and 5), designed by Hitzhusen (1969), was used during 1969 and 1970 to harvest high-moisture shelled corn and corn refuse. The shelled corn was collected in barge wagons pulled behind the machine and stored in a gastight silo. The corn refuse was collected in forage wagons pulled alongside the Beefmaker II by a second tractor. It was rechopped with a forage blower equipped with a recutting attachment (Figure 6) before being stored.

Three different combine attachments were used to harvest husklage. The first was a model 5400 Foster Harvest Master (Figure 7) obtained from the Foster Manufacturing Company, Madras, Oregon. An extension for the lower combine sieve carried the husklage into an auger mounted under the rear combine hood (Figure 8). A blower attached to the auger transferred the material to a trailer pulled behind the combine. The entire auger-blower assembly was attached to the combine and driven by a single v-belt from the combine cylinder shaft. When the trailer was filled, a latch on the front was released and the husklage was dumped on the ground (Figure 9). In some tests, forage wagons were used to collect the husklage (Figure 10).

The second attachment was a Johnson Strawbuncher (Figure 11) obtained from Hayti Industries, Inc., Hayti, South Dakota. It consisted of a two-wheeled trailer pulled by the combine and a large auger to fill the trailer. A short, oscillating pan, attached to the front of the auger hopper and driven by the auger, extended under the rear combine hood to direct the husklage into the auger.

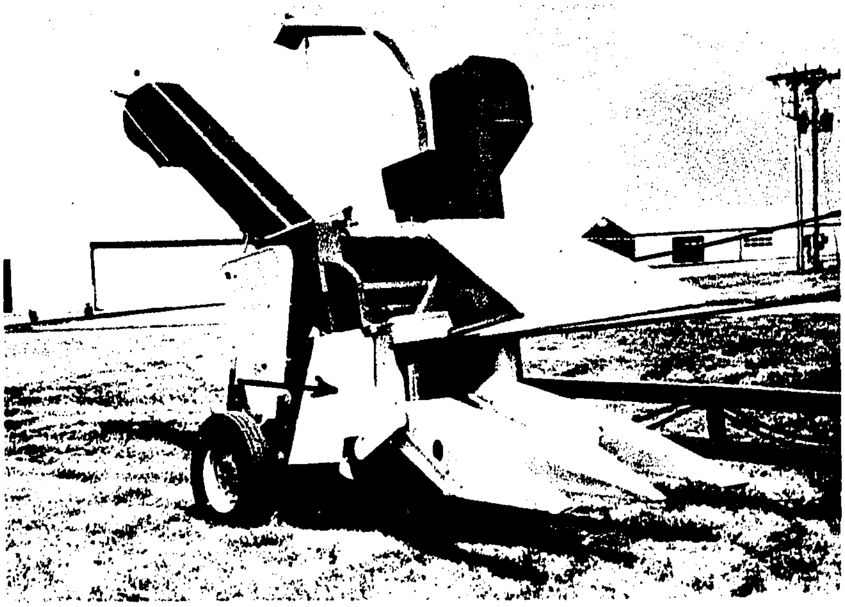


Figure 3. Beefmaker II; arrow indicates snapping attachment

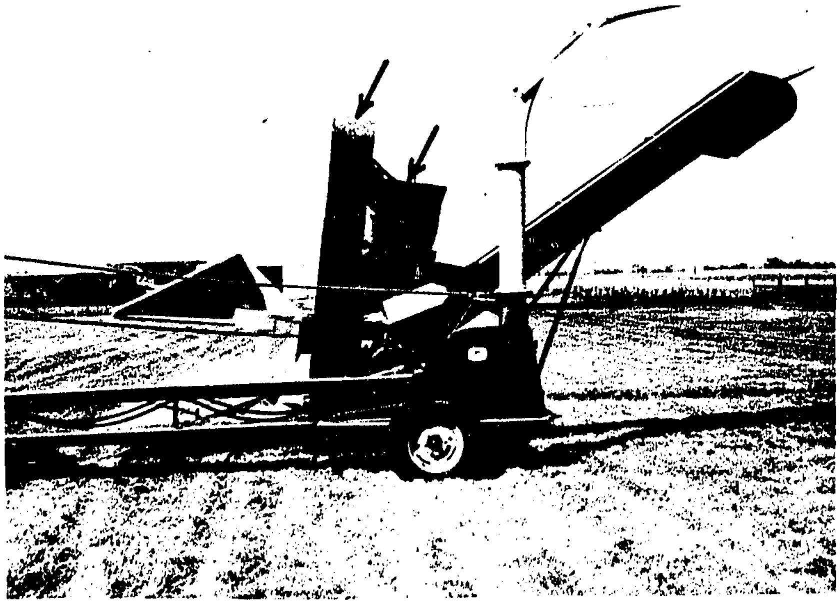


Figure 4. Beefmaker II; arrows indicate vertical ear corn elevator and sheller

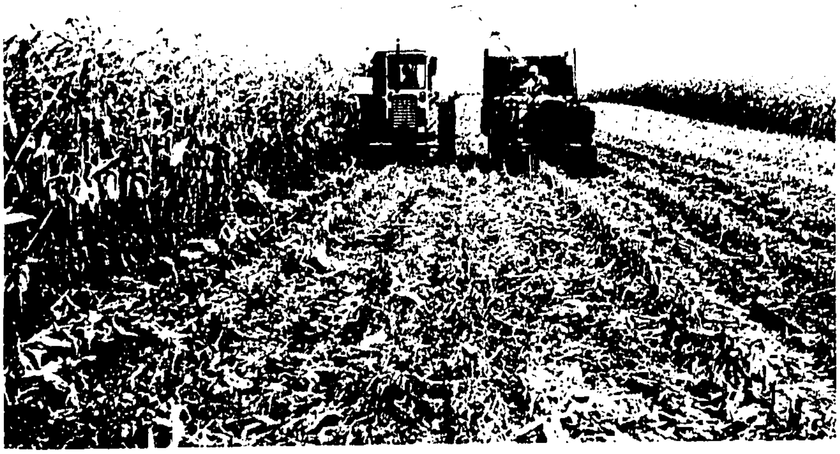


Figure 5. Beefmaker II during field operation

Figure 6. Blower with recutting attachment used to process corn plant forage

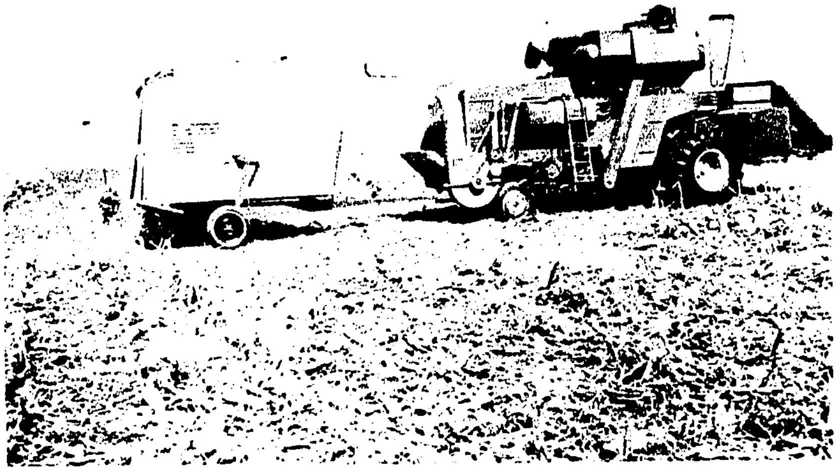


Figure 7. Foster Harvest Master for collecting husklage

Figure 8. Foster Harvest Master combine attachment

Figure 9. Dumping husklage with the Foster Harvest Master

Figure 10. Collecting husklage with a forage wagon

When the trailer was filled, a chain and flight apron in the bottom of the trailer conveyed the husklage out of the trailer and dropped it on the ground. The auger was driven by one wheel of the trailer through a detachable-link chain and gearbox. The unloading apron in the bottom of the trailer was driven by engaging a chain drive from the other trailer wheel.

The third combine attachment was obtained from the Hesston Corporation, Hesston, Kansas. It consisted of an extension for the lower combine sieve, a heavy-duty flail shredder, and a spout to direct material into a trailing wagon (Figure 12). The dump trailer from the Foster Harvest Master was used to collect the husklage.

In 1969, corn stalklage was harvested with a model IF546 Fox forage harvester equipped with an experimental flail pickup (Figures 13 and 14), manufactured by the Farm Division of Koehring Company, Appleton, Wisconsin. The flail pickup was 5 feet wide and harvested two 30-inch rows. The forage harvester was equipped with a recutting screen with 4-inch square holes. Stalklage was harvested from two fields, one in which the grain had been harvested with a combine and one that had been picked.

A model 30 Stakhand (Figure 15) was obtained from the Hesston Corporation, Hesston, Kansas, in 1971 and 1972 to harvest corn stalklage. The Stakhand consisted of a direct-throw flail pickup and a large stack-forming chamber mounted on a two-wheeled trailer. The roof of the stack-forming chamber was moved vertically with hydraulic cylinders to compress the stack during harvesting. When a stack was

Figure 11. Johnson Strawbuncher for collecting husklage

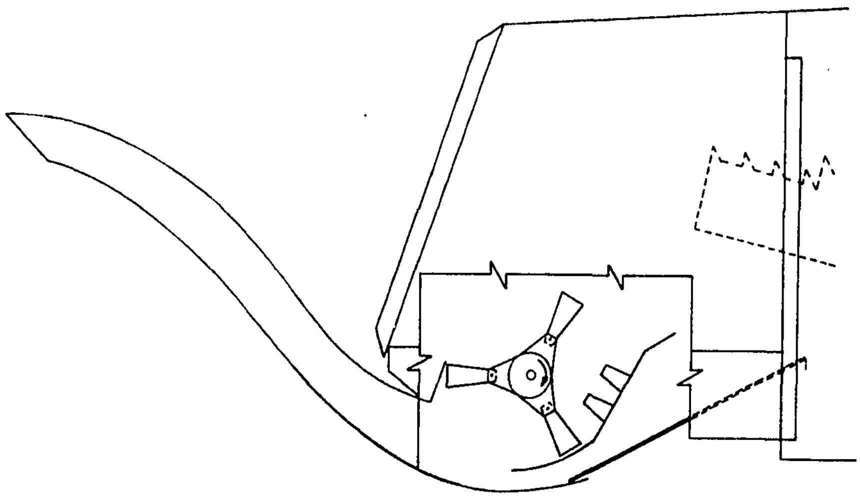


Figure 12. Hesston flail shredder for collecting husklage

Figure 13. Fox forage harvester with flail pickup

Figure 14. Fox forage harvester following a combine

completed it was unloaded through the rear of the chamber with a chain and flight apron (Figure 16).

Two different operating policies were used with the Stakhand when harvesting corn stalklage behind a combine. The first was to harvest all the rows behind a combine equipped with a straw spreader. Under the second operating policy, the straw spreader was removed from the combine so that the husks and cobs would fall on only the center two rows behind the six-row combine. The Stakhand was then operated on only those two rows so that the stalks from only one-third of the field area were harvested. Stalklage was also harvested from a field of corn that had been harvested with a picker.

Sampling Procedures

All loads of shelled corn and forage, except for the husklage dumps left in the field, were weighed before being unloaded. Random loads were selected for sampling each day, and three samples of harvested material were taken from each load. The samples were obtained from random locations within the load during the unloading process. The samples of shelled corn were labeled and sealed in pint jars. At the end of each harvest day, the samples were weighed to the nearest gram, placed in wire baskets, and left in a forced-air drier with an inlet air temperature of 185°F. until they ceased to lose weight. They were then reweighed to the nearest gram to determine percent dry matter.

The forage samples were placed in cloth bags and weighed to the

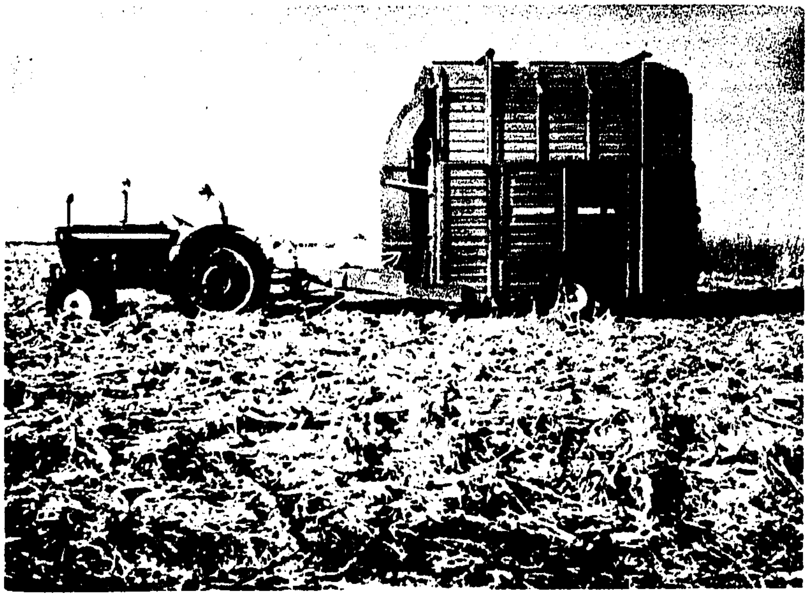


Figure 15. Hesston Stakhand 30 harvesting stalklage

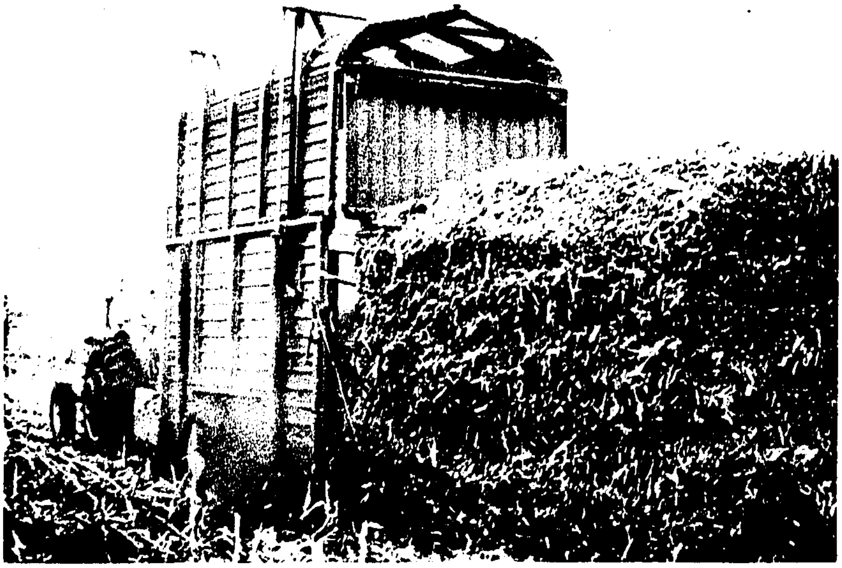


Figure 16. Unloading a stalklage stack

nearest 0.01 pound immediately after they were obtained. They were placed in a forced-air drier with an inlet air temperature of 140°F. and left until they ceased to lose weight. They were then reweighed to the nearest 0.01 pound to determine percent dry matter. One of the three samples obtained from each load of forage was selected for chemical analysis. The other two samples were placed in a large container of water to separate the grain from the forage. The two separated fractions from each sample were redried and weighed to determine the percent of forage dry matter contributed by the grain.

Random loads of husklage were weighed each day before being dumped in the field. Three samples of husklage were taken from each of these loads and treated in a manner similar to that described above for the other forage samples. All stacks made with the Hesston Stakhand 30 were weighed and sampled.

All fields harvested were measured after harvesting was completed to determine the harvested areas. The total quantity of material harvested from each measured area was used to determine an average field yield for each harvested product. Estimates of forage yields in the fields to be grazed were obtained by hand harvesting all the material from several 50-square foot plots at random locations in the field.

Time Studies

The time required to complete a harvesting cycle with each machine was measured using observation boards like the one shown in

Figure 17. Three stop watches mounted at the top of each board were operated from a single control lever. After the watches were properly sequenced, depressing the lever would stop one watch, start the next, and reset the third watch. A fourth stopwatch was operated separately.

A single harvesting cycle for a machine was defined as the sum of all field activities required to harvest one load of forage, including hitching and unhitching wagons. The following definitions, similar to those used by Von Bargen (1967, 1968) and listed in Table 3, were used to classify the field activities in a harvesting cycle:

> Potential operating time: The total time the machine was in the field on a given day. Idle time caused by this study, but not typical of a normal harvest, and idle time caused by inclement weather were not included, nor were daily service time and travel time to and from the field.
>
> Delay activity: An interruption in the operating activity, caused by mechanical failure, machine plugging, cleanup around a blower, etc.
>
> Operate activity: Machine performing its primary function or necessary support functions.
>
> > Primary function: On-row harvesting, transport, material conveying, etc.
> >
> > Support function: Nonproductive job required for primary function; turning at end of rows, hitching and unhitching, unloading a harvested product, etc.

Total harvesting cycle time was divided into three element times: primary function activity time, turning activity time, and delay plus support function activities time. The element times were measured and recorded by an observer riding on the machine. The end of a primary function activity and the beginning of a turning activity was defined as the instant the gathering mechanism of the machine left

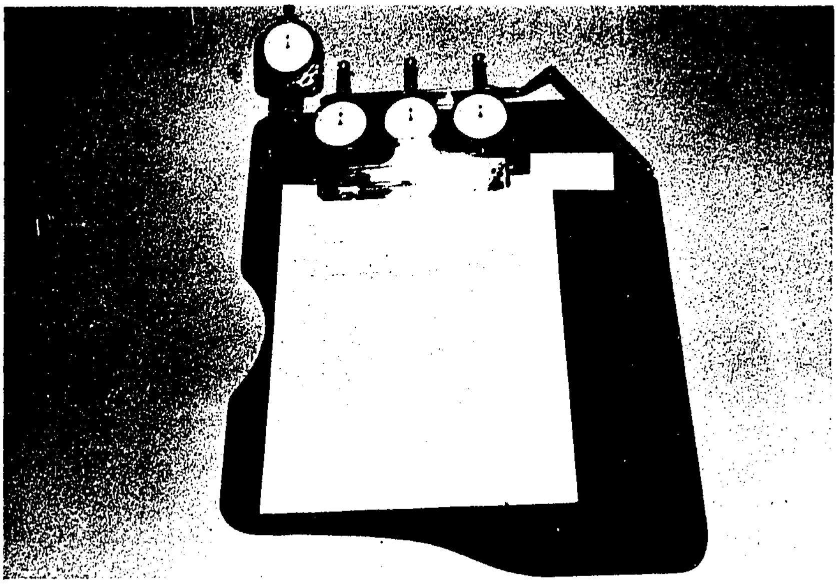


Figure 17. Observation board with stopwatches to measure activity times

the crop at the end of the field. The end of the turning activity and the beginning of the next primary function activity was defined as the instant the gathering mechanism re-entered the crop after completing the turn. A delay activity began when forward motion of the machine ceased and ended when forward motion resumed.

All delay and support function activity times, except for turning, were recorded in a single column on the data sheet. One of the following numbers was recorded with each entry in this column to distinguish between delay activities and support function activities:

1 = machine plugging

2 = mechanical failure repaired in the field

3 = mechanical failure repaired out of the field

4 = nonproductive activities (distributing a load, etc.)

5 = unloading

6 = hitching and unhitching wagons

7 = operator personal time

8 = nontypical interruptions caused by this study

9 = miscellaneous, unclassified above

The fourth stopwatch on the observation board was started at the beginning of a harvesting cycle and stopped at the completion of a cycle to obtain a measure of total cycle time and a check on the sum of all element times recorded. The weight of the load harvested during each cycle observed was recorded with the time observations to permit a determination of man-machine productivity.

Similar measurements of element times were made for each processing operation. A processing cycle was defined as the sum of all activities required to unload one load of forage or shelled corn. The forage blowers were positioned alongside a roadway so that wagons had only to be stopped with their discharge openings over the blower hopper, so no extra maneuvering was required to position a load. This made a determination of initial positioning time impossible for the forage loads. Occasionally, however, the operator would reposition the load during a processing cycle, and this activity was recorded as a delay activity. The time for initial positioning of the loads of shelled corn was measured.

Total processing cycle time was divided into four element times according to the following definitions:

> Primary function activity time: Time interval when material was entering the processing unit from the hauling vehicle.
>
> Cleanup activity time: Time interval when manual cleanup around the processing unit was performed after unloading a hauling vehicle.
>
> Idle activity time: Time interval when the processing unit was running empty with no material being processed. This included the time interval after the operator started the processing unit but before the unloading mechanism on the hauling vehicle was engaged, etc.
>
> Delay activity time: Nonproductive time during interruptions in the primary function activity caused by machine plugging, mechanical failure, etc.

These element times were measured and recorded together with the weight of the load processed to permit a determination of man-machine productivity.

RESULTS AND DISCUSSION OF HARVESTING STUDIES

During the development of the mathematical models to be discussed later, the decision was made to predict forage yield and moisture content from estimates of grain yield and moisture content. Because the harvested grain and forages were originally sampled only for moisture content and composition, the samples were taken from random loads of corn and forage each day rather than from paired loads. Therefore, to study the relationships between forage and grain yields, and forage and grain moisture contents, all the samples of each product collected on a particular day were combined and treated as a single composite sample. The number of individual samples represented by a single daily composite sample ranged from three to 18.

Statistical tests of hypotheses and analyses of variance were performed using the methods described in Steel and Torrie (1960) and Wine (1964). Linear regressions were calculated by the method of least squares (National Bureau of Standards, 1969). Higher order polynomial regressions were computed with the OMNITAB computer program described in Chamberlain and Jowett (1969).

Yield and Moisture Content of Harvested Products

The total quantities and average moisture and grain contents of the forages harvested and stored for feeding trails each year are listed in Tables A1 through A4 of Appendix A. The average yield of each forage was calculated by dividing the total quantity of forage harvested from a field by the measured area of the field.

The yields of corn refuse and grain from the three fields harvested with the Beefmaker are listed in Table 5. The "as harvested" yields are the actual quantities obtained from each field. Grain yields were corrected to bushels of corn at a moisture content of 15.5 percent. The total yield of grain from each field was the sum of the figures in the last two columns of Table 5. The forage dry matter yields were calculated by subtracting the grain dry matter in the refuse from the total refuse dry matter.

The Beefmaker harvested the whole corn plant in a single operation and forage recovery was high. Therefore, the refuse yields in Table 5 represent nearly complete recovery of the available forage. A small quantity of cobs was lost during harvesting (Table 21), and on windy days, dry pieces of leaf and husk were blown over the forage wagons. These losses were not measured, but they may have been as high as 5-10 percent of the harvested dry matter.

The shelled corn in the refuse was caused by the aggressive snapping rolls used in the machine. The snapping rolls also functioned as feed rolls to pull the corn plants through the snapping unit, and they shelled corn as the ears were being snapped. The variation in the quantity of grain in the refuse was caused by the two different pairs of snapping rolls used. The snapping rolls were designed by Hitzhusen (1969), one pair more aggressive than the other. The more aggressive rolls were used to harvest fields 1 and 10. The greater quantity of grain in the refuse from field 1 than

Table 5. Yields of corn refuse and grain harvested with the Beefmaker

Year and location	Corn refuse (lb./acre) As harvested	Corn refuse (lb./acre) Total dry matter	Corn refuse (lb./acre) Forage dry matter	Grain (bu./acre) As harvested	Grain (bu./acre) In refuse
1969, Field 1	13,798	6,721	5,421	105.9	27.5
1969, Field 4	15,708	7,088	6,303	147.6	16.6
1970, Field 10	12,759	6,114	5,038	69.6	22.7
Mean	14,088	6,641	5,587	107.7	22.3

from field 10 was caused by the uneven flow of plants through the snapping unit in field 1. The uneven flow of plants prevented some snapped ears from dropping into the ear corn elevator. As these ears were bounced against the snapping rolls by the plants being pulled through the snapping unit, additional shelling occurred. A pair of feed rolls was installed in front of the snapping rolls in 1970, and plant flow through the snapping unit was improved.

The smoother snapping rolls were used in field 4 in 1969 to reduce the quantity of grain in the refuse. A lower grain content was achieved, as indicated by the figures in Table 5. But the flow of plants through the snapping unit was very unsatisfactory, so the smoother rolls were not used in 1970.

The figures in Table 5 show that corn refuse yield increased as grain yield increased. A linear regression of total dry matter yield on grain yield was calculated, and the regression line is shown in Figure 18a. The regression coefficients, standard deviations, and coefficient of determination (R^2) are listed in Table 10. The analysis of variance (Table C1, Appendix C) indicated that the reduction in variance due to regression was significant at the 5 percent level.

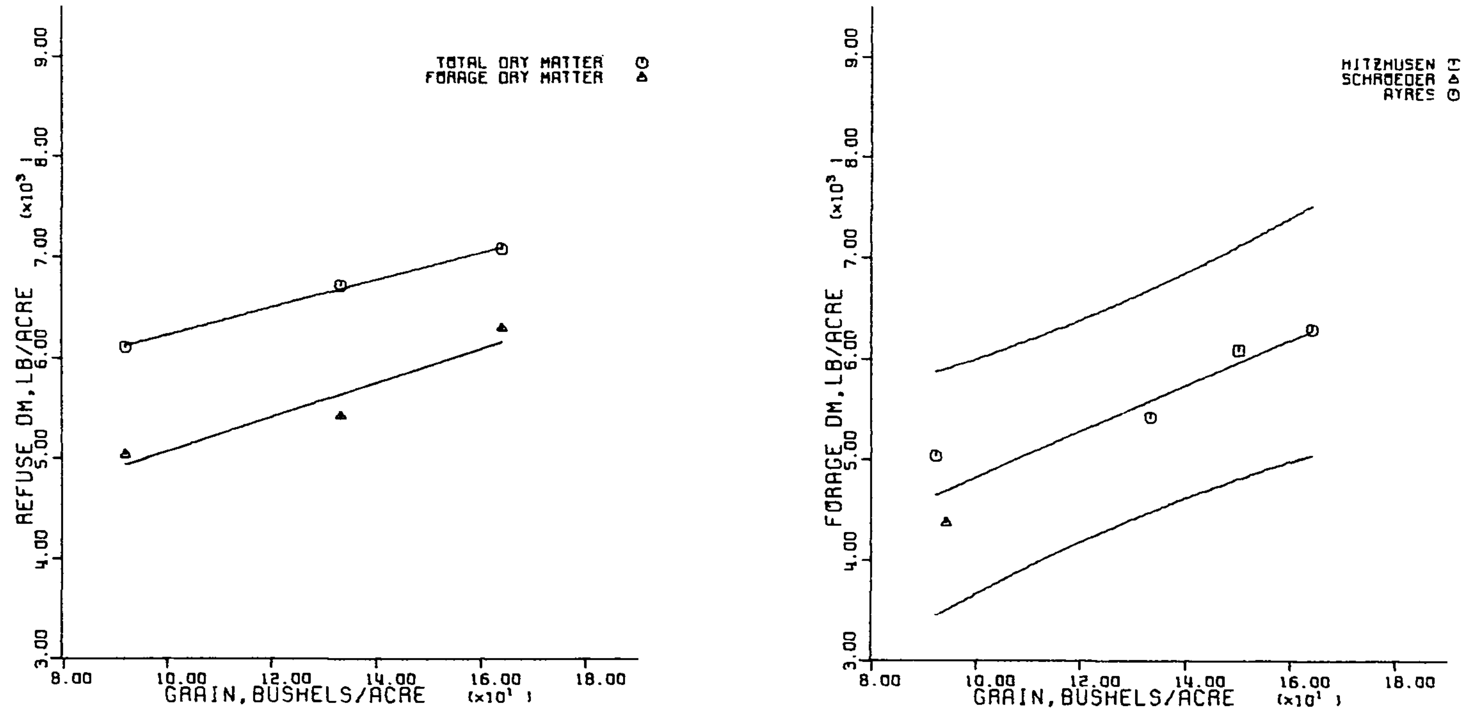
The quantity of grain in the refuse resulted from the design of the Beefmaker, and other machines designed to harvest the whole corn plant might produce forage with different grain contents. Therefore, mathematical relationships between corn refuse yield and grain yield should be based on forage dry matter rather than on total dry matter to be useful. A linear regression of forage dry matter on grain yield was calculated for the three values in Table 5, and the regression line is also shown in Figure 18a. The value of the coefficient of determination was 0.908, but the analysis of variance (Table C2, Appendix C) indicated that the reduction in variance due to regression was not significant ($P < 0.25$). With only three data points, an analysis of variance could not be made for a nonlinear relationship.

Support for the hypothesis that a linear relationship existed between forage dry matter and grain yield, at least in the range of 90-160 bushels of grain per acre, was obtained from Hitzhusen (1969) and Schroeder (1968a). Schroeder harvested corn refuse in 1967 and reported a forage yield of 4380 pounds of dry matter per acre and a grain yield of 94.5 bushels per acre. Hitzhusen obtained mean yields of 6092 pounds of forage dry matter and 150.2 bushels of grain per acre from his plots. These two data pairs were included with the three pairs listed in Table 5 and a new linear regression of forage dry matter on grain yield was calculated. The regression line is shown in Figure 18b, and the regression coefficients, standard deviations, and coefficient of determination are listed in Table 10. The 95 percent confidence interval for a single value of forage yield for a given grain yield is also shown in Figure 18b. The analysis of variance (Table C3, Appendix C) indicated that the reduction in variance due to regression was significant at the 5 percent level. The unexplained variation about the regression line may have been caused by errors in measurement, different grain to forage ratios among varieties, or both.

The average moisture contents of the corn refuse and the forage and grain fractions are listed in Table 6. The difference between the refuse and forage moisture contents varied slightly from day to day because of the variation in grain content.

Linear regressions of forage moisture content on grain moisture content for fields 1 and 10 were calculated, and the regression lines are shown in Figure 19. The regression coefficients, standard deviations, and coefficients of determination are listed in Table 11. The analyses of variance (Tables C4 and C5, Appendix C) indicated that the reduction in variance due to regression was highly significant ($P < 0.01$) for field 1, but was significant only at the 10 percent level for field 10.

The forage from field 1 was drier than the forage from field 10



(a) (b)

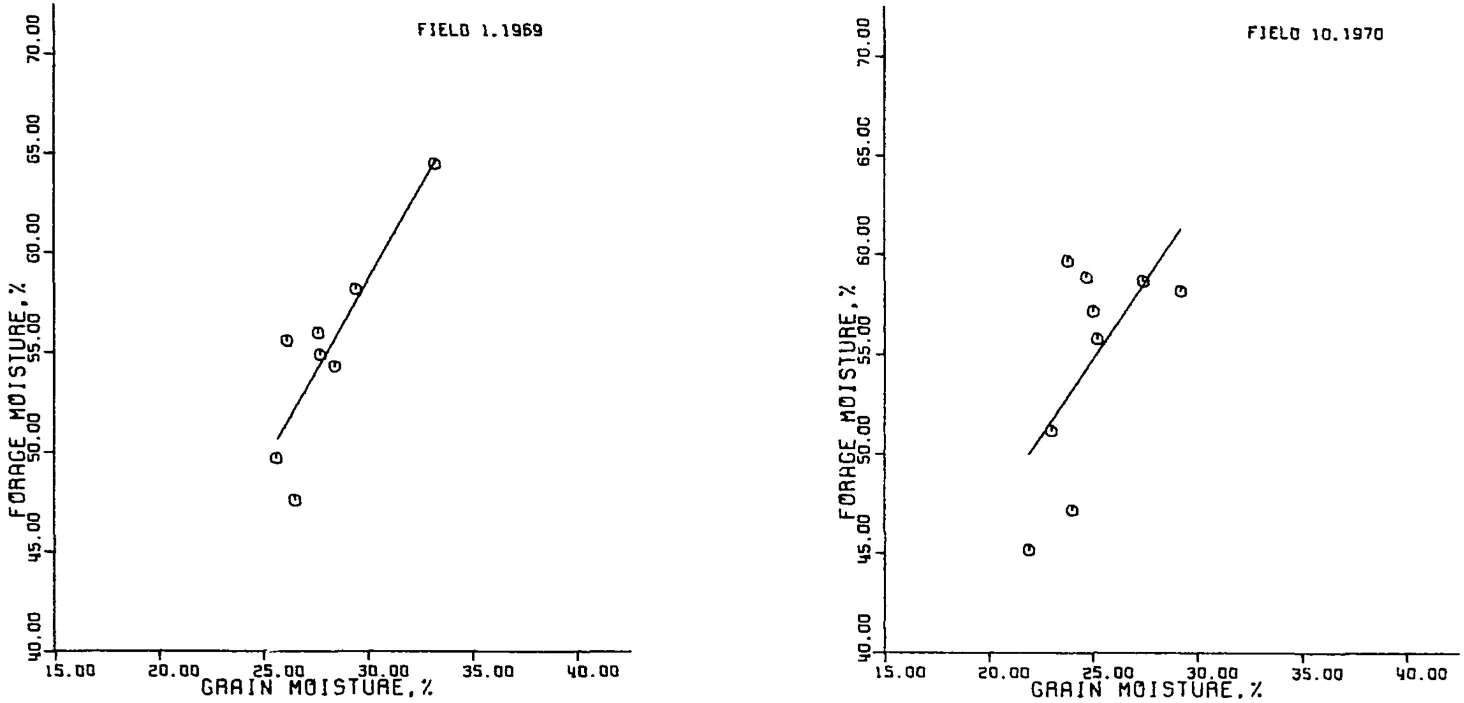
Figure 18. Regression of corn refuse dry matter yield on grain yield; (a) Values from Table 5; (b) Forage dry matter, with values from Hitzhusen (1969) and Schroeder (1968a) added, and with a 95 percent confidence interval for a single value

Table 6. Daily average moisture contents (%) of corn refuse and grain[1]

Date	1969 Refuse	1969 Forage	1969 Grain	1970 Refuse	1970 Forage	1970 Grain
		Field 1				
Sept. 24	62.6	64.5	33.2			
Sept. 29	53.8	58.2	29.4		Field 10	
Oct. 1	50.8	54.3	28.4	54.2	58.2	29.2
Oct. 2	52.3	--	--	55.0	58.7	27.4
Oct. 3	51.1	54.9	27.7	53.3	57.2	25.0
Oct. 4	52.3	56.0	27.6			
Oct. 5				52.1	55.8	25.2
Oct. 6	52.5	55.6	26.1	54.9	59.7	23.8
Oct. 7	46.8	49.7	25.6	54.2	58.9	24.7
Oct. 8	44.8	47.6	26.5			
		Field 4				
Oct. 11	53.4	54.6	27.0			
Oct. 13				50.0	51.2	23.0
Oct. 15	57.1	--	--	45.9	47.2	24.0
Oct. 16	54.3	57.2	26.5	42.5	45.2	21.9

[1] All values are averages of all samples of each product collected on one day.

throughout the harvesting season. The slope of the regression line for field 1 was also higher than the slope of the regression line for field 10, indicating a higher drying rate for the forage. A difference in the drying rate between the two fields was expected because the corn varieties were different. Hitzhusen (1969) and Schroeder (1968b) found significant differences in the forage drying rates among varieties.



(a) (b)

Figure 19. Regression of corn refuse forage moisture content on grain moisture content; (a) Field 1, 1969; (b) Field 10, 1970

The standard deviations of the regression coefficients (Table 11) for the two regressions shown in Figure 19 were quite large, and the 95 percent confidence intervals for the regression coefficients overlapped, suggesting that there might not be a significant difference between the two regression lines. Consequently, tests for homogeneity of slope and for equality of intercepts were made and are summarized in Table C7, Appendix C. The test for homogeneity of slope failed to provide sufficient evidence to reject the null hypothesis of equal slopes. Therefore, a pooled estimate of the slope ($b_1 = 1.70$) was calculated and used to calculate new estimates of the intercepts ($b_{01} = 7.33$, $b_{02} = 12.27$). When these two values were tested for equality, the test again failed to provide sufficient evidence to reject the null hypothesis of equal intercepts. These tests indicated that there was not sufficient evidence to conclude that the moisture contents and drying rates of forage from the two fields were different.

The regression line for the pooled regression of forage moisture content on grain moisture content, and the 95 percent confidence interval for a single value of forage moisture content, are shown in Figure 20. The regression coefficients, standard deviations, and coefficient of determination are listed in Table 11. The analysis of variance (Table C6, Appendix C) indicated that the reduction in variance due to regression was significant at the 5 percent level.

The yields of husklage and grain are listed in Table 7. The mean dry matter yield was slightly less than 1 ton per acre.

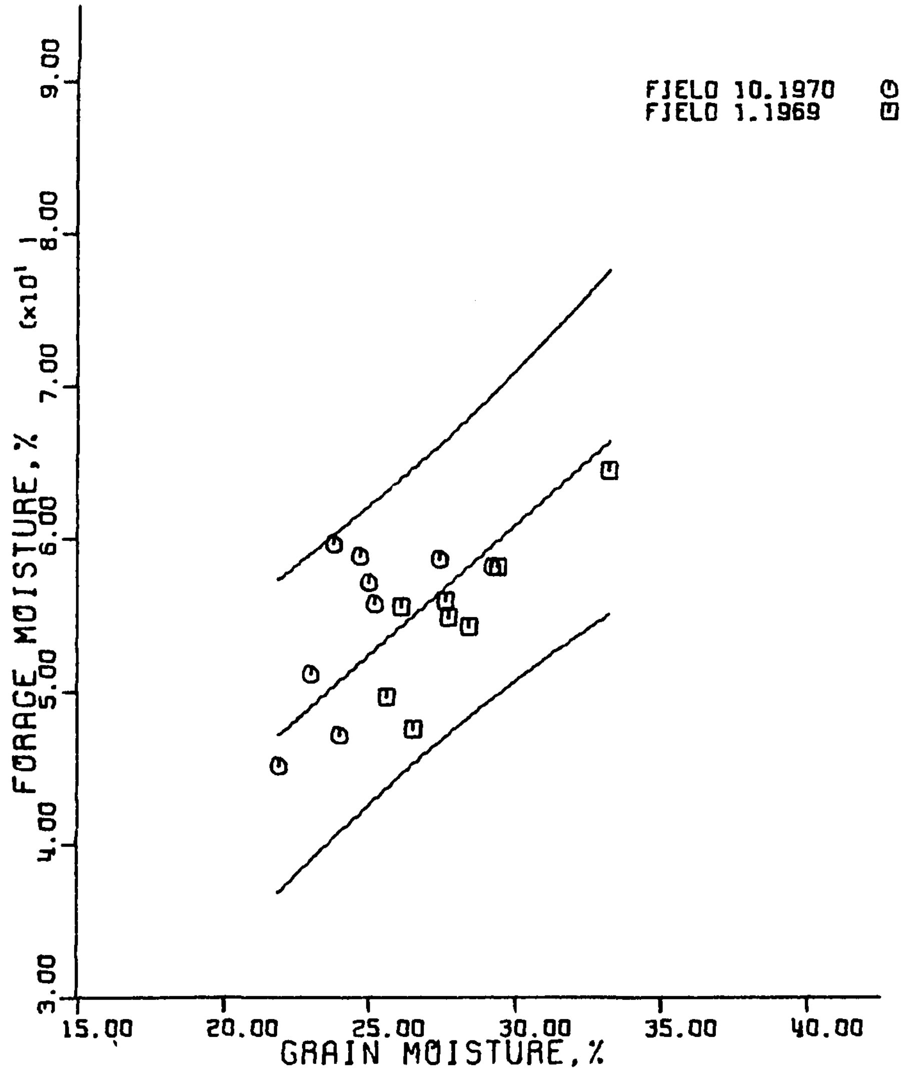


Figure 20. Pooled regression of corn refuse forage moisture content on grain moisture content, with a 95 percent confidence interval for a single value

Table 7. Yields of husklage and grain with the Foster Harvest Master

Year and location	Husklage (lb./acre)			Grain (bu./acre)	
	As harvested	Total dry matter	Forage dry matter	As harvested	In forage
1969, Field 3	3,537	2,438	2,358	169.3	1.7
1969, Field 6	3,141	2,098	2,075	143.2	0.5
1970, Field 11	2,384	1,688	1,681	100.0	0.1
1970, Field 2	2,356	1,713	1,686	87.5	0.6
1971, Field 1	2,285	1,782	-	101.0	-
1971, Field 6	2,395	1,917	-	105.0	-
1972, Field 1	3,024	1,923	-	143.0	-
Mean	2,732	1,937		121.3	

Harvesting losses were not measured, but visual estimates indicated a dry matter recovery of approximately 90 percent of the forage coming from the combine. Dry pieces of husk and cob were blown over the collection hopper by the air blast from the combine, and some forage missed the trailer during turns at the ends of fields.

The weights and moisture contents of randomly selected husklage dumps are listed in Table 8. The quantity of dry matter in a dump was affected by the moisture content of the husklage and by the length of the corn rows being harvested. Husklage at higher moisture contents would pack more tightly in the trailer than drier husklage, forming heavier dumps. When corn rows were short, the trailer was not filled

Table 8. Weights and moisture contents of husklage dumps made with the Foster Harvest Master

Year and location	Dump weight (lb.)		Moisture content (%)
	Wet	Dry	
1969, Field 3	1,820	1,160	36.3
	1,710	1,279	25.2
	1,740	1,195	31.3
1970, Field 2	1,260	882	30.0
	1,020	750	26.5
	1,200	888	26.0
	1,140	824	27.7
	1,040	770	26.0
1971, Field 1	870	678	22.1
	630	493	21.8
	710	555	21.9
	900	702	22.0
1972, Field 2	1,410	877	37.8
	1,500	990	34.0
	1,350	855	36.7
	1,470	973	33.8
	1,420	856	39.7

in a round trip and the dumps were small.

A linear regression of husklage dry matter yield on grain yield was calculated for the seven values in Table 7. The regression line and the 95 percent confidence interval for a single value of husklage yield are shown in Figure 21a. The regression coefficients, standard deviations, and coefficient of determination are listed in Table 10. The analysis of variance (Table C8, Appendix C) indicated that the reduction in variance due to regression was highly significant ($P < 0.01$).

The average moisture contents of husklage and grain are listed in Table 9. The grain from field 11 in 1970 was not stored for feeding trials, so samples were not obtained on many of the harvesting days. A linear regression of husklage moisture content on grain moisture content was calculated for all pairs of data in Table 9. The regression line and the 95 percent confidence interval for a single value of husklage moisture content are shown in Figure 21b. The regression coefficients, standard deviations, and coefficient of determination are listed in Table 11. The analysis of variance (Table C9, Appendix C) indicated the the reduction in variance due to regression was highly significant ($P < 0.01$).

The average yields and moisture contents of stalklage are listed in Table 12. The stalklage yield of 1,549 pounds of dry matter per acre with the forage harvester after combining was very low. With a grain yield of 153 bushels per acre, a forage dry matter yield of 6,035 pounds per acre would be predicted using the regression equation for refuse forage dry matter from Table 10. If that was assumed to be the potential yield, 1,549 pounds per acre represents a recovery of only 26 percent of the available forage.

Researchers at the Univeristy of Wisconsin harvested stalklage with a similar machine during 1968.[1] They measured an average yield

[1] Berge, Orrin I. 1970. Department of Agricultural Engineering, the University of Wisconsin, Madison, Wisconsin. Harvesting corn stalklage with a Fox forage harvester. Private communication.

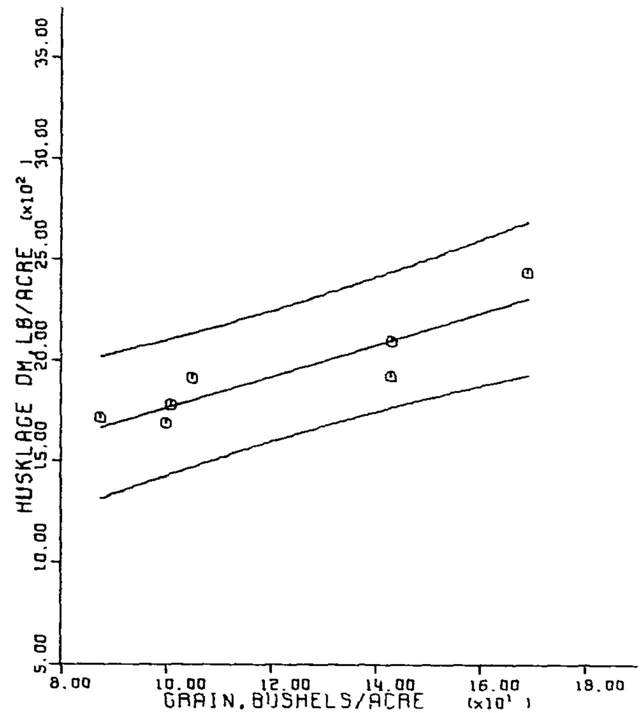
Table 9. Average moisture contents (%) of husklage and grain

Date	Husklage	Grain	Husklage	Grain
	Field 3, 1969		Field 11, 1970	
Oct. 21	37.2	24.7	29.0	20.1
Oct. 22	36.2	23.9	34.4	22.1
Oct. 23	31.3	23.7	36.7	
Oct. 26			25.4	
	Field 6, 1969			
Oct. 28	36.3		30.5	
Oct. 29	27.4	22.0	27.0	
Oct. 30			27.5	
Oct. 31			27.8	
	Field 1, 1971		Field 2, 1970	
Nov. 7			27.6	22.0
Nov. 11	22.0	20.0	22.7	18.0
	Field 1, 1972			
Nov. 29	36.4	25.8		

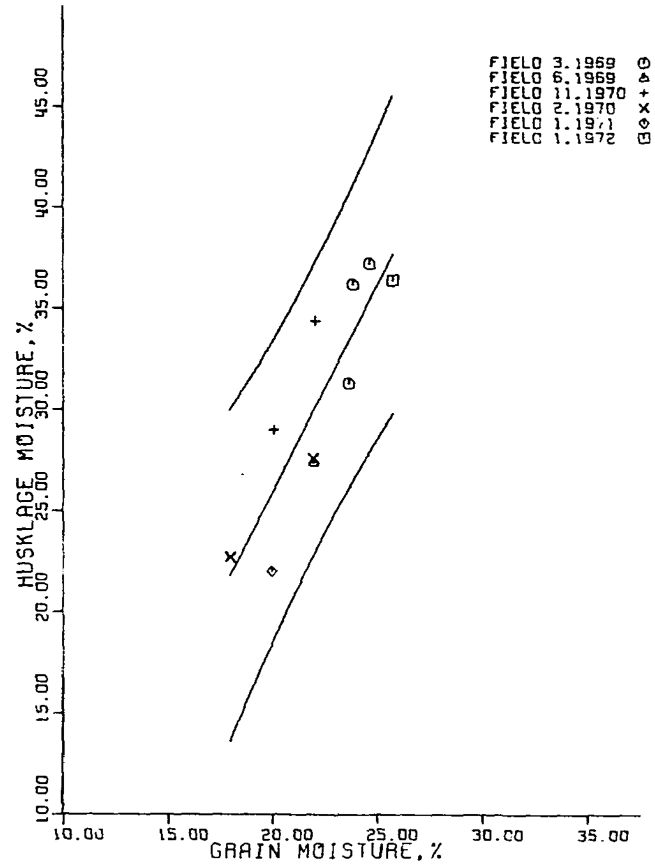
of 5,200 pounds of available forage dry matter per acre by weighing all the material obtained from several sampling areas of 90 square feet. They harvested an average yield of 2,780 pounds of stalklage dry matter per acre, for a recovery of 53.5 per cent of the available forage.

The stalklage yield after combining was low in this study for the following reasons:

1. A self-propelled combine with a 6-row cornhead was used to harvest the grain. The wheels on the combine ran on two rows



(a)



(b)

Figure 21. Regression and 95 percent single value confidence intervals for husklage; (a) Dry matter yield on grain yield; (b) moisture content on grain moisture content

Table 10. Linear regression of forage dry matter yield on grain yield[1]

Forage	Regression coefficients b_0	Regression coefficients b_1	Standard deviations b_0	Standard deviations b_1	Standard deviations y/x	(R^2)
Corn refuse						
Total	4,875	13.59	105	0.79	40.40	0.996*
Forage	3,363	17.12	723	5.43	277.35	0.908
Forage[2]	2,576	22.61	629	4.83	313.71	0.938*
Husklage	981	7.88	198	1.59	118.22	0.831**

[1] $y = b_0 + b_1x$, where y = forage yield, lb./acre, and x = grain yield, bu./acre.

[2] Regression of corn refuse forage dry matter on grain yield with values from Schroeder (1968a) and Hitzhusen (1969) added.

*Calculated F-statistic exceeds the tabulated value at the 5 percent level of significance; also for Table 11.

**Calculated F-statistic exceeds the tabulated value at the 1 percent level of significance; also for Table 11.

Table 11. Linear regression of forage moisture content on grain moisture content[1]

Forage	Regression coefficients b_0	Regression coefficients b_1	Standard deviations b_0	Standard deviations b_1	Standard deviations y/x	(R^2)
Corn refuse						
Field 1, 1969	3.18	1.85	12.01	0.43	2.73	0.758**
Field 10, 1970	16.09	1.55	17.93	0.72	4.51	0.400
Pooled	9.94	1.70	10.55	0.40	4.40	0.312*
Husklage	-14.77	2.03	9.17	0.41	2.94	0.754**

[1] $y = b_0 + b_1x$, where y = forage moisture content, %, and x = grain moisture content, %.

Table 12. Yields and average moisture contents of corn stalklage harvested after grain harvest

Harvesting System	Stalklage (lb./acre) As harvested	Stalklage (lb./acre) Dry matter	Stalklage moisture content(%)	Grain (bu./acre)
Fox forage harvester with flail pickup				
After combining, 1969	2,914	1,549	46.8	153
After corn picker, 1969	4,276	3,060	28.3	-
Hesston Stakhand 30				
After corn picker, 1971	4,119	3,398	17.5	-
After combining				
Harvesting all rows				
Field 2, 1971, heavy foxtail	10,617	6,795	36.0	101
Harvesting center 2 of 6 rows				
Field 3, 1971	2,617	1,800	31.2	105
Field 6, 1971	2,576	1,916	25.6	105
Field 3, 1972	3,318	1,921	42.1	113
Field 1, 1972	3,170	1,965	38.0	143

of cornstalks, making recovery of forage from the two rows impossible (Figure 14). Therefore, stalklage was harvested from only two-thirds of the actual field acreage.

2. The flails were operated approximately 2 inches above the corn rows to prevent picking up dirt.
3. The corn rows had been ridged 2-3 inches during cultivation, and the flails would not pick up the forage located between the rows.

Since only two-thirds of the field acreage was actually harvested, dry matter recovery was higher than 26 percent from the area actually harvested. Assuming two-thirds of 6,035 pounds per acre to be the available forage, 38 percent of the dry matter was recovered from the area harvested.

The stalklage yield obtained with the forage harvester after picking corn was almost twice the yield from the field that had been combined. This field was privately owned, and the farmer who harvested it did not measure the grain yield. However, with a potential forage yield of 5-6000 pounds of dry matter, 3,060 pounds of dry matter represents a recovery of over 50 percent.

The yield of stalklage harvested with the Hesston Stakhand from field 2 in 1971 should not be considered typical with this machine. The field was badly infested with giant foxtail, and almost 100 percent recovery of both cornstalks and foxtail was achieved. The yield in Table 12 includes both the cornstalks and the foxtail.

The last four yields listed for the Stakhand were from fields in which only the two center rows were harvested from each 6-row combine width. The yields are listed as dry matter per field acre, although only one-third of the field was actually harvested. If the regression equation for corn refuse forage yield (Table 10) was used to predict total available dry matter, the last four yields in Table 12 represent dry matter recoveries of 36, 39, 37, and 34 percent, respectively.

Three other aspects of this harvesting pattern should be mentioned. By disconnecting the combine straw spreader, the cobs and husks were dropped on the two center rows to be harvested, forming a loose windrow of material. Forage recovery from this windrow was high, and stalklage was higher in husk and cob contents, and lower in stalk content, than it would have been if all rows had been harvested.

By traveling over only one-third of the field area, harvesting capacity, in acres per hour, was almost three times as great as it was when all the rows were harvested. Since forage recovery from the two harvested rows was higher than from the other four rows, harvesting capacity, in tons of forage harvested per hour, was also higher with this harvesting pattern.

Finally, four of every six rows of cornstalks were left in the field for grazing and soil cover. Cornstalks are quite effective in reducing soil loss from wind and water, so this harvesting pattern was a better soil conservation practice than complete harvesting.

The moisture contents and weights of several stalklage stacks made with the Stakhand 30 are listed in Table 13. The two stacks made at 57 and 58 percent moisture heated badly after they were harvested, and mold was found when they were opened. The other stacks did not mold during the winter after they were harvested.

Composition of Harvested Products

One measure of the physical composition of the harvested products was the proportion of grain in each product. Samples of all the products harvested in 1969 and 1970 were divided into forage and grain fractions, and the average percentages of each fraction on a dry matter basis are listed in Table 14. The samples of the products harvested

Table 13. Weights and moisture contents of stalklage stacks made with a Hesston Stakhand 30

	Moisture content(%)	Stack weight (lb.) As harvested	Dry matter
After combining			
Harvesting all rows	36.0	5450	3480
	36.0	6130	3920
	58.0[1]	9280	3900
Harvesting center 2 of 6 rows	57.0[1]	9470	4060
	45.8	5820	3154
	44.0	5610	3141
	42.6	6000	3444
	41.2	5430	3193
	39.9	5760	3462
	39.2	5540	3368
	38.0	5960	3695
	31.0	4860	3380
	31.0	5040	3480
After corn picker	17.5	3870	3192

[1] Harvested after rain.

in 1971 and 1972 were not divided into forage and grain fractions.

The low grain content of the corn silage harvested in 1969 was not typical of normal silage. It was harvested from a field of late-planted corn and the kernels were only partially filled when it was harvested. The silage harvested in 1970 was considered to have a normal grain content.

The corn refuse contained a relatively high proportion of grain,

Table 14. Forage and grain fractions of products harvested in 1969 and 1970

Product	Percent of total dry matter Forage	Grain
Corn silage, 1969	75.0	25.0
1970	61.2	38.8
Corn refuse		
Field 1, 1969	80.6	19.4*
Field 4, 1969	88.9	11.1**
Field 10, 1970	82.5	17.5*
Husklage		
Field 3, 1969	96.7	3.3
Field 6, 1969	99.0	1.0
Field 2, 1970	98.4	1.6
Field 11, 1970	99.6	0.4
Field 3, 1970	99.3	0.7
Stalklage		
After combine, 1969	99.4	0.6
After picker, 1969	98.2	1.8

*Aggressive snapping rolls.
**Smooth snapping rolls.

as previously mentioned, and the effect of the two types of snapping rolls is evident.

The husklage contained very little grain, since it consisted of only the material discharged from the combine. A field survey of corn combines in central Iowa (Ayres et al., 1972) indicated that a properly adjusted combine should lose no more than 0.5 bushels of corn per acre from the rack and shoe. This would result in a husklage grain content of 1.2 percent on a dry matter basis with a husklage yield equal to the mean yield of 1937 pounds in Table 7.

Stalklage harvested with either the forage harvester or the Stakhand contained very little grain because it had to be recovered from the ground. Grain lost by the combine or the corn picker usually accumulated between the rows, and grain recovery was low with flails operating above the rows.

The composition and yield of each harvested product were also affected by the combination of corn plant parts included in it. The distribution of dry matter among these parts and the nutritional value of the dry matter within each part varies during plant growth. Plant samples were taken from fields being harvested in this study to determine the dry matter distribution at harvest, and samples of each harvested product were analyzed for crude protein and digestible dry matter. Before the results of these analyses are discussed, an analysis of dry matter distribution within the corn plant from data obtained by Schroeder (1968b) will be discussed.

Schroeder planted five hybrid corn varieties in a replicated field experiment in 1967. On successive harvest dates, he hand harvested four plants of each variety and separated them into five plant parts; grain, stalk (including the tassel), cob, leaves, and husk (including the ear shank). Average wet and dry weights of each plant part for each variety were measured to study the moisture content relationships within the corn plant. Since Schroeder was interested only in the moisture content relationships, he did not include the dry matter values for the plant parts in his thesis, and the original data could not be found. But he did include composite dry matter weights for all 20 plants harvested on each date in a mimeographed report of his research (1968a). The composite dry weights and moisture contents from that report are listed in Table D1, Appendix D.

Grain moisture content was used as the independent variable in the analysis of dry matter distribution. Polynomial regressions of dry matter yield per 20 plants on grain moisture content were calculated for each of the five plant parts listed in Table D1. The regression curves are shown in Figure 22a and the regression coefficents, standard deviations, and coefficients of determination are listed in Table 15. The analyses of variance (Tables C15-19, Appendix C) indicated that the reduction in variance due to regression was highly significant ($P < 0.01$) for all plant parts except the husks.

Grain dry matter increased rapidly as the moisture content of the grain decreased, reaching a maximum value at a grain moisture content of approximately 32.1 percent. It then decreased slightly as the grain continued to lose moisture. The coefficient of determination increased from 0.715 for the quadratic fit to 0.841 for the cubic fit, but the increase in grain dry matter below a grain moisture content of 20 percent, predicted by the cubic regression equation, would not occur in the corn plant.

Stalk, leaf, and cob dry matter decreased linearly with decreasing moisture, with stalk and leaf dry matter decreasing more rapidly than

Table 15. Regression of dry matter yield of 20-plant samples of corn plant products on grain moisture content[1]

Product	Regression coefficients				Standard deviations					(R^2)
	b_0	b_1	b_2	b_3	b_0	b_1	b_2	b_3	y/x	
Grain	227	290.32	-5.010	-	112	73.12	1.188	-	178.73	0.715**
Grain	10,169	-764.36	31.014	-0.397	4,031	421.26	14.281	0.160	141.35	0.841**
Stalk	-89	72.79	-	-	227	7.38	-	-	155.56	0.907**
Cob	813	7.86	-	-	74	2.41	-	-	50.85	0.515**
Leaf	-384	48.05	-	-	280	8.87	-	-	157.31	0.765**
Husk	654	4.07	-	-	146	4.75	-	-	100.27	0.068
Refuse	551	146.01	-	-	545	17.74	-	-	374.09	0.871**
Silage	-2,847	681.15	-8.981	-	2,719	179.79	2.897	-	435.89	0.841**
Husk & cob	1,467	11.94	-	-	203	6.59	-	-	139.04	0.247

[1] $y = b_0 + b_1x + b_2x^2 + b_3x^3$, where y = product dry matter yield per 20-plant samples, grams, and x = grain moisture content, %.

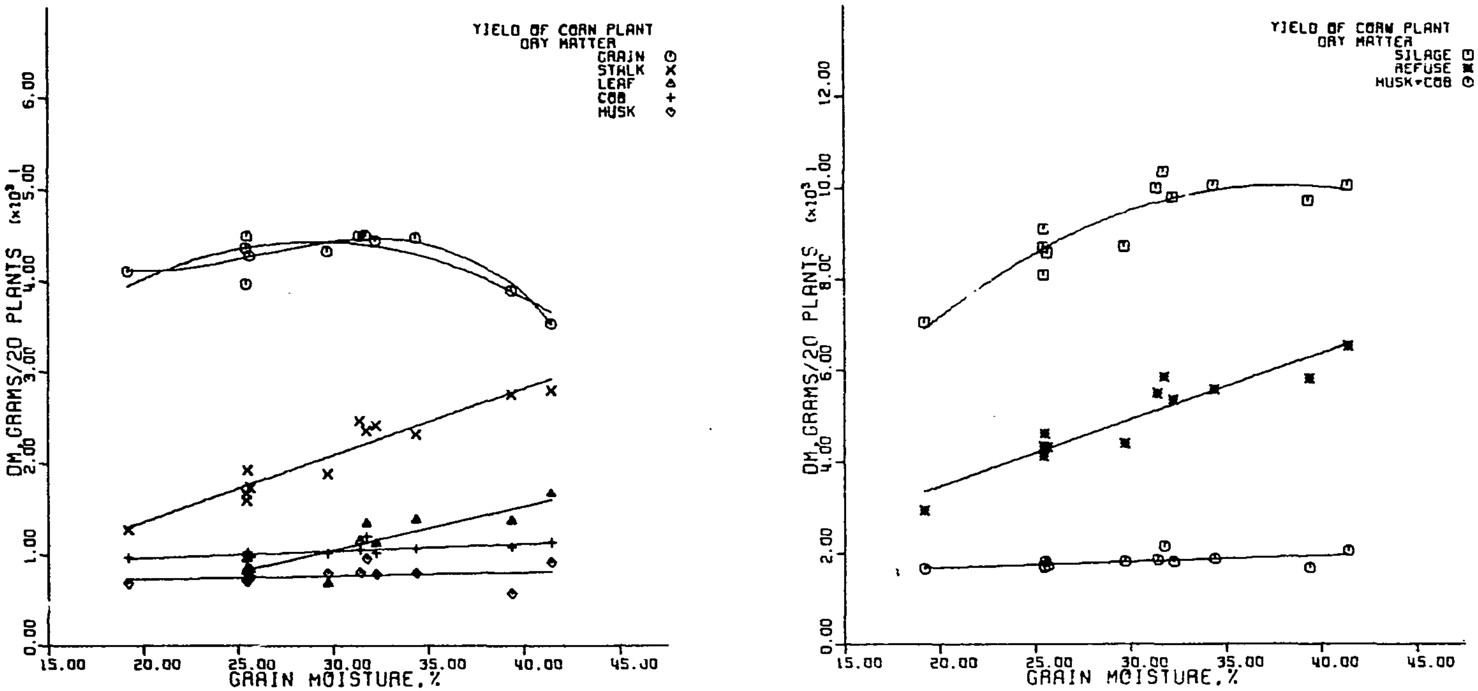
**Calculated F-statistic exceeds the tabulated value at the 1 percent level of significance.

cob dry matter. Husk dry matter did not decrease significantly as the grain dried down (Table C19, Appendix C), and the coefficient of determination was only 0.068 (Table 15). Consequently, husk dry matter was assumed to be constant at its mean value of 777 pounds per 20 plants over the range of measured grain moisture values.

The five plant parts were also combined to represent three of the harvested products described earlier. Dry matter values for all five parts were added to represent corn silage, dry matter values of the four nongrain parts were added to represent corn refuse, and the dry matter values for husk and cob were added to represent husklage. Polynomial regressions of dry matter per 20 plants on grain moisture content were calculated for these three combinations. The regression curves are shown in Figure 22b and the regression coefficients, standard deviations, and coefficients of determination are listed in Table 15.

The analyses of variance (Tables C20 and C21, Appendix C) indicated that the reduction of variance due to regression was highly significant ($P < 0.01$) for corn silage and refuse. The reduction in variance due to regression was not significant for the sum of husk plus cob dry matter (Table C22, Appendix C).

The percent of total plant dry matter contributed by each plant part at each value of grain moisture content was also calculated. Linear regressions of percent of total dry matter on grain moisture content were computed using all the values except those for November 7. Schroeder (1968b) reported that most leaves had fallen off by this



(a) (b)

Figure 22. Regression of dry matter yield per 20 plants on grain moisture content; (a) Individual plant parts; (b) Silage, refuse, and husk plus cob

harvest date and were not harvested. The regression lines are shown in Figure 23 and the regression coefficients, standard deviations, and coefficients of determination are listed in Table 16.

The percent of total plant dry matter contributed by the grain increased as grain moisture content decreased, and an analysis of variance (Table C10, Appendix C) indicated that the reduction in variance due to regression was highly significant ($P < 0.01$). The regression curve for grain dry matter per 20 plants on grain moisture content (Figure 22a) shows that grain dry matter production increased as the grain dried to approximately 32 percent moisture. Below 32 percent moisture, the percent of the total plant dry matter in the grain increased because the dry matter in the other plant parts was lost at a greater rate than grain dry matter.

The percent of total plant dry matter in the stalk and leaves decreased singificantly as the grain dried (Tables C12 and C13, Appendix C). The percent of total plant dry matter in the cob and husks did not change significantly as the grain dried (Tables C11 and C14, Appendix C).

The dry matter distributions at selected values of grain moisture content were predicted from the regression equations and are listed in Table 17. Deviations from these predicted dry matter distributions should be expected. The dry matter distribution within a plant is a function of variety, plant population, and weather during the growing season. The data used to compute the regressions were obtained from plants in experimental plots that produced grain yields

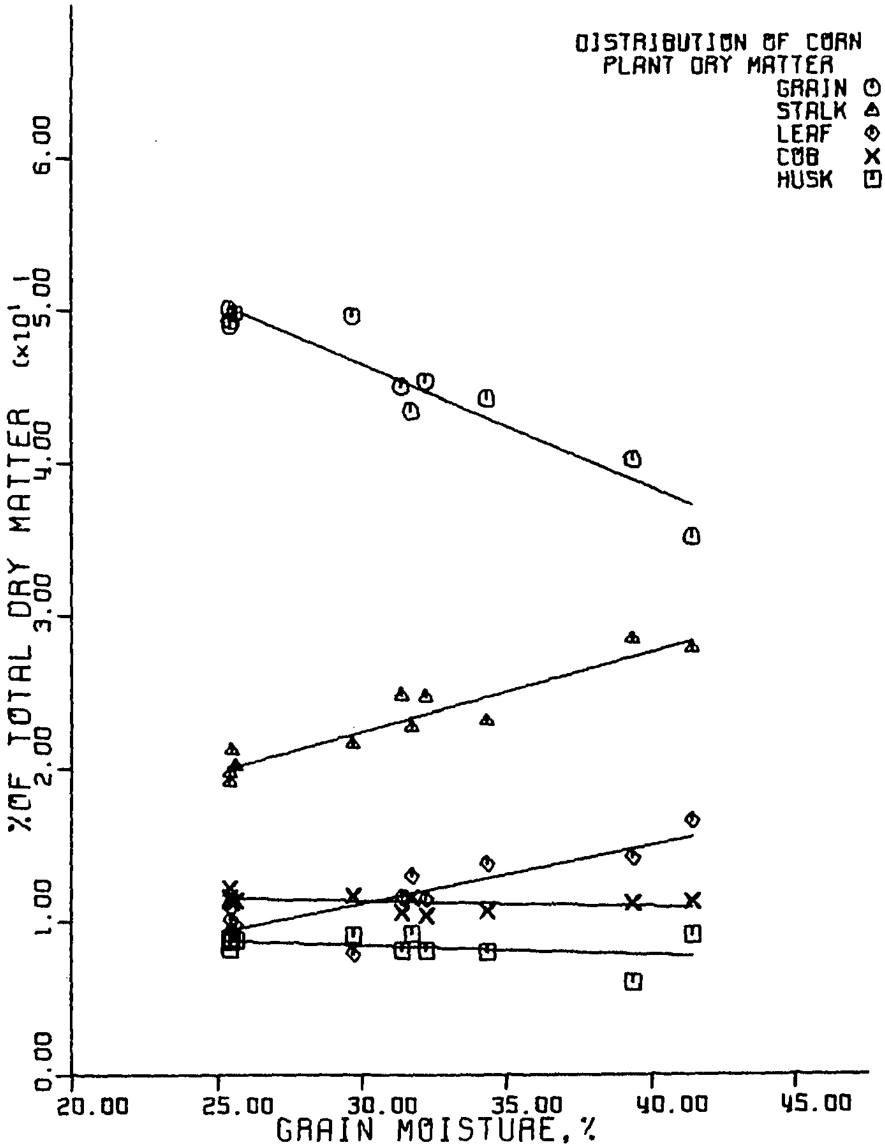


Figure 23. Regression of percent of total plant dry matter on grain moisture content

Table 16. Linear regression of percent of total plant dry matter on grain moisture content[1]

Plant part	Regression coefficients		Standard deviations			(R^2)
	b_0	b_1	b_0	b_1	y/x	
Grain	70.63	-0.806	2.75	0.087	1.548	0.905**
Cob	12.41	-9.036	0.94	0.030	0.527	0.141
Stalk	6.77	0.523	1.93	0.061	1.087	0.890**
Leaf	-0.19	0.383	2.44	0.077	1.369	0.732**
Husk	10.35	-0.063	1.59	0.050	0.895	0.149

[1] $y = b_0 + b_1x$, where y = percent of total plant dry matter, x = grain moisture content, %.

**Calculated F-statistic exceeds the tabulated value at the 1 percent level of significance.

Table 17. Predicted dry matter distribution (% of total dry matter) within corn plants

Plant part	Kernel moisture (%)				
	40	35	30	25	20
Grain	38.4	42.4	46.4	50.5	54.4
Cob	11.0	11.1	11.3	11.5	11.7
Stalk	27.7	25.1	22.5	19.9	17.2
Leaf	15.1	13.2	11.3	9.4	7.5
Husk	7.8	8.1	8.5	8.8	9.1

of 122-152 bushels of corn per acre, and the predicted values should be most accurate for grain yields within this range.

Weber (1970) conducted feeding trials with corn plant forages harvested by Gustafson (1969) and with the forages harvested during this study in 1969. He selected corn plants at random on September 28, 1968 from the field being harvested by Gustafson, and on October 4, 1969 from field 1 as it was being harvested with the Beefmaker II. The corn variety was the same in both fields. The two-year average dry matter values from Weber's samples are listed in Table 18. The percent of total plant dry matter in the grain and leaves was higher, and the percent of total dry matter in the stalk, cob, and husk was lower than the values predicted with the regression equations at a grain moisture content of 24.3 percent. But this variation was expected because Weber's values were obtained in different years and from a corn variety that was not included in Schroeder's study. The regression equations were also calculated from composite values for all five hybrids grown by Schroeder, and not from the values for a single variety. However, all of Weber's values are within the 95 percent confidence intervals for single values of percent of total dry matter for each regression line in Figure 23.

The nutritional composition of each part of the corn plant is also important for an evaluation of potential forage products that could be produced by harvesting different combinations of plant parts. Weber (1970) reported the average crude protein and *in vitro* digestible dry matter values listed in Table 19 for the corn plants he harvested by hand in 1968 and 1969. Adding the values for all the plant parts except the grain shows that the forage fraction of the plants contained 32.8 percent of the *in vitro* digestible dry matter

Table 18. Two-year average dry matter distribution of corn plant parts from Weber (1970)[1]

Plant part	Dry matter (%)	Percent of total dry matter
Grain	75.7	54.4
Cob	55.7	9.7
Stalk	32.7	16.7
Leaf	72.5	12.3
Husk	65.4	6.8

[1] 30-40 plants harvested each year.

Table 19. Two-year average nutritional composition of corn plant parts from Weber (1970)[1]

Plant part	Crude protein(%)[2]	% of total crude protein	IVDDM(%)[2,3]	% of total IVDDM[3]
Grain	9.64	74.3	90.0	67.2
Cob	3.59	4.3	45.2	6.0
Stalk	2.93	7.1	51.7	11.8
Leaf	6.16	11.4	54.1	9.0
Husk	3.29	2.9	63.2	5.9

[1] 30-40 plant samples each year.

[2] Dry matter basis.

[3] *In vitro* digestible dry matter.

and 25.7 percent of the crude protein in the whole plant. These figures represent the potential nutrient recovery in the forage produced with a machine like the Beefmaker. Within this forage fraction, the leaves had the highest crude protein content and the husks were the most digestible. Consequently, a harvesting system that maximized the recovery of these two plant components should produce a high quality forage.

The ranges of crude protein and *in vitro* digestible dry matter contents for plant samples obtained during this research are listed in Table 20. These values were obtained from the Animal Science department at Iowa State University where the samples were analyzed. The high protein content of the leaf fraction and the high dry matter digestibility of the husks are also shown in these values. These data also emphasize the wide range of nutrient contents within a single component of the corn plant and the difficulty of establishing and using standard values for evaluating forages.

The nutrient contents of the harvested forages are also listed in Table 20. The corn refuse silage had the highest nutrient value, as expected. The dry matter digestibility values for some of the husklage samples were quite high, with the average value of 65 percent only slightly below that for husks alone. The stalklages harvested with the flail forage harvester and the Hesston Stakhand were very similar in their range of nutrient values, but the stalklage harvested with the Stakhand had slightly higher average values for both crude protein and digestible dry matter. This improvement may have resulted

Table 20. Nutritional composition[1] of corn plant parts and harvested corn plant forages

Material	Crude protein (%) Range	Crude protein (%) Average	IVDDM (%)[2] Range	IVDDM (%)[2] Average
Grain	9.5-11.2	10.2	88-95	91
Cob	2.1- 3.8	2.8	59-65	60
Stalk	3.0- 5.1	3.7	45-60	51
Leaf	6.2- 7.5	7.0	41-65	58
Husk	2.6- 3.8	2.8	63-72	68
Refuse silage	5.6- 6.9	6.2	62-71	67
Husklage dumps	3.5- 4.5	3.7	50-75	65
Flail-chopped stalklage	2.7- 5.0	3.8	42-60	51
Hesston stacks	3.8- 5.1	4.2	45-60	56

[1] Dry matter basis.

[2] *In vitro* digestible dry matter.

from the greater percentage of cobs, husks, and leaf material in the stalklage harvested with the Stakhand than in the stalklage harvested with the forage harvester.

The mineral composition of each type of forage, and the availability of the protein and minerals to the animal, are also important for proper animal nutrition. Nutrient availability may be affected by the stage of plant maturity at harvest, and analytical studies to determine this information should be included in future research with corn plant forage.

Functional and Mechanical Performance of Equipment

The principal functions of the Beefmaker were (1) to gather and harvest the whole corn plant, (2) to separate the grain from the forage, (3) to chop the forage, and (4) to convey the grain and forage into separate wagons. Hitzhusen (1969) conducted short field tests with the machine in 1968 to evaluate its functional performance, but only a small quantity of refuse was harvested. Consequently, several design changes were made during this study to improve the functional performance of the machine. Diagrams of the functional components of the Beefmaker after all modifications were made are shown in Figures 24 through 29.

Hitzhusen used an auger to convey the snapped ears from the snapping unit to the sheller. A short horizontal auger under the snapping unit and a longer vertical auger terminating at the sheller were connected by a right-angle gearbox inside an elbow. Because there was no auger flighting in the elbow, material had to be pushed through the elbow by incoming material. Hitzhusen found that husks and other plant material conveyed with the snapped ears accumulated around the gearbox in the elbow and restricted the flow of material, eventually plugging the auger.

The auger was removed before the 1969 harvesting season and a continuous chain-and-flight elevator was designed to replace it (Figure 24). Because the elevator was continuous, ear corn was conveyed around an inside corner at the transition from the horizontal to the vertical section. To reduce the possibility of plugging in

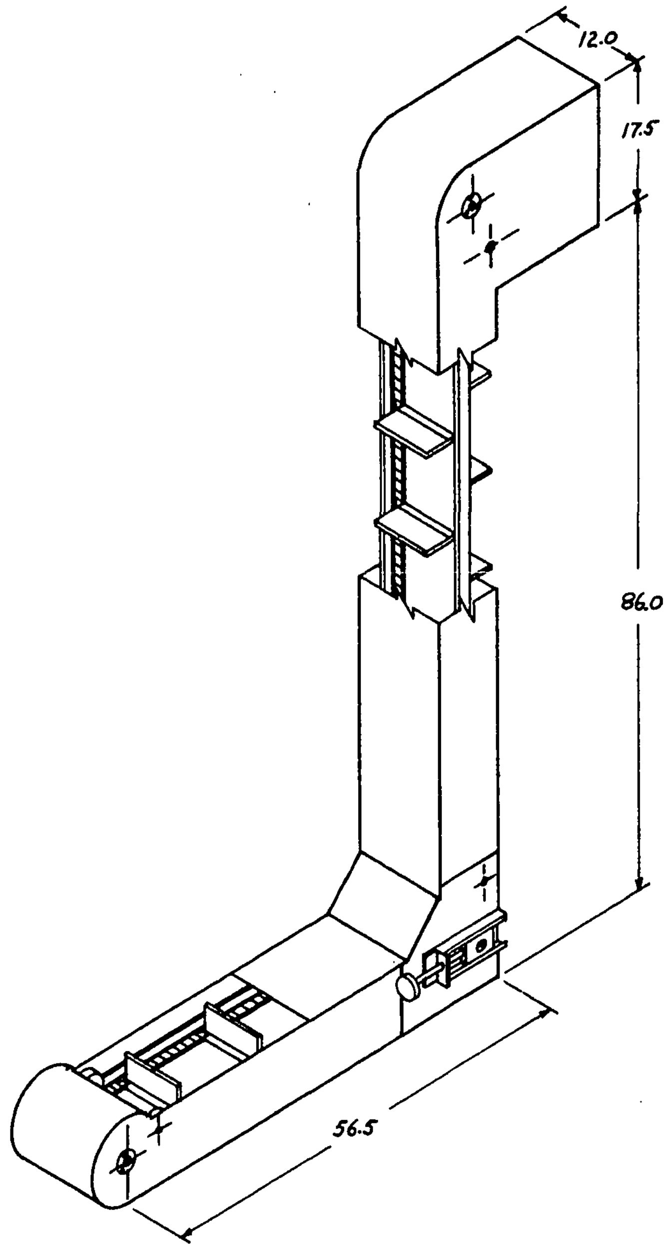


Figure 24. Ear corn elevator added to the Beefmaker

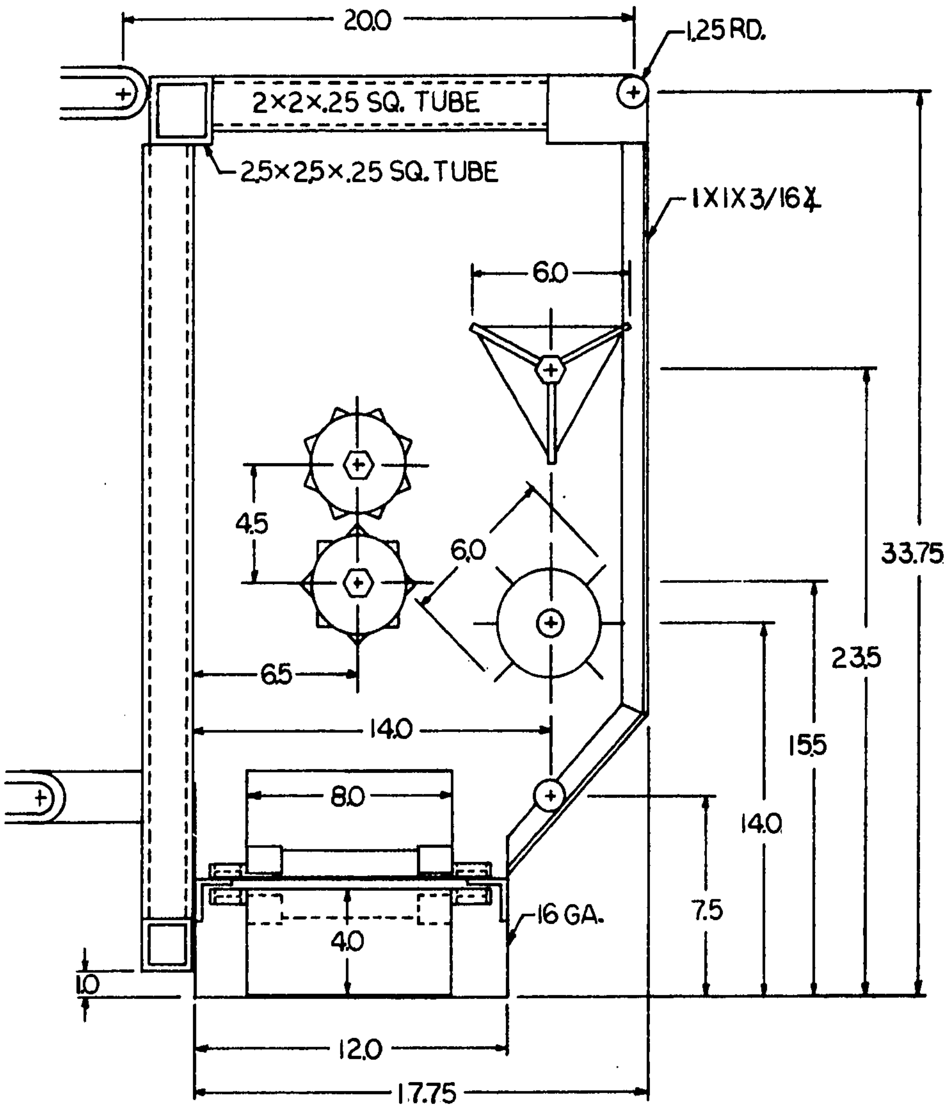


Figure 25. Modified snapping attachment for the Beefmaker

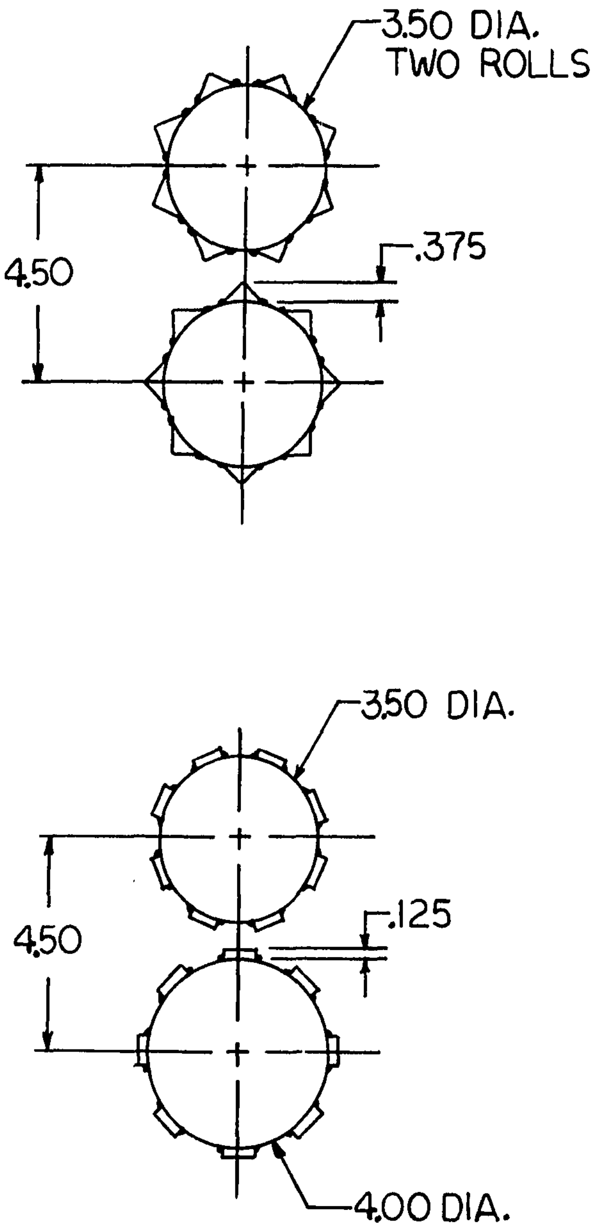


Figure 26. Snapping rolls used in the Beefmaker

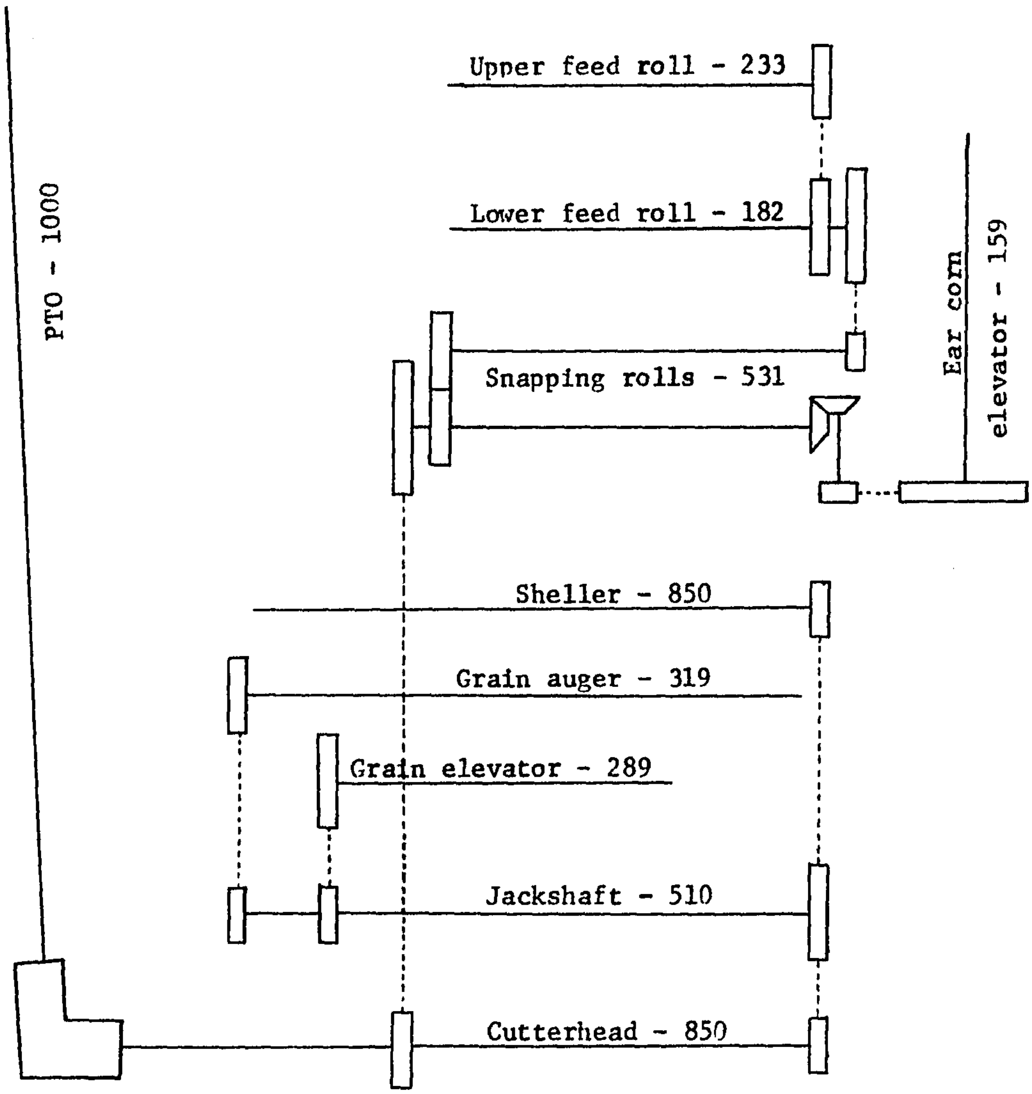


Figure 27. Rotational speeds (rpm) of the functional components of the Beefmaker

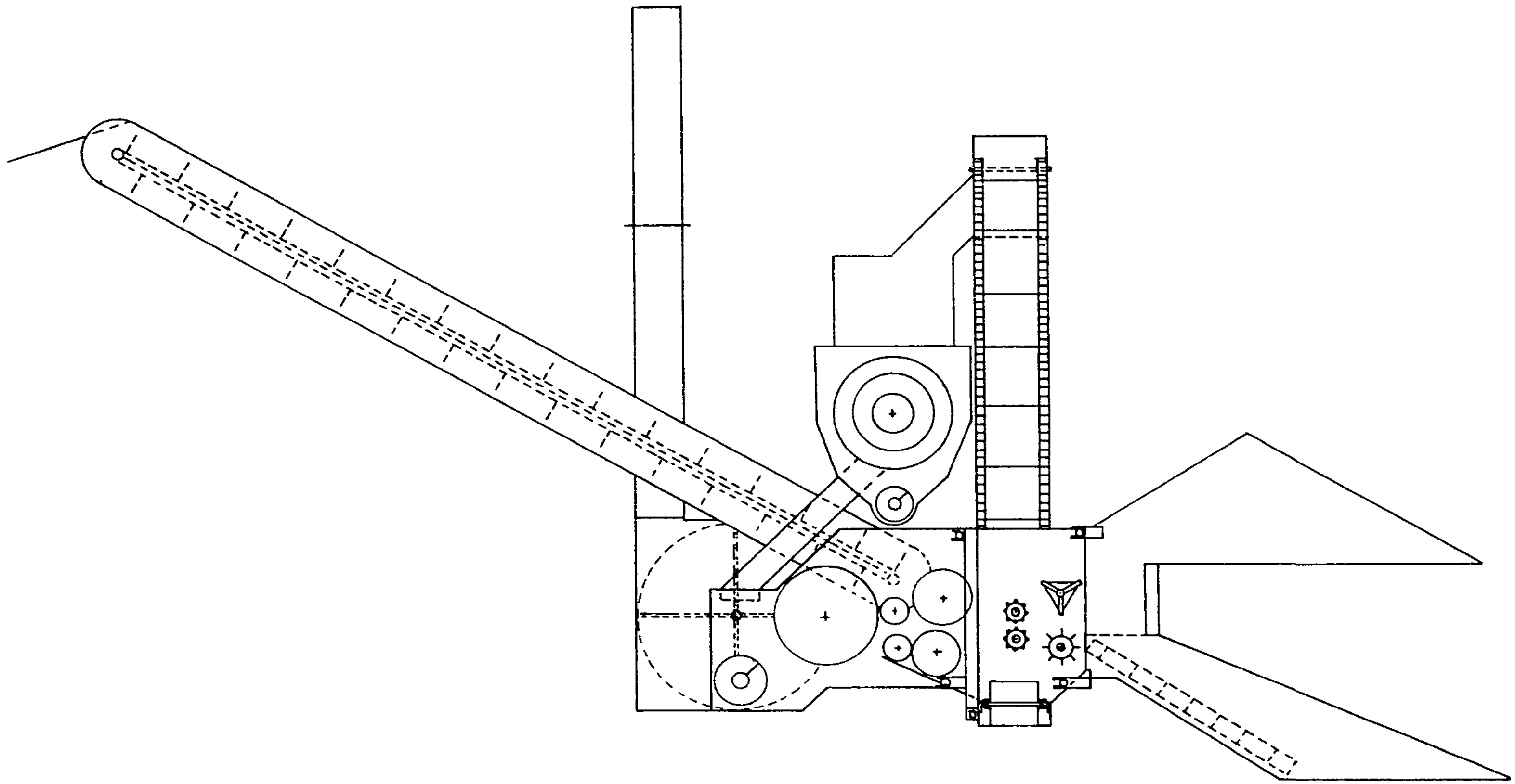


Figure 28. Functional components of the Beefmaker, right side view

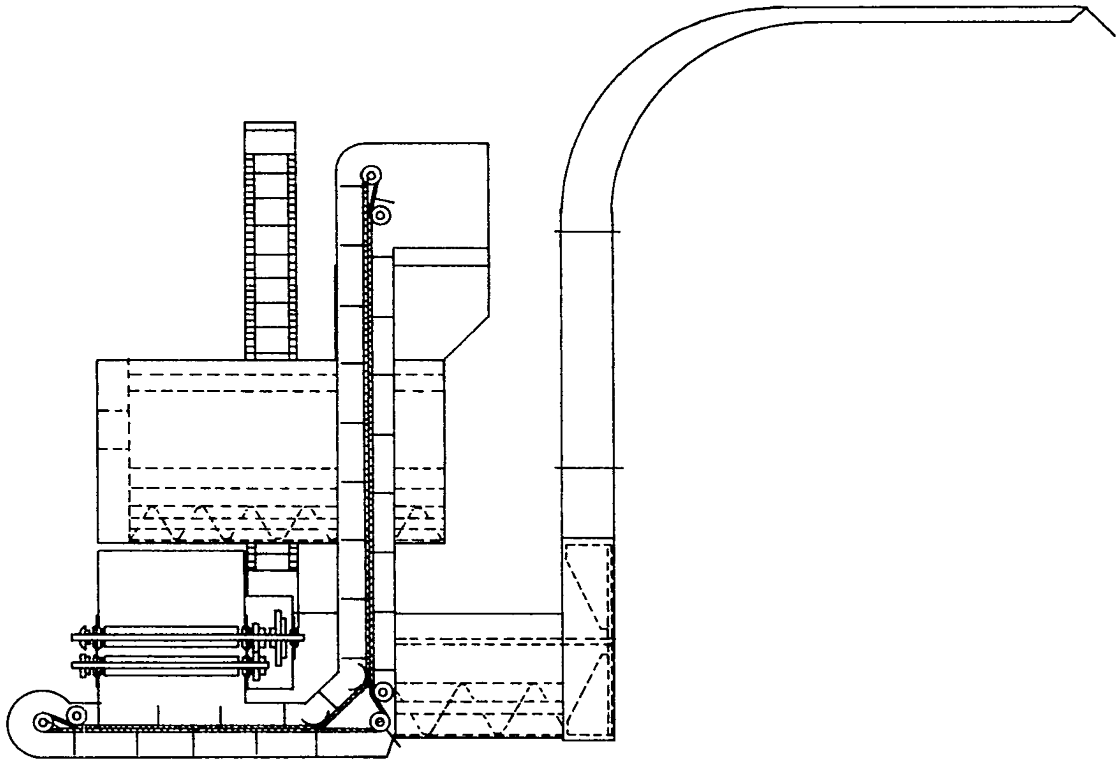


Figure 29. Functional components of the Beefmaker, front view

this corner, the elevator flights were made from rubber and cord belting material that could flex if an ear wedged between a flight and the elevator housing.

Measurements of field losses with the Beefmaker were made several times during the 1969 harvesting season. Initial measurements at the beginning of the season showed a loss of 10 to 14 bushels of shelled corn per acre. Almost all of this grain was found on the ground under the feed rolls of the cutterhead, indicating that it had been shaken out of the forage. Observations made during operation of the machine indicated that some grain shelled from the ears by the snapping rolls was carried through the rolls by the forage. Additional loose grain came from the sheller, where it had failed to separate from the cobs. The original cob return from the sheller discharged the cobs and unseparated grain on the forage directly behind the snapping rolls.

A small quantity of shelled corn was also lost from the return side of the elevator. Because of the possibility of elevator plugging, part of the return side of the elevator had not been covered, allowing the machine operator to observe the motion of the elevator chain. Loose grain that failed to drop into the sheller intake opening was lost as it passed this open section in the elevator.

A grain return pan was constructed below the feed rolls (Figure 28), sloped toward the ear corn elevator. The mean field losses after installing the grain pan are listed in Table 21. Ignoring the elevator loss, the total losses of 1.84 bushels of grain and 16.5 pounds of cobs per acre from the rest of the machine were acceptable. The magnitude

Table 21. Field losses with the Beefmaker[1]

Source	Ears (bu./acre)[2]	Shelled corn (bu./acre)	Cobs (lb./acre)[3]
Elevator		1.22	21.8
Other	0.95	0.89	16.5
Total	0.95	2.11	38.3

[1] Shelled corn and cob losses were measured in 0.001 acre sample areas. Ear corn losses were measured in sample areas of 500 square feet.

[2] Equivalent bushels of shelled corn.

[3] Dry matter weight.

of the ear loss from the gathering unit on the machine was typical of the gathering losses from other harvesting machines operating under similar conditions (Ayres et al., 1972). A small quantity of shelled corn and cobs appeared to have been lost from the sides of the grain pan. Elimination of this loss would require that the feed roll housing of the forage harvester be totally enclosed. The majority of the grain and cob losses after installing the grain pan came from the intake opening of the sheller. It had not been covered, and small pieces of cob and grain were thrown out of the sheller by the rotor. A cover was installed over this opening before the 1970 harvesting season to eliminate this source of grain loss.

A major function of the Beefmaker was to separate the grain from the forage, and its performance of this function was considered unsatisfactory throughout this study. An optimum level of separation was not determined because it was affected by the use of the harvested products. Complete separation might be considered optimum from an economic viewpoint if the grain were to be sold. On the other hand, previous feeding trials (Gay et al., 1969; Vetter and Buchele, 1968) indicated that corn plant forage was only marginally adequate as a wintering ration for beef cows unless a small quantity of grain was included. Therefore, from a nutritional viewpoint, optimum separation might be at some level less than complete separation so that the process of adding grain during feeding could be eliminated.

Grain separating efficiency was defined as the ratio of grain dry matter separated from the refuse to total grain dry matter per acre, expressed as a percent. The separating efficiencies measured in the three fields harvested with the Beefmaker are listed in Table 22. All separating efficiencies were too low if grain recovery comparable to other harvesting machines was an objective. However, feeding trials indicated that an optimum grain content might be 10 percent of the total refuse dry matter, or 200 pounds of grain dry matter per ton of refuse dry matter. On that basis, grain separation with the smooth snapping rolls might be acceptable.

Some of the grain in the refuse came from the shelling unit. An axial-flow cage-type shelling unit was used on the Beefmaker, and grain that failed to pass through the cage was discharged with the cobs and husks. All attempts to obtain more complete separation of the grain by retarding the flow of material through the sheller were unsuccessful. The sheller had been salvaged from a large picker-sheller, and failure

Table 22. Grain separation with the Beefmaker

		Snapping roll design	
		Aggressive	Smooth
1969:	Grain yield, bu./acre	133.4	164.2
	Grain in refuse, bu./acre	27.5	16.6
	lb./ton[1]	387.2	221.6
	Separating efficiency, %	79.4	89.9
1970:	Grain yield, bu./acre	92.2	
	Grain in refuse, bu.,/acre	22.6	
	lb./ton[1]	349.8	
	Separating efficiency, %	75.5	

[1] Pounds of grain dry matter per ton of refuse dry matter.

to obtain complete separation of the grain was attributed to two features of its original design that were not included when it was mounted on the Beefmaker. In the original picker-sheller, the shelling unit was inclined at an angle of 15 degress from the horizontal, presumably to retard the flow of material through the unit to obtain more complete shelling and separation of grain. The cobs were also discharged onto a large oscillating screen for final separation of grain, and this cleaning unit was not included on the Beefmaker.

The rest of the grain in the refuse came from the snapping unit. The snapping rolls used in the Beefmaker (Figure 26) were much more aggressive than the spiral-fluted snapping rolls normally used in cornpickers, and they shelled more grain from the ears during the snapping operation. Aggressive snapping rolls were needed because they also had to function as feed rolls to convey plants through the snapping unit. The smoother snapping rolls shown in Figure 26 were used in one field during 1969 to reduce the amount of grain in the refuse. But they did not function well as feed rolls, and frequent plugging occurred in the snapping unit.

Feeding plants through the snapping unit was the most serious problem encountered with the Beefmaker. In the original design of the snapping unit, the 3-bar feed roll (Figure 25) was located in the lower position, and a top feed roll was not used. A sheet metal deflector, located above the single feed roll, guided the stalks into the snapping rolls. However, control of the plants was lost when they were released by the gathering belts. The single feed roll would not pull the plants into the snapping rolls, and plants would accumulate in the snapping unit until they were pushed into the snapping rolls by the plants behind them, or until the machine plugged.

Because plant flow through the snapping rolls was not continuous, several ears were snapped at a time. The opening between the lower snapping roll and the feed roll was quite narrow (Figure 25), and ears would bounce against the snapping rolls several times before dropping to the elevator. This caused additional shelling and increased the grain content of the refuse.

The uneven flow of plants through the snapping rolls also caused several mechanical failures in 1969. The shaft through the upper snapping roll failed three times when too many plants had been pulled into the rolls. The bearing located at the end of this shaft next to the driving sprocket (Figure 29) was not included on the original snapping unit used in 1969. Consequently, the extension of this shaft, on which the sprocket and the timing gear driving the lower snapping roll had been mounted, was a cantilever. All three failures occurred at the face of the timing gear hub. An analysis of the stresses in the shaft, using estimated values for applied forces and torques, showed that the principal stresses and the shear stress were maximum at the outer face of the gear itself. The gear hub apparently prevented failure at that location.

When the first two shaft failures occurred, three 0.25-inch steel machine bolts with no grade markings had been used to assemble the driving sprocket and its hub. One of the bolts was removed after the second shaft failed. Subsequent plugging of the snapping rolls caused the remaining two bolts to shear, and harvesting continued for several days. However, the third shaft failure occurred with only two shear bolts in the sprocket hub. All three shaft failures and all shear bolt failures occurred with the more aggressive snapping rolls. The smoother rolls would slip on the plants when they plugged, preventing mechanical failures.

Mechanical failure also occurred in the gear reducer used to transmit power to the gathering unit and to the feed rolls of the forage harvester. A shifting mechanism in the gear reducer enabled the machine operator to reverse the direction of rotation of the feed rolls and the direction of travel of the gathering belts. By reversing the gathering mechanism, the operator could often unplug the snapping unit without leaving the tractor. Four 0.375-inch grade five cap screws sheared on three occasions as the gear reducer was shifted into reverse. The gear reducer was shifted more often than it would have been under normal service because of the frequent plugging of the snapping unit. But the loads on the gear reducer were no greater than those that would be encountered under normal service with a forage harvester. The bolt failures were apparently fatigue failures from the shock loading caused by repeated shifting of the gear reducer with the machine running at full speed.

After the 1969 harvest had been completed, two design changes were made to reduce the incidence of mechanical failure and to improve the flow of plants through the snapping unit:

1. The shaft through the upper snapping roll was lengthened and the third bearing was installed next to the sprocket (Figure 29).
2. The 3-bar feed roll was replaced with a smaller feed roll salvaged from a forage harvester, and the 3-bar roll was installed as a top feed roll (Figure 25).

Plant flow through the snapping unit was much better in 1970 than it had been the previous year because the two feed rolls would pull the plants into the snapping rolls. Feeding was still uneven because of the 4-inch clearance between the feed rolls, and the snapping rolls plugged occasionally, causing the shear-bolts in the driving sprocket to fail. Only two shear bolts were used during 1970, and no shaft failures occurred.

The shelled corn harvested by the Beefmaker contained a large quantity of fines because a cleaning unit had not been designed for the sheller. All the grain harvested during this study was stored in a gastight silo at high moisture contents and this additional material did not cause any storage problem. However, if the grain had been dried before being stored, an additional cleaning operation probably would have been required.

In the original Beefmaker design, the cob return from the sheller discharged the cobs onto the forage behind the snapping rolls. Observations made during 1969 indicated that many pieces of cobs were shaken out of the forage as they passed through the feed rolls, carried to the ear corn elevator by the grain pan, and recycled through the sheller. The cob return was reversed in 1970 so that material discharged directly into the rear cross-auger of the forage harvester. No reduction in the quantity of fines in the shelled corn nor improvement in grain separation was observed, but the loss of cobs from the return side of the ear corn elevator (Table 19) was practically eliminated. Apparently the pieces of cob lost in 1969 were those being recycled.

Three men were required to operate the Beefmaker harvesting system; one to operate the Beefmaker, one to drive the tractor pulling the forage wagon alongside the machine, and one to haul and unload harvested material. One man could not haul and unload both refuse and shelled corn as fast as they were harvested when the machine was operating without plugging. Consequently, a fourth man would be required for continuous operation unless several extra wagons were available for temporary storage. Further development of the harvesting system should center around materials handling to reduce the labor required.

The final distribution of weight after all modifications were made to the Beefmaker is shown in Table 23. The addition of 2600 pounds to the original forage harvester did not cause any structural failure in the machine frame or lifting mechanism during this study.

The final performance of the Beefmaker, after all modifications were made in 1970, was considered satisfactory for an experimental machine. But the frequency of plugging, the quantity of grain in the refuse, and the quantity of fines in the shelled corn were all too high for acceptable performance as a commercial machine. A more uniform flow of plants through the snapping unit might be obtained by replacing the 3-bar feed roll with a smoother roll. The upper feed roll should also be designed to move vertically against a spring in response to the volume of material entering the snapping unit. This would permit the feed rolls to be positioned closer together to pull plants into the snapping unit as soon as they were released by the gathering belts, and would still allow ears to pass between them. With a more uniform flow of plants, smoother snapping rolls could be used to reduce the quantity of grain in the refuse. The snapping rolls could also be positioned farther behind the feed rolls to provide a larger opening for the removal of snapped

Table 23. Weight distribution of the Beefmaker

Location	Weight (lbs.)
Right wheel	3030
Left wheel	2420
Hitch	540
Total	5990
Original forage harvester[1]	3233
Special equipment[2]	160
Beefmaker attachment[3]	2597

[1] Base unit plus 2-row gathering unit, obtained from manufacturer's literature.

[2] Long tongue, axle extensions, spout extension; estimated.

[3] Snapping unit, ear corn elevator, sheller, and shelled corn elevator.

ears. The shelling unit should be replaced with one that includes a cleaning section to remove the fines from the shelled corn.

The field performance of the Foster Harvest Master combine attachment was excellent. There were no mechanical failures during the four harvesting seasons. The power required to operate the attachment did not cause a noticeable effect on the operation of the rest of the combine, and normal harvesting speeds were maintained at all times. Some dry pieces of husk and leaf were blown over the hopper by the air blast from the combine, but forage recovery was estimated to be 90 percent or better.

This harvesting system did not require any additional labor when the husklage was dumped in the field. One man operated the combine and one man hauled and unloaded shelled corn, just as they would have done without harvesting husklage. This was an important advantage of this harvesting system for many smaller farms.

The box on the dump trailer was connected to the trailer frame by an intermediate link, shown at the extreme left in Figure 9. When the machine operator released the latch at the front of the box, the box was supposed to dump and return to the latched position without stopping the combine. However, the box occasionally failed to dump properly and the operator would have to stop the machine and either dump or re-latch the box manually.

Three positions of the linkage connecting the box to the trailer frame are shown in Figure 30 for a normal dumping cycle. The center of gravity of the loaded box was located to the right of the pin connection between the intermediate link and the frame. When the machine operator released the latch, the box and the intermediate link rotated together about the pin connection to the frame, as shown in Figure 30b. As the husklage slid out of the trailer, the downward force on the right side of the intermediate link decreased, and the spring at the other end of the link caused it to rotate to the position shown in Figure 30c. The center of gravity of the empty box was located between the two pin connections, and the box returned to the latched position shown in Figure 30a when it was empty.

This dumping cycle worked well when the box was not overfilled.

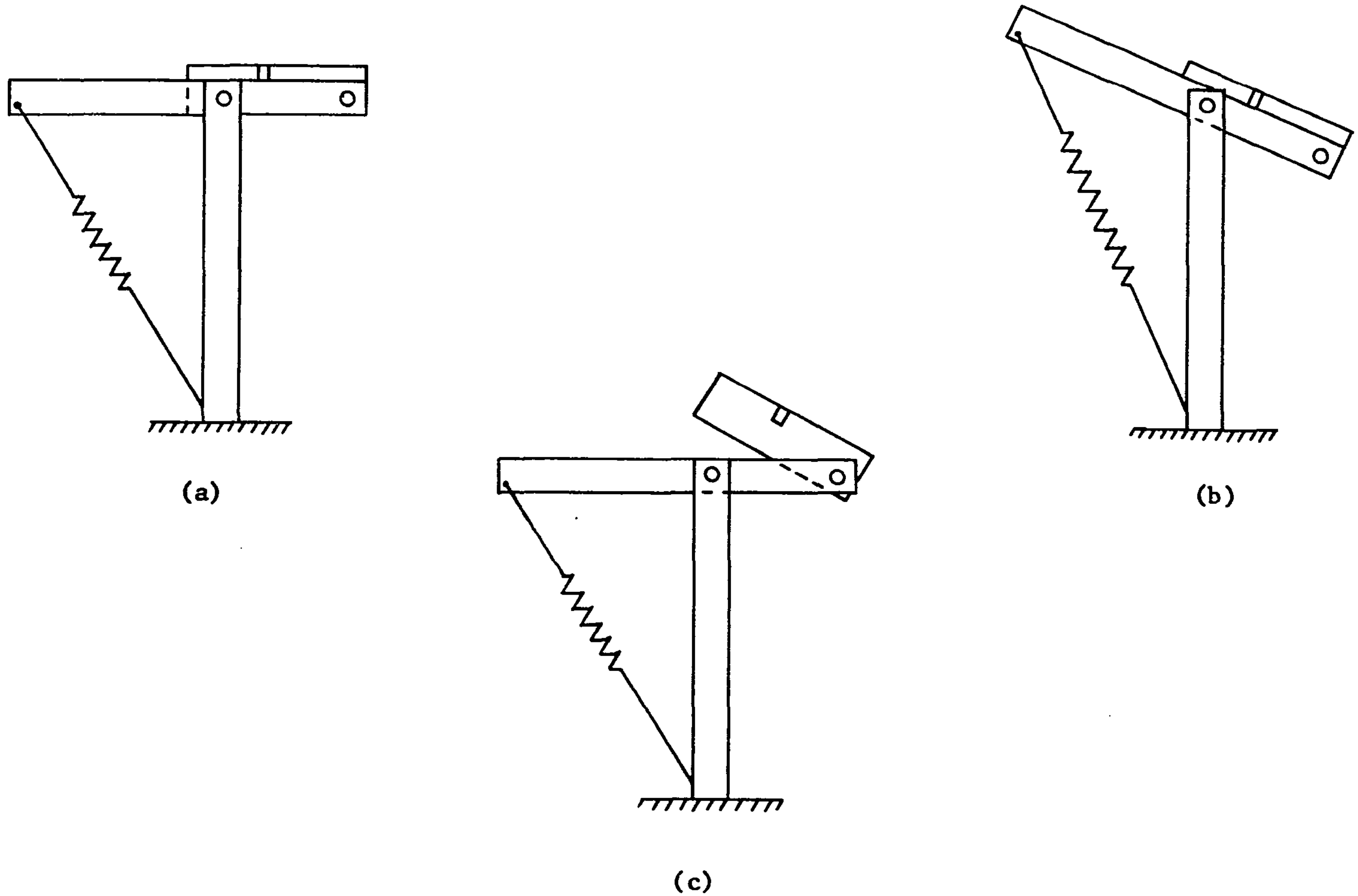


Figure 30. Connecting link between the box and frame on the Foster Harvest Master trailer; (a) Box latched; (b) Dumping; (c) Box return

For example, 80 dumps were made in field 1 in 1971 and the trailer dumped and relatched every time. The trailer was only about three-quarters full in this field when it was dumped.

When the trailer was completely filled, the box would occasionally fail to complete a dumping cycle properly. This occurred when husklage dumps were placed at the ends of a field with either quarter- or half-mile rows. A dump was made each round trip with quarter-mile rows, and two dumps were made per round trip with half-mile rows. In either case, the volume of the trailer box was too small and it would be filled before reaching the end of the field. The husklage from the remaining length of rows was blown against the front of the load, and because of the fibrous nature of the husklage, enough would occasionally stick to the load to prevent the trailer from dumping when the latch was released. This extra material apparently was heavy enough to move the center of gravity of the loaded box forward so that it would not dump.

A second problem caused by overfilling the box occurred when a piece of cob wedged in the latch as it fell from the front of the load. It would either prevent the latch from releasing or from returning to its original position. In either case, the machine operator would have to stop the combine and remove the cob.

Failure to dump properly occurred less than 20 percent of the time, but it was annoying to the machine operator and reduced the harvesting capacity of the combine. The linkage connecting the box to the trailer frame should be redesigned to assure proper dumping every time. The volume of the trailer box should also be increased 10-15 percent so that it will hold all the husklage harvested from four half-mile rows. Dumps could then be placed at one end of the field and two-thirds of the distance across the field if a 6-row combine was used, and in the center and at both ends of the field if an 8-row combine was used.

The machine operator could not see the combine attachment or the trailer without stopping the combine and leaving the operator's station. Some method of monitoring the equipment would be a desirable addition on future models because a mechanical failure might not be noticed by the operator until the combine became plugged.

When husklage was collected in forage wagons, the speed of the blower on the combine attachment was increased to its maximum, but it would still not fill the back of the forage wagons. The dry matter density of loose husklage was quite low, and only 1500-1700 pounds of husklage dry matter could be loaded into a wagon. The combine had no difficulty pulling the wagons, but turning at the ends was difficult when fields were wet.

The inability of the combine operator to see the forage wagon from the operator's station was a liability with this harvesting system. The unloading apron and the space ahead of the beaters in the forage wagon filled with husklage if harvesting continued after the wagon box was filled. This made unloading difficult because the forage ahead of the beaters had to be unloaded by hand. Hitching empty wagons to the combine was also difficult and caused a significant decrease in the field efficiency of this harvesting system.

The husklage collected with forage wagons was chopped with the recutter-blower shown in Figure 6 before being stored. A screen with 1-inch holes was used in the recutter. Power to operate the recutter-blower was limiting, and the operator had to control the material flow from the forage wagons very carefully to avoid stalling the 105 horsepower tractor on the blower. The finely chopped dry material also created a very dirty environment for the operator when filling the trench silos.

The field performance of the Johnson Strawbuncher was completely unsatisfactory, and it was abandoned after harvesting two loads of husklage in 1969. Material would not flow smoothly into the auger, and forage would accumulate on the collecting pan until the combine became plugged. When material did reach the auger, cobs wedged between the auger flighting and the housing. The auger was ground-driven, and the increased torque required to break the cobs caused the single drive wheel to skid.

As the size of the load increased, the increased weight on the driving wheel allowed it to produce a greater input torque to the auger drive before skidding. A detachable-link steel chain was used to transmit power from the axle to the input shaft of the right angle gearbox driving the auger. The input torque from the driving wheel eventually increased enough to cause the chain to either break or to climb the sprocket when cobs wedged in the auger.

Since the auger was ground driven, it would also not turn unless the combine was moving. Consequently, plugging occurred whenever the combine separator continued to operate after the forward motion of the combine ceased. This usually occurred when the combine was stopped and backed up to clear a plugged gathering unit. But it also occurred whenever the forward speed of the combine was reduced, such as for turning at the ends of the field or because of poor tractive conditions.

The Johnson Strawbuncher had a chain-and-flight apron conveyor in the bottom of the box to unload the husklage, and it was also ground-driven. Unloading was as difficult as loading the trailer, because either the driving-wheel skidded or the sprocket on the axle slipped on the chain. Approximately an hour was required to unload the first dump. After harvesting a second load and experiencing similar unloading problems, the machine was abandoned.

A chopping mechanism on the combine might improve the performance of the Johnson Strawbuncher if it chopped the cobs fine enough to be handled by the auger. But the unsatisfactory characteristics of the ground drive made this machine unacceptable.

The Hesston flail shredder combine attachment did not perform satisfactorily either. Frequent plugging occurred, particularly in the early morning and late afternoon when the forage was damp. Forage from the straw walkers dropped into the shredder and was thrown up the dischrage spout satisfactorily. But the housing around the shredder (Figure 12) prevented material from the combine sieves from passing through the flails, and this material had to slide under the shredder housing and be picked up by the air stream from the flails.

Lighter pieces of forage were carried through the 3-inch slot satisfactorily, but heavier pieces of stalk and cob lodged along the edges of the slot and restricted the flow of material. Eventually material accumulated in this slot until it was completely blocked.

The Hesston shredder attachment did break the cobs into smaller pieces than the Foster attachment, which might have improved the utilization of the husklage. Several husklage dumps were made with the Hesston attachment in 1970 for a feeding trial to measure consumption. But a heavy snow storm on January 2, 1971 caused snow to drift over the fence around the dumps, allowing the two groups of cattle in the trail to mix and to break open all the dumps, and the feeding trial was abandoned.

The functional performance of the Fox forage harvester with the flail pickup attachment was quite satisfactory except for the low forage recovery behind the combine (Table 12). The flails were unable to pick up the cobs, grain, and heavier pieces of stalk that had fallen between the rows. Careful adjustment of cultivating equipment to prevent the formation of ridges around the rows would improve forage recovery.

Adjustment of the operating height of the flails was a compromise between low forage recovery and low soil pickup. Soil was very abrasive, and the knives in the cutterhead of the forage harvester dulled rapidly. Soil also accumulated under the chain-and-slat feeder ahead of the cutterhead, and had to be cleaned out frequently to prevent damage to the chain.

A 4-inch recutting screen was installed in the cutterhead of the forage harvester to reduce the number of long pieces of husk and leaf and to grind the cobs in the stalklage. A 75-horsepower tractor was used and after harvesting three or four loads of stalklage, the tractor was unable to maintain a forward speed of 2 miles per hour. The operator would either have to stop and sharpen the knives or shift the tractor into low gear in order to continue harvesting. The forage harvester was equipped with an electric knife grinder, and sharpening caused a significant harvesting delay because it could not be done in the field. Tungsten carbide knives are available for the Fox forage harvester, and they should be used for harvesting stalklage to avoid the inconvenience and delay caused by frequent knife sharpening.

The recutting screen was removed from the forage harvester after the second day of operation. Without the screen, the tractor could maintain a forward speed of approximately 4.0 miles per hour when the knives were sharp. To reduce the number of long pieces in the stalklage, a 3-inch screen was used in the recutter-blower at the silo. Frequent sharpening of the knives in the recutter was required, but it could be done in place by one of the operators unloading stalklage.

Stalklage was harvested with the forage harvester immediately after combining the grain because a forage moisture content above 45 percent was desired. Consequently, competition with the grain harvesting system for labor was not eliminated even though the forage and grain were harvested separately. Three men were needed to harvest stalklage without waiting time, one to operate the harvester and two to haul and unload stalklage. One man hauling could not keep up with the forage harvester because the silo was located 2 miles from the field. Since two men were required to combine and haul the grain, a minimum of our or five men would be needed for simultaneous operation of both systems.

The major advantage of using a forage harvester for stalklage was the ability to handle and store the forage with conventional silage equipment. A forage harvester, self-unloading wagons, and a blower are available on many midwestern farms, so the investment in additional equipment to harvest stalklage would be limited to only the flail pickup attachment and a suitable storage structure.

Additional research should be done to establish a minimum allowable moisture content for safe storage of chopped stalklage. Simultaneous harvesting of grain and forage could not be done on many farms because of insufficient labor. Grain could be harvested for a part of the day and stalklage for the remainder of the day, but this would reduce the harvesting capacity of each system. A delay between grain and stalklage harvesting would be desirable if the loss of moisture from the forage could be tolerated.

The field performance of the Hesston Stakhand 30 was excellent. The harvested stalklage was essentially the same as the forage obtained with the Fox forage harvester. But it was stacked in the field instead of being ensiled. At higher moisture contents (Table 13), forage heated in the stack and visible mold formed. But heating and mold growth were not evident when the moisture content of the stalklage was below 40 percent when it was stacked. Presumably, the drier the forage, the lower the risk of spoilage in the stack. Consequently, a delay between grain harvesting and stalklage harvesting to allow the forage to lose moisture was a requirement with this harvesting system. This allowed a complete separation of grain harvesting and stalklage harvesting, eliminating the competition for labor that occurred with the forage harvester. Only one man was required to operate the Stakhand, and since stacks were stored in the fields in which they were harvested, handling equipment and storage structures were not required.

Dry matter recovery was higher for the Stakhand than for the forage harvester (Table 12), primarily because the flail pickup on the Stakhand was carried on a roller instead of skid shoes. The roller was positioned directly behind the flails and ran on the two rows being harvested. This permitted the operating height of the flails to respond directly to changes in elevation of the rows, and the flails could be adjusted closer to the ground.

The dry matter remaining in the field after harvesting two rows with the Stakhand is shown in Figures 31 and 32. The ridges around the rows from cultivation are evident in Figure 31. Even with the flails adjusted to operate within an inch of the soil on top of the ridges, a significant quantity of husks and cobs was left between the rows. This illustrates the difficulty of recovering forage after it

Figure 31. Forage left after harvesting two rows with the Hesston Stakhand

Figure 32. Forage left between the rows by the Hesston Stakhand

has been dropped on the ground by the combine. However, in fields with erosive soil, the forage left between the rows would be quite effective for soil conservation.

Capacitive Performance of Equipment

Several observations of each harvesting and handling machine were made in 1969 and 1970 to determine their harvesting and processing rates and to identify activities that reduced capacitive performance. Observations of all activities during the scheduled harvesting time could not be made because the harvesting systems were not operated under normal production conditions. Many nonproductive activities, such as sampling harvested products or moving a blower back and forth between two storage structures, were required to support the research being conducted. These activities interrupted harvesting operations each day, making continuous system observation impossible.

Von Bargen's (1967, 1968) classification of field machine activities (Table 3 and Figure 1) was used but only operate and delay activities were measured. They were divided into several element activities as shown in Figures 33 and 34. Observations of discrete harvesting and processing cycles were made which excluded idle and service activities and travel to and from the field.

The activity times measured during each observed cycle are listed in Tables B1 through B12 of Appendix B. The mean values of the observations of each harvesting machine are listed in Table 24. Support functions required a significant portion of total harvesting cycle

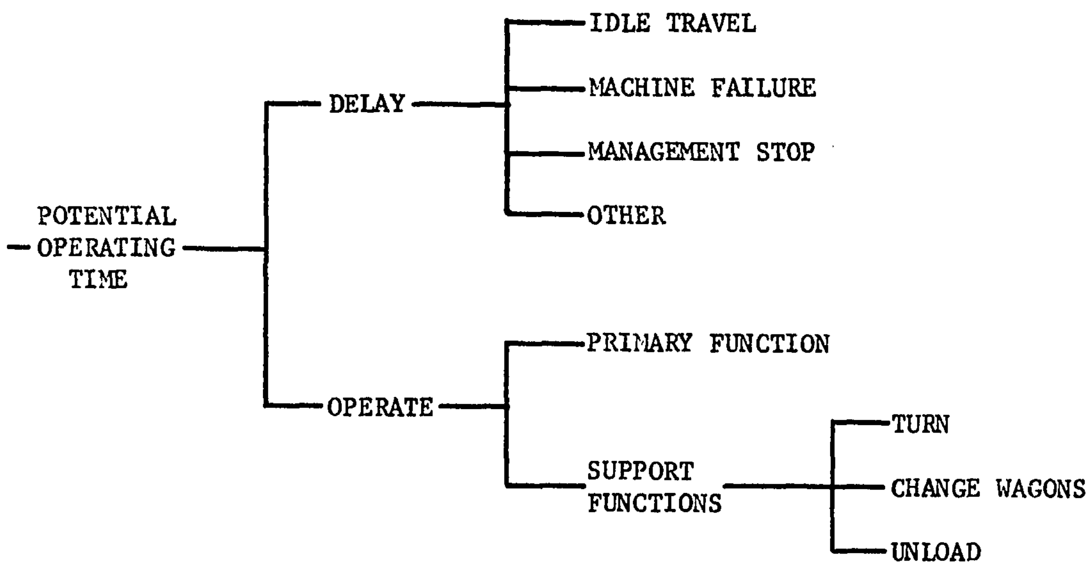


Figure 33. Division of field activities for harvesting machines

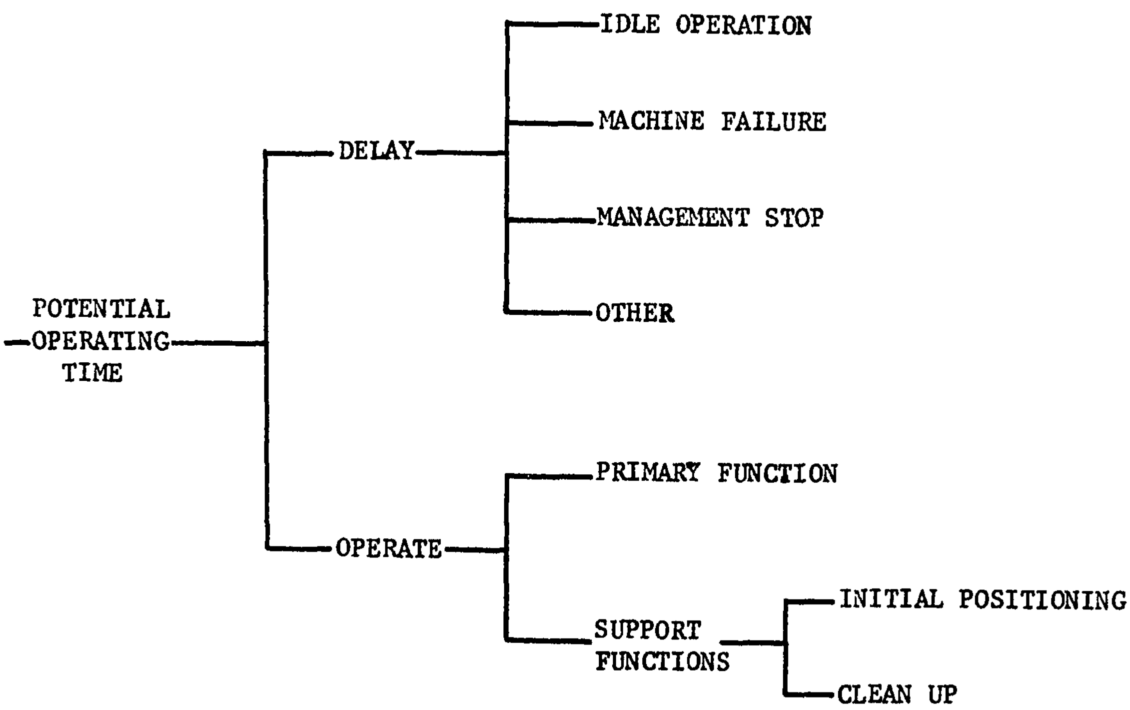


Figure 34. Division of activities for processing machines

Table 24. Mean observations of harvesting machines

Machine	Activity times (min.)				Forage (lb.)	
	Harvest	Support functions	Delay	Total	Wet	Dry
3-row forage harvester	12.08	4.09	0.24	16.41	9040	4330
Beefmaker II						
Field 1	24.06	3.27	8.96	36.29	6586	3207
Field 4	32.07	6.28	33.92	72.27	6103	2688
Fox forage harvester						
Behind combine						
4-inch screen	44.32	4.16	0.91	49.39	4778	2683
no screen	24.25	4.68	0.00	28.93	4488	2321
Behind picker	17.98	2.49	0.20	20.67	2847	2034
4-row combine with Foster Harvest Master						
Stacking dumps	9.31	6.62	2.64	18.57	1757	1186
Dumping on headland	11.91	4.64	1.17	17.72	1136	816
Operator A	10.41	4.40	1.95	16.76		
Operator C	13.41	4.97	0.40	18.78		
Random dumping	11.76	3.81	0.64	16.21	1127	845
Using forage wagons	12.57	6.99	1.29	20.85	2474	1667
4-row combine with Hesston flail shredder	12.18	3.49	1.75	17.42	1032	797

time for all machines, and delay time was high for the Beefmaker, as explained in the previous section on functional performance.

Several measures of capacitive performance are listed in Table 25, defined as follows:

<u>Field efficiency</u>: The ratio of primary function time to potential operating time.

<u>Man-machine activity</u>: The ratio of primary plus support functions time to potential operating time.

<u>Man-machine productivity</u>: The quantity of material harvested or processed per hour, or the field area covered per hour, for a man-machine activity equal to 1.

This definition of field efficiency is compatible with the usual definition of field efficiency given in equation 1 because all the harvesting machines listed in Table 25 were row-crop machines. Their effective operating widths were equal to their theoretical operating widths, so field efficiency was a measure of time use efficiency only.

The values of field efficiency, man-machine activity, and forage dry matter productivity in Table 25 were calculated from the activity times and forage weights listed in Table 24. Grain and acres per hour productivities were calculated from the forage dry matter productivity and the mean forage and grain yields listed in Tables 5, 7, and 12.

Man-machine activities were high for the 3-row forage harvester and for the Fox forage harvester, indicating very little delay activity for either of these machines. Man-machine activity was also high for the 4-row combine with the Foster Harvest Master except when stacking

Table 25. Mean capacitive performance of harvesting machines

Machine	On-row speed (mph)	Field efficiency (%)	Man-machine activity (%)	Man-machine productivity		
				Forage (lb.DM/hr.)	Grain (bu./hr.)	Acres/ hour
3-row forage harvester	1.86	0.736	0.985	16,067	-	1.24
Beefmaker II						
Field 1	1.97	0.663	0.753	7,041	111	1.05
Field 4	1.16	0.444	0.531	4,205	88	0.59
Fox forage harvester						
Behind combine						
4-inch screen	1.72	0.897	0.982	3,321	-	1.43
no screen	2.72	0.838	1.000	4,814	-	2.07
Behind picker	3.66	0.870	0.990	5,962	-	1.95
4-row combine with Foster Harvest Master						
Stacking dumps	2.59	0.501	0.858	4,467	310	1.83
Dumping on headland	1.98	0.672	0.934	2,958	151	1.73
Operator A	2.27	0.621	0.884	3,306	169	1.93
Operator C	1.75	0.714	0.979	2,664	136	1.56
Random dumping	2.08	0.725	0.961	3,256	166	1.90
Using forage wagons	3.13	0.603	0.938	5,113	349	2.44
4-row combine with Hesston flail shredder	1.95	0.699	0.900	3,052	250	1.84

dumps.

A comparison of operators A and C with the combine and Foster Harvest Master dumping husklage on the headland shows why both man-machine activity and man-machine productivity need to be included in an evaluation of the capacitive performance of a machine or system. Both operators had the same machine in the same field on the same day, and operator C had the highest field efficiency and man-machine activity. But the forage output of operator A was higher because of his higher man-machine productivity, resulting from a higher field speed. Operator A harvested 2922 pounds of forage dry matter per hour, and operator C harvested only 2608 pounds of forage dry matter per hour.

Activity ratios and times for the support functions and delay activities are listed in Table 26 and 27. The time to change wagons was measured for the 3-row forage harvester and for the combine and Foster Harvest Master when husklage was collected in forage wagons. The time for this activity was not recorded for the Beefmaker or for the Fox forage harvester for an undetermined reason. Because the operations required to perform this activity with these two machines were similar to the operations required with the 3-row forage harvester, the forage harvester activity time was used for all three machines. One-half of this activity time was used for the Beefmaker because the grain wagon was changed after harvesting two loads of forage.

The support functions of turning and changing wagons required almost 25 percent of the field time for the 3-row forage harvester because of the short rows and the relatively short primary function

Table 26. Support function activities of harvesting machines

Machine	Activity ratio	Support function activity times (min.) Turn	Change wagons	Unload grain	Unload forage
3-row forage harvester	0.249	3.01	1.08	-	-
Beefmaker II					
Field 1	0.090	2.73	0.54[1]	-	-
Field 4	0.087	5.74	0.54[1]	-	-
Fox forage harvester					
Behind combine					
4-inch screen	0.084	3.08	1.08[2]	-	-
no screen	0.162	3.60	1.08[2]	-	-
Behind picker	0.120	1.41	1.08[2]	-	-
4-row combine with Foster Harvest Master					
Stacking dumps	0.356	2.10	-	1.82	2.70
Dumping on headland	0.262	2.71	-	1.03	0.90
Operator A	0.263	2.57	-	1.10	0.73
Operator C	0.265	2.85	-	0.96	1.16
Random dumping	0.235	2.25	-	1.11	0.45
Using forage wagons	0.335	1.42	3.86	1.71	-
4-row combine with Hesston flail shredder	0.200	1.51	-	1.00	0.98

[1] This activity time was not measured so one-half of the time measured for the 3-row forage harvester was used.

[2] This activity time was not measured, so the time measured for the 3-row forage harvester was used.

Table 27. Delay activities of harvesting machines

Machines	Activity ratio	Delay activity times (min.) Machine plugging	Mech. failure	Idle travel	Other
3-row forage harvester	0.015	0.24	-	-	-
Beefmaker II					
Field 1	0.247	6.12	1.43	-	1.41
Field 4	0.469	21.94	11.98	-	-
Fox forage harvester					
Behind combine					
4-inch screen	0.018	0.91	-	-	-
no screen	0.000	-	-	-	-
Behind picker	0.010	0.20	-	-	-
4-row combine with Foster Harvest Master					
Stacking dumps	0.142	1.31	1.11	-	0.22
Dumping on headland	0.066	0.41	-	0.69	0.07
Operator A	0.116	0.74	-	1.17	0.04
Operator C	0.021	0.09	-	0.21	0.10
Random dumping	0.039	0.30	-	-	0.34
Using forage wagons	0.062	-	-	-	1.29
4-row combine with Hesston flail shredder	0.100	0.88	0.44	-	0.43

time (Table 24). A reduction of this activity ratio would be expected in a field with longer rows because fewer turns would be required per load.

The reasons for the low man-machine activity with the Beef-maker can be seen in the high delay activity times listed in Table 27. Plugging of the snapping unit caused most of the delay and the poor performance of the smooth snapping rolls used in field 4 is obvious. The average delay time of 11.98 minutes because of mechanical failure was caused by one 36-minute delay when the shaft through the upper snapping roll failed. The average delay of 1.41 minutes in field 1 was caused by the operator stopping to distribute corn in the grain wagon. This activity could be eliminated by redesigning the grain elevator discharge to distribute grain more evenly in the wagon.

The forage unloading times with the combine and Foster Harvest Master were higher in 1969 and 1970, when the observations were made, than they were in 1971 and 1972. In 1969, the husklage dumps were all placed in one corner of the field. This operating policy increased the field time per dump by 2.70 minutes (Table 26) because the combine had to be moved to the dumping area and back and the trailer had to be backed alongside the previous dump before unloading. This extra activity was found to be unnecessary for maximum forage utilization and should not be recommended unless it is desirable for other reasons.

In 1970, two operating policies were followed to reduce forage unloading time while maintaining a high level of forage utilization. In one field, the dumps were placed in a single row on the headland close to the field fence. An electric fence was used to prevent access to the dumps by the cattle during the early grazing period. But this operating policy also proved to be a management error, at least from the standpoint of maximum system capacitive performance. The requirement that dumps be placed close to the fence caused the machine operator to reduce the forward speed of the combine during the turn. The extra time for making the turn was recorded as forage unloading time, as shown in Table 26. Part of this activity time was also a result of the occasional failure of the trailer to dump properly.

In 1972, the same operating policy was followed except that dumps were placed on the ends of the field rows before the combine began the turn. This change allowed the operator to make the turn at the normal speed and reduced the forage unloading time to zero.

The second operating policy in 1970 was to place the dumps in semi-windrows across the field as the trailer became full. The field was then fenced into four strips and cattle were allowed to graze one strip at a time. Unloading time for forage with this operating policy should have been zero. But the trailer failed to dump frequently enough to cause an average forage unloading time of 0.45 minutes per dump. This extra time resulted from improper adjustment of the return springs on the trailer.

In 1971, a single row of dumps was placed across the center of a field. After adjusting the return springs on the trailer, it dumped properly every time, reducing the forage unloading activity time to zero.

When forage wagons were used to collect the husklage, 3.86 minutes were required per load to change wagons. This was caused by the inability of the combine operator to see the hitch without leaving the operator's station on the combine. An automatic wagon hitch should be used with this harvesting system to reduce the time for this activity.

The activity times for the forage blowers are listed in Tables 28, 30, and 31. The man-machine activity and productivity for each material processed are shown in Table 29.

The man-machine productivity of the recutter-blower handling husklage and refuse was quite low. Part of this reduction was attributed to the lower dry matter density of these two forages, with husklage having the lowest dry matter density of all the forages harvested. These two materials also required more chopping by the recutting attachment, which reduced the rate of material flow through the machine.

Support function activities were minimal for the blowers handling forage, but initial positioning of the wagon required about 10 percent of the total time per load for the blower handling shelled corn. The barge wagon had to be backed up to the blower with very little misalignment to avoid spillage. Coupling of hydraulic hoses to the tractor and raising the box was included in this activity.

Table 28. Mean observations of processing machines

Machine	Activity times (min.) Primary	Support functions	Delay	Total	Forage (lb.) Wet	Dry	Grain (bu.)
Blower with recutter							
105 PTOhp. tractor							
Corn refuse	11.94	0.42	3.49	15.88	6403	3064	
Husklage	21.18	-	3.92	25.10	2620	1901	
95 PTOhp. tractor							
Corn silage	8.80	-	2.95	11.75	8830	4163	
Operator C	8.31	-	1.90	10.21	8718	4039	
Operator W	8.53	-	3.38	11.91	8531	4014	
Operator X	9.66	-	2.92	12.78	9458	4528	
Blower, corn silage							
95 PTOhp. tractor	6.98	-	2.02	9.00	8522	3433	
Blower, shelled corn							
50 PTOhp. tractor							
Barge wagon	14.69	2.58	1.39	[illegible]			145
Gravity flow	15.26	1.70	1.09				135

Table 29. Mean capacitive performance of processing machines

Machine	Man-machine activity (%)	Man-machine productivity: Forage (lb.DM/hr.)	Man-machine productivity: Grain (bu./hr.)
Blower with recutter			
105 PTOhp. tractor			
Corn refuse	0.778	14,874	
Husklage	0.844	5,385	
95 PTOhp. tractor			
Corn silage	0.749	28,384	
Operator C	0.814	29,162	
Operator W	0.716	28,234	
Operator X	0.756	28,124	
Blower, corn silage			
95 PTOhp. tractor	0.776	29,510	
Blower, shelled corn			
50 PTOhp. tractor			
Barge wagon	0.926		504[1]
Gravity-flow	0.940		478[2]

[1] Processing rate limited by available tractor power.

[2] Processing rate limited by capacity of unloading auger.

Table 30. Support function activities for blower processing high-moisture shelled corn

Wagon type	Activity ratio	Initial position (min.)	Cleanup (min.)
Barge, hyd. hoist	0.138	2.12	0.46
Gravity flow, hyd. auger	0.094	1.70	-

Table 31. Delay activites for processing machines

	Activity ratio	Delay activity times (min.)			
		Idle operation	Machine plug	Mech. failure	Other
Blower with recutter					
105 PTOhp. tractor					
Corn refuse	0.220	2.54	-	-	0.95
Husklage	0.156	1.00	-	-	2.92
95PTOhp. tractor					
Corn silage	0.251	1.88	0.01	0.14	0.92
Operator C	0.186	1.87	0.03	-	-
Operator W	0.284	1.26	-	0.27	1.85
Operator X	0.228	2.92	-	-	-
Blower, corn silage					
95 PTOhp. tractor	0.224	2.02	-	-	-
Blower, shelled corn					
50 PTOhp. tractor					
Barge wagon	0.074	0.89	0.19	-	0.31
Gravity-flow	0.060	1.09	-	-	-

This activity time might be reduced to 0.5 minutes if a dumping pit were used to avoid backing the wagon. Initial positioning with the gravity wagon included unlatching the unloading auger and swinging it into position, raising or lowering the auger to position the discharge spout over the blower hopper, and coupling the hydraulic hoses from the auger motor to the tractor.

Idle operation was the delay activity requiring the greatest time for the forage blowers. It included the operations of starting the blower, dismounting and walking around the tractor to the front of the forage wagon, coupling the forage wagon PTO to the tractor, engaging the forage wagon unloading mechanism, and repeating these operations in reverse order when the wagon was empty. Little opportunity for reducing this activity time was evident except for practice by the operators.

The average load sizes for the forage wagons used in 1969 and 1970 are listed in Table 32. Wagon capacity is important for planning a handling system to prevent excessive waiting time by the harvesting machine, particularly if the field is located away from the storage area so that hauling time is significant.

The capacities of several of the storage structures that were filled are listed in Table 33. Measurements were not made to determine the fraction of storage volume filled for the structures that were not filled completely, so they were not listed in the table. The upright structures listed were refilled once after the initial filling.

Table 32. Capacities of forage wagons

Harvested product	Average load (lb.) Wet	Dry	Moisture content (%)
Corn silage, 1969	8652	3506	60
Corn silage, 1970	8838	4189	53
Corn refuse, 1969	6030	2937	51
Corn refuse, 1970	6419	3076	52
Stalklage, 1969	4005	2142	47
Husklage, 1969	2415	1613	33
Husklage, 1970	2109	1493	29

Table 33. Capacities of filled storage structures

Structure and harvested product		Average capacity (tons) Wet	Dry	Moisture content (%)
16x50 concrete stave silo				
Corn refuse, 1969		118	57.8	51
Corn silage, 1970		128	60.2	53
Corn silage, 1971		147	58.8	60
17x50 gastight silo				
Corn silage, 1969		143	57.2	60
Stalklage, 1969		54	28.6	47
Trench silos	Approx. vol. (cu. ft.)			
Husklage	3300	32	23.0	28
Husklage	4180	30	24.9	17
Refuse	4800	70	32.2	54
Stalklage	4400	22	16.3	26

Summary

Several harvesting systems for corn plant forage were operated during four harvesting seasons to observe their performance and to harvest material for feeding trials with beef cows. Yields and moisture contents of forage and grain were measured in each field harvested, and the capacitive performance of each machine was measured during the first two years.

Forage yield increased as grain yield increased for all harvesting systems. Analyses of the data obtained for corn refuse and husklage indicated that, within the range of measured values, the relationship between forage yield and grain yield was linear. Forage moisture content decreased linearly as grain moisture decreased for corn refuse and husklage. Stalklage moisture decreased with time after the grain was harvested, but sufficient data to develop a statistical relationship were not obtained.

Analyses of the dry matter distribution in the corn plant indicated that grain dry matter increased and forage dry matter decreased as the grain matured, with stalk and leaf dry matter decreasing at the highest rate. When the grain moisture was approximately 24 percent, nutrient analyses of whole corn plants indicated that approximately 45-49 percent of the total dry matter, 32 percent of the *in vitro* digestible dry matter, and 25 percent of the crude protein produced by the corn plant were located in the forage fraction of the plant. Within this fraction, the leaves had the highest crude protein content and the husks were the most digestible.

The performance of the Beefmaker was satisfactory for an experimental machine, but the quantity of grain in the corn refuse and the quantity of fines in the shelled corn were too high for a commercial machine. An average yield of 5587 pounds of refuse dry matter per acre was obtained, and the refuse was stored successfully in upright and horizontal silos at moisture contents above 45 percent.

The performance of the Foster Harvest Master was excellent. An average yield of 1937 pounds of husklage dry matter was obtained per acre, and the quality of the husklage stored in the dumps and in a horizontal silo was satisfactory. The ground-driven Johnson Strawbuncher was completely unsatisfactory for the harvesting conditions encountered during this research, and frequent plugging made the Hesston combine attachment unacceptable.

The performance of the forage harvester with the flail-type pickup attachment was satisfactory except for the low forage recovery between the corn rows. Attempts to increase forage recovery by operating the flails closer to the ground resulted in an undesirable quantity of soil in the forage.

The performance of the Hesston Stakhand 30 was excellent, and the quality of the stacked forage was good when it was harvested below 40 percent moisture. An average yield of 1900 pounds of stalklage dry matter per acre was obtained by harvesting only the center two of every six rows, and it contained more husks and cobs and fewer stalks than forage harvested from all rows.

RESULTS AND DISCUSSION OF ANIMAL PERFORMANCE STUDIES

The animal performance research discussed on the following pages was conducted by members of the Animal Science department at Iowa State University, whose cooperation was essential for the evaluation of the harvesting systems. It was conducted to study the utilization of both harvested and unharvested corn plant forages during the winter period by dry, pregnant beef cows and heifers.

Experiments were conducted with bred heifers and cows of all ages that were predominantly Hereford, Hereford X Angus, or Angus X Holstein crosses. Animal weights were measured at 28-day intervals, and beginning and ending weights were an average of the animal weights on two successive days. Salt was available free-choice and all animals not fed a complete ration had access at all times to a complete mixture of 40% salt, 20% trace mineral salt, 20% steamed bone meal, and 20% vitamin A premix containing 2.3 million International Units of vitamin A per pound.

The nutrient requirements for growing heifers and mature cows, published by the National Research Council (1970), are listed in Table 34. They will be referred to during the following discussions and will be assumed to be minimum values for satisfactory animal performance.

Cornstalk Grazing

A low cost method of utilizing part of the forage available in the corn field is to permit animals to graze the cornstalks during the winter, because harvesting equipment and storage structures for

Table 34. Partial summary of nutrient requirements for growing heifers and mature beef cows (National Research Council, 1970)

Body weight (lb.)	Average daily gain (lb.)	Daily dry matter per animal (lb.)	Total protein (%)	Total protein (lb.)	TDN (%)	TDN (lb.)
		Growing heifers				
441	0.00	7.3	7.8	0.57	57	4.2
	0.55	10.1	10.0	1.01	57	5.7
	1.10	11.0	11.1	1.22	63	7.0
661	0.00	9.9	7.8	0.77	57	5.6
	0.55	13.7	8.9	1.22	57	7.8
	1.10	18.1	10.1	1.81	57	10.3
882	0.00	12.3	7.8	0.96	57	7.0
	0.55	17.0	8.3	1.41	57	9.7
	1.10	22.5	8.9	2.00	57	12.8
		Dry pregnant mature cows				
772	-	12.8	5.9	0.76	50	6.4
882	-	14.1	5.9	0.83	50	7.1
992	-	15.0	5.9	0.89	50	7.5
1102	-	16.8	5.9	0.99	50	8.4
		Cows nursing calves, first 3-4 months postpartum				
772	-	19.0	9.2	1.75	57	10.8
882	-	20.5	9.2	1.89	57	11.7
992	-	21.8	9.2	2.01	57	12.4
1102	-	23.1	9.2	2.13	57	13.2

harvested forage are not required (although harvested forage may be needed in areas where snow accumulation prevents continuous grazing). Therefore, cornstalk grazing can be used as a base for evaluating alternative harvesting systems for corn plant forage. The additional costs resulting from harvesting, processing, and storing the forage should be recovered through improved animal performance, a greater animal carrying capacity per acre of corn, or a reduced need for reserve supplies of other harvested forage compared to grazing.

The performance of animals grazing cornstalks may be affected by the environmental conditions during the grazing period. Stress on the animals during periods of extremely low temperatures, particularly when low temperatures are accompanied by wind or snow, can be expected to cause reduced performance. Accumulations of snow on the ground that prevent continuous grazing will reduce the animal carrying capacity of the cornstalk fields and increase the quantities of supplementary feed required. The monthly average temperatures and snowfall amounts for Ames for the winter grazing seasons during which this research was conducted are listed in Table 35. The depth of snow on the ground that would prevent grazing depends on the time during the grazing season when the snowfall occurred. Early in the season, when cornstalks are still standing, animals might be able to continue grazing with a greater accumulation of snow than later in the season after cornstalks have been matted down by snow and animals. Hunsley et al. (1966b) reported that cows were allowed to graze cornstalks whenever snow was less than 4 inches deep. But that criterion

Table 35. Monthly average temperature ($^{o}F.$) and total snowfall (in.) for Ames, Iowa (U.S. Dept. of Commerce, 1965-1973)

Season	November		December		January		February		March	
	Temp.	Snow	Temp.	Snow	Temp.	Snow	Temp.	Snow	Temp.	Snow
1931-60 Normals	36.7	2.9	25.1	5.6	20.0	7.2	23.9	6.4	34.2	6.7
1965-66	39.0	0.1	33.4	0.5	12.8	3.2	24.5	0.1	40.5	3.3
1966-67	37.4	0	23.6	8.4	22.7	5.9	21.7	2.1	39.4	1.0
1967-68	35.7	0.1	27.5	0	19.7	9.0	22.2	1.5	43.6	0
1968-69	34.8	6.0	22.4	7.8	14.7	8.2	23.7	12.7	25.8	0.9
1969-70	38.0	0	22.8	15.2	10.4	2.2	25.8	0.3	30.9	13.5
1970-71	36.6	0	24.4	3.3	13.7	17.2	21.7	13.5	33.1	9.4
1971-72	38.4	4.6	26.5	5.3	16.0	6.0	16.8	15.2	36.0	2.1
1972-73	33.9	6.4	17.6	7.7	20.8	13.2	26.1	5.9	42.7	0

was used only with new snow accumulations that never exceeded a 4-inch depth. If snow melt is slow after a long period at greater depths, a 4-inch depth might be too great to allow resumption of grazing. Therefore, a minimum depth of 3 inches was used to estimate the number of days when grazing animals might not be able to obtain adequate forage from cornstalks. Depths of snow on the ground are not published for Ames, but they are recorded on the daily Record of Evaporation and Climatological Observations from the Agronomy-Agricultural Engineering Research Center. These records are available in the Climatology-Meteorology office at Iowa State University. The number of days during the last eight grazing seasons with depths of snow on the ground of 3 inches or more are listed in Table 36. These data indicate a high probability that supplemental feed will be required for part of the winter grazing season in central Iowa. Supplemental feed was fed for more than the total number of days listed in Table 36 during four of the last five grazing seasons, indicating that conditions other than snow depth were also important. In 1966-67, no supplemental feed was fed, although Table 36 shows a total of 17 days with snow depths of 3 inches or more. However, the depth of snow was equal to 3 inches on almost all of those days and cows continued to graze.

The results of the winter cornstalk grazing trials with bred heifers and mature cows are listed in Tables 37 and 38. During the first three grazing seasons (1965-66, 1966-67, and 1967-68), snow did not accumulate for long enough periods to prevent continuous

Table 36. Number of days with snow accumulation on the ground of 3 inches or more, Ames, Iowa[1]

Season	November	December	January	February	March	Total
1965-66	0	0	2	0	0	2
1966-67	0	4	13	0	0	17
1967-68	0	0	5	0	0	5
1968-69	5	10	26	25	16	82
1969-70	0	17	24	0	4	45
1970-71	0	0	29	22	9	60
1971-72	3	5	14	26	0	48
1972-73	8	15	11	5	0	39

[1] Values from the daily Record of Evaporation and Climatological Observations recorded at 5 p.m. c.s.t. at the Agronomy-Agricultural Engineering Research Center, Ames, Iowa. 1965-73.

Table 37. Summary of winter cornstalk grazing trials with bred heifers

	1966-1967	1967-1968	Average
Length of trial, days	112	100	106
Number of heifers	10	10	
Stocking rate, acres/heifer	2.0	2.0	2.0
Average weight change, lb.	+94	+52	+73
Days on stalks	112	100	106
Heifer days/acre of stalks	56	50	53
Salt, mineral, vitamin A	+[1]	+	+

[1] + indicates free choice access by all animals.

Table 38. Summary of winter cornstalk grazing trials with mature, dry, pregnant beef cows

	1965-1966	1966-1967	1967-1968	1968-1969[1]	1969-1970[1]	Average
Length of trial, days	112	112	100	127	114	113
Number of cows	12	10	10	24	24	
Stocking rate, acres/cow	2.0	2.0	2.0	1.67	1.67	1.87
Average weight change, lb.	+98	-2	+24	-28	+12	22
Days fed hay	0	0	0	90	70	32
Days on stalks only	112	112	100	37	44	81
Cow days/acre of stalks	56	56	50	32[2]	36[2]	46.6
Supplemental feed, lb./day						
Hay when fed	-	-	-	13.7	13.5	
Salt, minerals, vitamin A	+[3]	+	+	+	+	

[1] Figures are averages of a paired experiment comparing whole field grazing with strip-grazing. (See Table 39)

[2] Includes 0.23 cow days/day from cornstalks when hay was fed, assuming 15 pounds of dry matter required/day/animal and hay at 85 percent dry matter.

[3] + indicates free choice access by all animals.

grazing (Table 36), and the only supplemental feed required during these three seasons was the salt, mineral, and vitamin A mixture. Under these favorable grazing conditions, the performance of all animals was excellent (Hunsley et al.,1966b; Hunsely et al.,1967b; Vetter and Buchele, 1968). These trials demonstrated that mature cows in good condition at the beginning of the winter feeding period do not have to gain weight during this period to produce healthy calves and to rebreed satisfactorily (Hunsley et al., 1967; Weber, 1970).

During the 1966-67 and 1967-68 winters, the bred heifers had greater overall weight gains than the older cows. All animals gained during the early part of the grazing season, probably because they were selectively grazing the unharvested grain and more nutritious forage fractions (Vetter and Buchele, 1968; Weber, 1970). As the quality of the forage decreased, the bred heifers continued to gain but the older cows were unable to maintain their body weight. This may have resulted from more aggressive grazing habits by the heifers or a higher efficiency in converting the forage to usable nutrients by the younger animals (Hunsley et al, 1967b).

The grazing program was tested more severely during the 1968-69 and 1969-70 seasons. A record snowfall on November 10, 1968 delayed early season grazing, and snowfall continued above normal throughout the winter. The Iowa Crop and Livestock Reporting Service (1970) reported that the 1968-69 winter had the most prolonged glaze period in two decades. This ice and snow cover prevented continuous grazing for most of the season, and supplemental feeding of hay was required for 90 days of the trial.

The 1969-70 season began with the second highest December snowfall on record. January temperatures averaged 10 degrees below normal causing snow to remain on the ground continuously from December 7 through the end of January. A total of 70 days of supplemental hay feeding was needed during the 114-day trial.

Overall animal performance for the two years was satisfactory in spite of the stress caused by the low temperatures and snow. But the animal carrying capacities of the cornstalk fields were reduced significantly below the average carrying capacity of 54 cow days per acre obtained during the three previous years. Animal carrying capacities of only 22 and 26 cow days per acre were obtained during the periods when the cows had access only to cornstalks. Some additional feed was obtained from the cornstalks during the periods when supplemental hay was fed at levels below the maintenance requirement of the cows. Hay was fed three times per week, when it was needed, at levels ranging from 5.9 to 18.4 pounds per head per day (Weber, 1970), with an average feeding level of 13.7 pounds per head per day in 1968-69 and 13.5 pounds per head per day in 1969-70. Assuming a mature cow weighing approximately 1000 pounds requires about 15 pounds of dry matter per day for maintenance (Table 34), and assuming the hay fed contained approximately 85 percent dry matter, the hay supplied only 77 percent of the total maintenance dry matter required per cow per day. If the other 23 percent of the cows' dry matter requirements came from the cornstalks, additional animal carrying capacities of 21 cow days during 1968-69 and 16 cow days during 1969-70 were obtained from the cornstalks. Adding these to the cow days obtained when only cornstalks were fed, and dividing by the stocking rate of 1.67 cows per acre, resulted in total animal carrying capacities of 35 and 36 cow days per acre for the two seasons. These adjusted carrying capacities were still over 14-21 cow days lower than those obtained during the three previous open winters.

The results listed in Table 38 for those two trials are averages of two groups of cows on two different grazing systems. A 40-acre cornstalk field was divided in half during those two winters, and one group of cows grazed 20 acres for the entire grazing trial. The other 20 acres were divided into four strips of 5 acres each, and cows were initially allowed to graze only one 5-acre strip. They were given access to an additional 5-acre strip after each 28-day weigh period.

The results for each group of cows for those two grazing trials are listed in Table 39. Overall performance was similar for both groups of cows in 1968-69, but the cows under the strip-grazing system had a higher overall weight gain than the cows under the whole-field-grazing system in 1969-70. In both trials, the cows under the strip-grazing system lost weight during the initial 28-day period, probably because they were on a limited acreage. The cows under the whole-field-grazing system gained weight during the initial grazing period, presumably because they could select the unharvested grain from the whole 20-acre area. Both groups of cows had similar rates of gain during later

Table 39. Summary of winter cornstalk grazing trials with mature, dry, pregnant beef cows comparing two grazing management systems

	1968-69		1969-70	
	Strip-grazing	Whole field grazing	Strip-grazing	Whole field grazing
Length of trial, days	127	127	114	114
Number of cows	12	12	12	12
Stocking rate, acres/cow	1.67	1.67	1.67	1.67
Average weight change, lb.	-27	-29	+22	+1
Days fed hay	90	90	70	70
Days on stalks	37	37	44	44
Cow days/acre of stalks	35[1]	35[1]	36[1]	36[1]
Supplemental feed, lb./day				
Hay when fed	13.7	13.7	13.5	13.5
Salt, minerals, vitamin A	+[2]	+	+	+

[1] Includes 0.23 cow day/day from cornstalks when hay was fed, assuming 15 pounds of dry matter required/day/animal and hay at 85 percent dry matter.

[2] + indicates free choice access by all animals.

periods when hay was fed, and both groups lost weight during the late grazing period when the quality of the forage was lower. But the gains during the middle of the grazing season were higher, and the weight loss toward the end was lower, for the cows under the strip-grazing system, indicating a benefit from delaying their access to the unharvested grain.

The results of four trials combining cornstalk grazing with harvested forage stored in the field are listed in Table 40. For all four trials, husklage was harvested with the Foster Harvest Master. For the 1972-73 trial, stalklage stacks were harvested with the Hesston Stakhand 30.

For the 1969-70 trial, husklage was harvested and stored in a field near the one in which the strip- and whole-field-grazing systems were being compared, and cows were randomly allotted to the three grazing systems. Because of differences in yield of grain and forage between the two fields, cows were allotted on the basis of one cow per 200 bushels of corn. This resulted in stocking rates of 1.67 acres per cow in the field with the strip- and whole-field-grazing systems (Table 39) and 1.2 acres per cow in the field with the husklage dumps (Table 40).

The husklage dumps were placed in one corner of the field, Figure 35, and an electric fence was used to prevent access by the cows for the first 20 days of the trial. The cows were allowed to graze the remainder of the field throughout the winter whenever weather permitted. After the first snowfall, the cows were allowed to self-feed on the

Table 40. Summary of winter cornstalk grazing trials with mature, dry, pregnant, beef cows using field-stored reserve supplies of harvested forage

	1969-70	1970-71		1971-72		1972-73	
	Husklage dumps	Husklage dumps		Husklage dumps		Husklage dumps	Stalklage stacks
Length of trial, days	114	85	85	84	84	62	62
Number of cows	13	12	12	13	13	25	25
Stocking rate, acres/cow	1.2	1.67	1.67	1.3	1.3	0.67	0.67
Grazing system[1]	WF	S	WF	WF	WF	WF	WF
Days grazing only[2]	20	0	28	35	35	14	14
Days grazing + forage[2]	94	85	57	49	49	48	48
Days fed hay	0	0	0	0	0	12	0
Days fed corn	0	30	30	0	0	0	0
Days fed liquid supplement	22	0	0	0	4	62	62
Average weight change, lb.	-15	-70	-76	+24	+72	+15[3]	-8[3]
Cow days/acre of stalks	95	51	51	65	65	75	93
Supplemental feed, lb./day							
Hay when fed	-	-	-	-	-	20	-
Corn when fed	-	6.2	4.8	-	-	-	-
Protein supp. (32% CP)	2.0	-	-	-	1.9	2.1	2.1
Salt and mineral	+[4]	+	+	+	+	+	+

[1] S = strip grazing, WF = whole field grazing.

[2] Reserve supplies of forage were fenced to prevent access by cows until sufficient snow had accumulated to prevent grazing. After reserve forage supplies were made available, cows had access to both cornstalks and forage.

[3] Weight change during only 48-day period when cows had access to harvested forage.

[4] + indicates free choice access by all animals.

husklage dumps, and access was controlled with head gates which were moved forward approximately twice per week.

The performance of the cows in the husklage field was satisfactory. Both groups of cows in the adjacent grazing study had greater weight changes between weigh periods than the cows in the husklage field, with the cows in the husklage field gaining less early in the grazing season and losing less later in the season. The lower weight loss late in the grazing season by the cows in the husklage field may have resulted from the urea-molasses supplement fed. It was top-dressed over the husklage at the rate of 2 pounds per head per day for the last 22 days of the trial. Measurements were not made to determine any change in husklage consumption during this period, but the supplement did appear to increase palatability of the husklage (Weber, 1970).

The animal carrying capacity of the cornstalks was increased significantly in the husklage field because of the higher stocking rate and because hay was not required. A carrying capacity of 95 cow days per acre was obtained in that field (Table 40), compared to only 36 cow days per acre in the adjacent grazing study (Table 39).

The husklage dumps had an average moisture content of 32.5 percent in 1969. They appeared to keep well, with only a few pockets of moldy forage. The cows consumed the husklage readily, but continued to graze the field throughout the winter whenever the weather permitted. A total of 37,540 pounds of dry matter was harvested, providing 30.7 pounds per head per day over the 94 days that the cows had access to the dumps. Assuming an average consumption of approximately 15 pounds of dry matter per head per day, about 50 percent of the husklage was utilized. The cows consumed the husks and leafy forage but refused the cobs. At the end of the feeding period, the cobs and manure in the area where the dumps had been stacked had to be cleaned up with a tractor-loader before the field could be plowed.

During the 1970-71 season, field stored husklage was combined with the strip- and whole-field-grazing systems. In the 20-acre field to be strip-grazed, husklage dumps were randomly placed in each 5-acre strip, Figure 36. In the other half of the field, where cows would have access to the entire 20 acres throughout the trial, husklage dumps were placed next to the fence, Figure 37. This row of dumps was fenced to prevent access by the cows until snow had accumulated on the ground. After 28 days of grazing, the cows were allowed to self-feed from the husklage dumps. Access to the dumps was controlled by moving the electric fence, and cows were given access to two dumps each time the fence was moved.

The weather during January and February 1971 did not favor optimum animal performance from any grazing system. A severe blizzard on January 3 and 4 left over 15 inches of snow on the ground. Two blizzards in February and below normal temperatures in January and February resulted in a continuous snow cover for the two months. Animals were unable to graze the cornstalks for most of the winter, obtaining almost all their feed from the husklage dumps.

The cows were unable to maintain their body weight on husklage

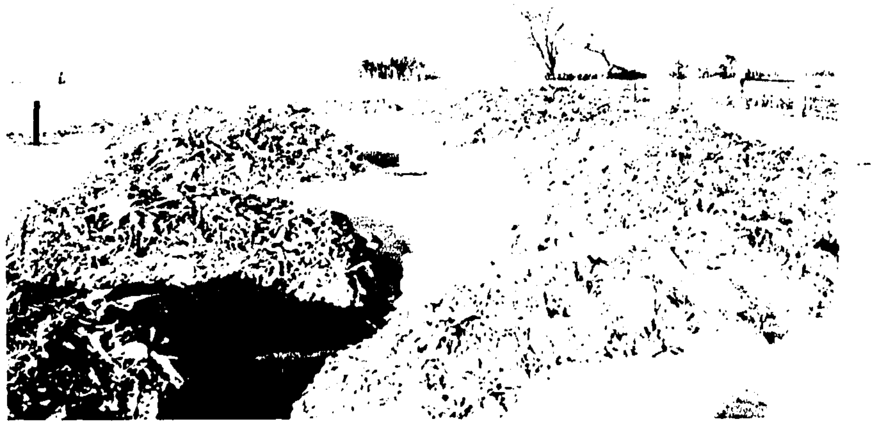


Figure 35. Husklage dumps stacked for reserve feed in 1969

Figure 36. Husklage dumps unloaded randomly for strip grazing in 1970

under the stress created by the snow and low temperatures in January, so supplementary feeding of shelled corn was provided during the last 30 days of the trial. Even with this supplemental feeding, animal performance was only marginal. The overall weight loss of 73 pounds per head was undesirable for good animal condition, although the subsequent calving and rebreeding performance of the cows was satisfactory.

The decreased animal performance on the husklage grazing system in 1970-71 compared to 1969-70 may have resulted from a combination of several factors. The yield of husklage was lower in 1970 than in 1969, and it contained a high percentage of giant foxtail, making it lower quality feed than the husklage harvested in 1969.

The heavy snowfall in 1970-71 also reduced the availability of the husklage to the animals. The strip-grazing cows had access to all the dumps in a strip, and they would tear them apart without cleaning up the forage. Consumption of the forage was poor after they had bedded on the dumps, and subsequent snowfall would cover the uneaten forage, making it unavailable to the cows. The cows on the whole-field-grazing system wasted less forage because they had access to only two dumps at a time.

Forty-two husklage dumps containing 35,490 pounds of dry matter were available to the cows on the strip-grazing system, and all available forage was consumed when the grazing trial was terminated at the end of February. Consequently, 34.8 pounds of husklage dry matter was available per animal per day for the 85 day trial. If they consumed an average of 15 pounds of dry matter per day, only 43 percent of the husklage was consumed. However, very little husklage was eaten during the first 28 days of the trial when the cows could graze the cornstalks. Therefore, assuming that 15 pounds of husklage dry matter per animal were consumed only during the last 57 days of the trial indicates a husklage utilization of only 30 percent. Actual utilization was probably between these two figures.

Forty husklage dumps containing 32,640 pounds of dry matter were available to the cows on the whole-field-grazing system. At the conclusion of the grazing trial, eight of the dumps had not been used. Therefore, approximately 26,640 pounds of husklage dry matter were utilized over the 57 days that husklage was fed, or 38.9 pounds of dry matter per animal per day. Assuming an average consumption of 15 pounds of dry matter per animal per day indicates a utilization of only 39 percent of the husklage.

The total animal carrying capacity per acre of cornstalks was only 51 cow days per acre in 1970-71. But without the husklage, the animals would have been able to graze only 28 days, for a carrying capacity of only 17 cow days per acre. Therefore, husklage increased the animal carrying capacity 34 cow days per acre. If the animals on the whole-field-grazing system had been left until the eight unused dumps had been consumed, approximately 15 days of additional grazing would have been obtained. This would have resulted in a carrying capacity of 60 cow days per acre, 43 cow days per acre more than grazing alone. This is still significantly lower than the 59 additional cow days per acre obtained with husklage in 1969-70. But an additional

34-43 cow days per acre probably represents the improvement that could be expected from harvesting husklage during most grazing seasons in central Iowa by average farmers, with 59 additional cow days per acre being the goal of top managers.

In 1971-72, husklage was dumped in a windrow across the center of the field, Figure 38, and cows were allotted to the two halves of the field. Both groups of cows were allowed to graze the cornstalks on their side of the field for the entire trial, and one group of cows was also given access to a liquid protein supplement. After 35 days of grazing, both groups of cows were allowed to self-feed on the husklage by moving the electric fence to expose three dumps at a time to each group of cows.

The cows receiving the liquid supplement had an average gain 48 pounds greater than the other cows. This additional gain occurred during the first 35 days of the grazing trial before the husklage was fed. During the 49-day period when husklage was fed, there was no difference in gain between the two groups of cows. Most of the grain left in the field by the combine was consumed during the first 35-day grazing period. The energy from this grain may have resulted in better utilization of the nonprotein nitrogen in the supplement during this initial period than during the later period when the cows were eating stalks and husklage. The crude protein content of the supplement was increased from 32 percent to 41 percent toward the end of the initial grazing period by adding more urea to the supplement, and this decreased consumption of the supplement during the remainder of

Figure 37. Husklage dumps placed on a headland for whole-field grazing animals in 1970

Figure 38. Husklage dumps placed in a windrow across the field in 1971

the trial. The supplement may also have reduced the desire of the cows to graze above a maintenance level of roughage intake during the husklage-feeding period.

An animal carrying capacity of 65 cow days per acre was obtained during this trial. This was lower than had been expected, but all remaining forage was covered with 7 inches of snow on February 8 when the grazing trial was terminated. The dumps were small in this field and the waste per dump was high because the cows worked them down quickly. Additional forage consumption might have been obtained in March after the snow had melted, but this was not attempted. A total quantity of 44,550 pounds of husklage dry matter was available to the 26 cows during the 49-day feeding period, or 35 pounds per head per day. Assuming a consumption of approximately 15 pounds per head per day indicates a utilization of approximately 43 percent of the husklage.

For the 1972-73 grazing season, husklage was harvested from half of the grazing field with the Foster Harvest Master and stalklage was harvested from the other half of the field with the Hesston Stakhand 30. The husklage was dumped on one headland, and the stalklage was stacked on the same headland in the other half of the field, Figure 39. Twenty-five cows were allotted to each half of the field and forced to graze cornstalks for the first 14 days by fencing off the stacked forage. After the initial grazing period, the cows in one half of the field were allowed to self-feed on the husklage by moving the electric fence to expose three dumps at a time. The cows in the other half of the field were allowed to self-feed from one stalklage stack at a time. Access to the stacks was controlled with movable feeding panels, Figure 40. The panels were connected with pins in each corner so that the animals could push them into the stack as they consumed the forage. The panels were moved to a new stack every 7-8 days. Both groups of cows were given free-choice access to a liquid protein supplement throughout the trial.

The cows on this trial were reallotted after the initial 14-day grazing period. Several animals were removed for another experiment, and were replaced by other cows for the 48-day period during which the forage was fed. Therefore, the average weight changes listed in Table 40 were the changes for the final two groups of cows during the last 48 days. The initial 14 grazing days were included in the total animal carrying capacity per acre because the same number of cows were allotted during both phases of the trial.

Overall animal performance during the last 48 days of the trial was satisfactory. However, the difference in gain between the two groups of cows cannot be attributed to the difference between husklage and stalklage. The husklage dumps were consumed after 27 days of feeding because of the high stocking rate of 0.67 acres per cow. The cows receiving the husklage were forced to graze cornstalks during the final 22 days of the trial, receiving supplemental hay for the last 12 days. The cows receiving stalklage were not fed hay during this period.

The 12-day period during which hay was fed reduced the carrying

Figure 39. Stalklage stacks placed on a headland in 1972

Figure 40. Portable feeding panels for stalklage stacks in 1972

capacity in the husklage half of the field to 75 cow days per acre (62 - 12 ÷ 0.67). The stalklage stacks provided forage for the total 48-day feeding period, resulting in an animal carrying capacity of 93 cow days per acre.

Approximately 22,280 pounds of husklage dry matter were available to the cows during the 27-day feeding period, or 33 pounds of dry matter per cow per day. Assuming a consumption of 15 pounds of dry matter per day results in an estimated husklage utilization of 45 percent. A total of 22,270 pounds of dry matter were available in the six stalklage stacks, or 18.5 pounds per cow per day during the 48-day feeding period. Assuming an average daily consumption of 15 pounds of dry matter per cow results in a stalklage utilization of 81 percent. However, the cows continued to graze during most of the feeding period, obtaining some part of their daily forage consumption from the cornstalks. Therefore, utilizations of 40 and 70 percent were believed to be more accurate estimates for the husklage and stalklage, respectively.

Stored Forage

In the early feeding trials with corn refuse harvested by Schroeder (1968b) and Gustafson (1969), the cows and bred heifers were unable to maintain their body weight until a protein supplement was added (Vetter and Buchele, 1968; Gay et al., 1969). In both trials, mature cows performed better than heifers. The decreased animal performance from corn refuse compared to grazing may have been caused by the ability of the grazing animals to select only the more nutritious or palatable portions of forage (Weber, 1970).

During the winter of 1969-70, forages from the harvesting systems described in this dissertation were each fed to mature cows and bred heifers. Husklage was harvested with the Foster Harvest Master, collected in forage wagons, and recut at the blower. Stalklage was harvested with the Fox forage harvester and corn refuse was harvested with the Beefmaker II.

The results of the feeding trial are listed in Table 41. The corn silage was limit-fed at the rates shown in Table 41. All other forages were fed ad libitum, and forage not consumed was removed from the feedbunks and weighed. The values listed in Table 41 were the actual weights of forage consumed. All animals received 0.5 pound per day of urea-based supplement providing minerals, vitamin A, and 100 percent crude protein equivalent. Animals receiving stalklage and corn refuse were fed the quantities of shelled corn listed in Table 41 each day. The animals receiving husklage were fed varying amounts of shelled corn, depending on their performance, and the average quantities over the 114-day trial are listed in Table 41.

The cows and heifers on all the forages gained weight. The cows receiving husklage and stalklage had the lowest gains, indicating the lower quality of these forages. However, calves born to the cows and heifers receiving stalklage had the highest average birth weights (Weber, 1970).

The corn refuse silage contained 19.4 percent grain as harvested (Table 14), and the addition of 5 pounds of shelled corn per day improved

Table 41. Feeding trial (114 days) with harvested corn plant forage, winter 1969-70

	Husklage		Stalklage		Refuse silage		Whole plant silage	
	Cows	Heifers	Cows	Heifers	Cows	Heifers	Cows	Heifers
Number of animals	6	12	6	12	6	12	6	12
Avg. weight change, lb.	31	78	20	87	91	127	55	125
Daily feed, lb./head								
Forage, as fed	22.0	17.6	28.8	25.3	33.1	30.0	33.7	33.7
dry matter	14.7	11.8	15.4	13.6	14.9	13.7	13.7	13.7
Corn, 73% dry matter	4.8	6.7	3.0	5.0	3.0	5.0	-	-
Supplement (100% CP)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

its feeding value to a level where the heifers receiving it gained as well as heifers receiving regular corn silage. These gains were desirable because of the lower initial body weights of the heifers. But the cows receiving corn refuse gained more weight than was necessary for satisfactory performance. Less than 3 pounds of shelled corn per day would have been adequate to maintain body weight. With husklage and stalklage, 3-4 pounds of shelled corn per day appeared to be adequate for mature cows.

One of the criteria discussed in the previous section as a measure of the performance of a harvesting system was the animal carrying capacity of the cornfield in cow days per acre. When cow days per acre were calculated for the forages in this feeding trial, the dry matter consumption values in Table 41 were assumed to be 80 percent of the total amount of harvested forage needed per cow per day. Because farmers might store these forages in above-ground stacks or in trench silos, and because the cows sorted out and refused coarser particles of forage, an additional 20 percent was believed to be a reasonable estimate of these losses.

The average husklage dry matter yield from all the fields harvested during this research was 1937 pounds per acre (Table 7). Assuming a total requirement of 18.4 pounds of dry matter per cow per day (14.7 ÷ 0.80, Table 41), the average animal carrying capacity would be 105 cow days per acre with a husklage harvesting system. This is greater than 75-95 cow days per acre obtained under the best grazing conditions when husklage was stored in the field (Table 40), reflecting the higher forage utilization obtained by drylot feeding.

A stalklage dry matter yield of 1549 pounds per acre was obtained with the flail forage harvester after combining (Table 12). Assuming a total stalklage requirement of 19.3 pounds of dry matter per cow per day (15.4 ÷ 0.80, Table 41), the animal carrying capacity would be 80 cow days per acre. If a yield of 3060 pounds of dry matter per acre was assumed, Table 12, animal carrying capacity would be 159 cow days per acre. Later harvesting research with the Hesston Stakhand, and reports from others who have used a flail-type forage harvester, indicate that this second figure is a better estimate of average performance with this harvesting system.

The average yield of corn refuse during this research was 6641 pounds of dry matter per acre (Table 5). Assuming a total daily requirement of 18.6 pounds of dry matter per animal (14.9 ÷ 0.80, Table 41), the expected animal carrying capacity would be 357 cow days per acre of corn. Consequently, the Beefmaker would provide almost enough forage from an acre of corn to feed a cow for a year. However, the refuse would have to be supplemented with additional protein and energy to meet the needs of a cow during lactation (Table 34).

A good field of corn should produce about 12,000 pounds of dry matter per acre when harvested as corn silage (15 tons of silage per acre at 60 percent moisture). Assuming a total daily requirement of 17.1 pounds of dry matter per cow (13.7 ÷ 0.80, Table 41), results in an animal carrying capacity of 702 cow days per acre if silage was limit-fed as in this feeding trial. However, silage losses during storage and feeding should be lower than 20 percent with good management. If they could be held to 10 percent by using an upright silo, animal carrying capacity could be increased to 789 cow days per acre. Thus, corn silage offers the greatest animal carrying capacity per acre of corn of all the harvesting systems, but it must be limit-fed to keep cows from becoming overfat, and it does not permit the grain to be fed separately to the calves produced by the cows or to other feedlot animals.

The results of a feeding trail with husklage and corn refuse silage in 1970-71 are listed in Table 42. Animal performance during this trial was satisfactory. The results indicate that corn refuse alone wou not supply enough energy to mature cows to allow them to maintain their initial bodyweight. Comparing the gains by the mature cows in this trial to the gains by the cows in the 1969-70 trial indicates that 1-1.5 pounds of shelled corn per day, or its equivalent, should be adequate to allow cows to maintain their weight. The cows fed corn refuse every other day did as well as those fed every day, indicating that this management practice could be used to reduce feeding labor without any expected ill effects.

The results of a feeding trial conducted during the winter of 1971-72 are listed in Table 43. The corn stalklage was harvested with the Hesston Stakhand 30 and stored in a trench silo. The soybean stalklage was baled, and the corn refuse silage had been stored in a gastight silo during the 1970 harvesting season and not used.

The gains of all cows in this trial were excellent. One pound

Table 42. Feeding trial (82 days) with harvested corn plant forage, winter 1970-71

	Husklage		Refuse silage		
	Cows	Heifers	Cows	Cows[1]	Heifers
Number of animals	12	16	12	6	16
Avg. weight change, lb.	-21	+4	-44	-35	-10
Daily feed, lb.					
Forage, as fed	23.0	22.0	32.0	34.0	30.5
dry matter	15.0	14.4	14.7	14.3	14.1
Corn, 85% dry matter	4.0	6.8	-	-	2.0
Supplement (100% CP)	0.5	0.5	0.5	0.5	0.5

[1] Cows fed only every other day. All other groups fed every day.

Table 43. Feeding trial (69 days) with harvested corn plant forage, winter 1971-72

	Corn silage	Corn refuse	Corn stalklage	Soybean stalklage
Number of cows	9	9	8	8
Average weight change, lb.	+172	+45	+26	+53
Daily feed, lb.				
Forage, as fed	31.9	30.1	18.6	14.8
dry matter	12.8	14.9	13.8	13.3
Corn, 85% dry matter	-	-	1.00	0.00
Molasses	-	1.00	1.00	2.96
Supplement (100% CP)	0.25	0.50	0.50	0.50

of molasses per head per day was substituted for the shelled corn used in previous trials as an energy source with the corn refuse silage and proved to be quite adequate. The addition of a pound of shelled corn and a pound of molasses to the stalklage also provided satisfactory animal gains. The soybean stalklage, although not considered elsewhere in this dissertation, proved to be an adequate roughage when properly supplemented, although its palatability was low without the added molasses.

The animal carrying capacity per acre of corn silage would be 750 cow days per acre with the daily consumption of 12.8 pounds of dry matter per cow listed in Table 43. The daily consumption of corn refuse silage during the feeding trial reported in Table 43 was exactly the same as the consumption shown in Table 41, so the estimated animal carrying capacity per acre of corn refuse harvested remained at 357 cow days. An average yield of 1900 pounds of corn stalklage dry matter was obtained with the Hesston Stakhand 30 when only the two center rows behind a 6-row combine were harvested (Table 12). Assuming a total daily stalklage requirement of 17.25 pounds of dry matter per cow (13.8 ÷ 0.80, Table 43) resulted in an animal carrying capacity of 110 cow days per acre. If 3398 pounds of stalklage dry matter per acre, obtained in 1971 by operating the Stakhand behind a corn picker (Table 12), was assumed as a reasonable yield when the whole field was harvested, animal capacity would be increased to 197 cow days per acre of corn.

Observations of cows sorting out the coarse pieces of forage during feeding trials suggested that grinding the forage to make a more uniform product might improve consumption and animal performance. A short feeding trial was conducted during the winter of 1971-72 to investigate the effects of recutting the forage, and the results are listed in Table 44. A Fox forage harvester with an ear corn hopper in place of the gathering attachment and a 1.5-inch recutting screen was used to recut the forage. Corn stalklage, harvested with the Hesston Stakhand 30, was fed to three groups of cows. One group received unrecut stalklage every other day, one group received stalklage that was recut and fed daily, and the third group received stalklage that was recut and fed every other day. Two groups of cows received husklage that had been collected in forage wagons, chopped with the recutter-blower shown in Figure 6, and stored in a trench silo. One group of cows received husklage just as it came from the silo every other day, and the second group received husklage that was recut again and fed every other day.

Very little improvement was obtained by recutting the stalklage. This lack of response was probably a result of the shredding performed by the flail pickup on the Stakhand. Increased consumption and an additional 48 pounds of gain resulted from recutting the husklage. This was attributed to the high percentage of cobs in the husklage and the coarse chop obtained as it was being stored. If a recutting screen with smaller openings had been used in the blower during the first chopping operation, the response from the second chopping might not have been as great.

Table 44. Feeding trial (46 days) with harvested corn plant forage, winter 1971-72

	Stalklage			Husklage	
	Not recut	Recut daily	Recut every other day	Not recut	Recut every other day
Number of cows	6	6	7	7	6
Average weight change, lb.	+76	+87	+75	+35	+83
Daily feed, lb.					
Forage, as fed	18.00	18.00	18.00	13.60	15.40
Corn, 85% dry matter	3.40	3.40	3.40	3.40	3.40
Molasses	0.87	0.91	0.91	0.91	0.91
Supplement (100% CP)	0.46	0.46	0.46	0.46	0.46
Soybean oil meal	0.03	0.03	0.03	0.03	0.03

Summary

The grazing trials indicated that cornstalks can provide the basic forage needs of dry, pregnant beef cows in good condition in the fall if the cornstalks are properly supplemented during periods of low temperature and snow. They also indicated that reserve supplies of forage should be available on farms in the central and northern Corn Belt; supplemental feeding was required during five of the last eight winters in central Iowa.

A combination of grazing and controlled feeding of field-stored forage was a satisfactory system for wintering cows. Forage stacked in the field can be fenced during periods when the cows can obtain adequate forage from grazing and held as reserve feed for periods when snow prevents grazing (Figure 41). Controlled feeding with an electric fence resulted in a husklage utilization of 35-45 percent. Cobs and coarser pieces of forage in the husklage were not eaten (Figure 42) and had to be cleaned up or scattered in the spring. Stalklage utilization was estimated to be 70 percent in one trial when feeding panels were used to prevent cows from scattering the forage. Smaller panels might increase husklage utilization to a similar level.

The feeding trials indicated that harvested corn plant forage can be fed ad libitum as the major part of the wintering ration for beef cows if it is properly supplemented. Additional protein and energy were required with all the harvested forages, except corn silage, to ensure that cows would maintain their bodyweight. Bred heifers required a higher level of supplementation than mature cows to enable

Figure 41. Husklage dumps after a 6-inch snowfall

Figure 42. Wasted husklage during feeding

them to gain weight during the winter. Cows fed on alternate days performed as well as cows fed daily.

The range of animal carrying capacities estimated from the grazing and feeding trials, and estimates of expected carrying capacities in central Iowa with good feeding management, are listed in Table 45 for each of the grazing and harvesting systems. Greater carrying capacities will occur with the grazing systems during mild winters and in southern areas of the Corn Belt. Carrying capacities with the grazing systems may be lower during winters with heavy snowfall, but the advantage of field-stored husklage and stalklage should also be greater during those years. If controlled feeding of field-stored forage is not practiced, carrying capacities 15-20 cow days per acre lower than the values in Table 45 may occur.

Carrying capacities will be less dependent on the weather if harvested forage is stored and fed in bunks. But the level of energy supplementation should be increased during periods of below normal temperatures. Whole-plant silage will provide the greatest carrying capacity of all the harvesting systems presently available. A corn refuse harvesting system will maximize the carrying capacity if the grain is needed for other livestock, and further development of a harvesting system should be considered if the demand for beef continues to increase.

Table 45. Estimated animal carrying capacities of an acre of corn for selected harvesting and feeding systems

Harvesting and feeding system	Carrying capacity, cow days/acre	
	Range[1]	Expected value[2]
Grazing cornstalks only	35-56	45
Grazing plus husklage dumps	51-95	75
Grazing plus stalklage stacks	93	90
Husklage, chopped and stored dry	105	105
Stalklage silage	80-197	165
Refuse silage	357	350
Whole-plant silage	702-789	750

[1] Range of values estimated from reported grazing and feeding trials.

[2] Expected value for winter feeding with good management. Stocking rates of 1.8-2.0 acres per cow for grazing only, 1.2-1.4 acres per cow for grazing plus field-stored husklage or stalklage. Ad libitum feeding of all forages except whole-plant silage plus proper supplementation. Whole-plant silage limit-fed at 30-35 pounds per animal per day.

A MODEL TO SIMULATE HARVESTING PERFORMANCE

The feasibility of harvesting corn plant forage with the machines discussed in this dissertation also depends on harvesting and handling costs of the forage and on the total quantity of forage that can be harvested in a season with each system. Harvesting and handling costs for various levels of use can be estimated with the economic models discussed in the literature (American Society of Agricultural Engineers, 1972; Bowers, 1968; Hunt, 1973; Smith, 1968). The quantity of forage that can be harvested with each machinery system will depend on the interactions within the weather-crop-machinery system.

One of the more important variables affecting the quantity of a particular type of forage that can be harvested is the length of the potential harvesting season. The earliest date for starting harvest is a random variable because of the random effects of weather on the rate of crop development during the growing season. The latest harvesting date may be deterministic if it is selected *a priori* because of other field activities that must be performed. But it will also be a random variable if it is determined by the occurrence of an unacceptable crop condition, or if it occurs after a specified quantity of forage has been harvested.

Within the potential harvesting season, the number of actual harvesting days is a random variable because of the interactions between the weather and the machinery system. The number of acres harvested per day will vary because man-machine performance is a random variable affected by field, crop, and machine conditions. Finally, the recoverable yields of grain and forage will change during the harvesting season, being functions of time, machine field losses, weather, and other factors.

The expected values of some of these variables could be estimated from data reported in the literature. By properly combining the mean values and standard deviations of the variables (Haugen, 1968), the expected quantity of forage harvested could be calculated. But unless all the variables were normally distributed, one could only guess at the distribution of values over a period of several years.

The manager of a large beef cow enterprise might also prefer not to select a machinery system based only on the mean values of its output. If the variances of output values were large, the risk of not being able to harvest enough forage in some years would be too high. Rather, he might prefer to select a machinery system based on its expected output at a probability of 80, 90, or even 98 percent. With that kind of information, he could balance the risk of not completing his harvest against the cost of a machinery system with a larger capacity.

Therefore, a decision was made to mathematically model the variables so that the performance of each harvesting system could be simulated on a digital computer. This would enable the distributions of system output variables to be determined so that a better description of the capabilities of each harvesting system could be made.

In the machine-crop system model, the harvesting season was limited to the period of time between August 30 and December 26, inclusive. These dates were chosen to coincide with climatic weeks 27-43. The calendar dates for each climatic week within this interval are listed in Table 46. Climatic weeks were chosen as the smallest uniform time intervals to be used for simulating the random effects of weather.

The following assumptions were made about the state of the machine-crop system on August 29:

1. The crop had been planted, had grown, and was approaching normal maturity.
2. The climatic conditions required for the crop to reach maturity, and values for the parameters describing the condition of the crop at maturity, were known.
3. The grain and forage conditions required to produce harvested products of acceptable quality were specified.
4. The particular set of harvesting equipment to be used was fixed, and values for the parameters describing its functional, mechanical, and capacitive performances were known.

The flow of time in the model was represented by a sequence of uniform increments. The model simulated the condition of the crop at the end of each time increment after August 30, proceeding from one increment to the next increment sequentially. Whenever the grain

Table 46. Relationship between the climatic year[1] and the calendar year

Climatic week	Climatic days	Calendar dates
27	183-189	Aug. 30 - Sept. 5
28	190-196	Sept. 6 - Sept. 12
29	197-203	Sept. 13 - Sept. 19
30	204-210	Sept. 20 - Sept. 26
31	211-217	Sept. 27 - Oct. 3
32	218-224	Oct. 4 - Oct. 10
33	225-231	Oct. 11 - Oct. 17
34	232-238	Oct. 18 - Oct. 24
35	239-245	Oct. 25 - Oct. 31
36	246-252	Nov. 1 - Nov. 7
37	253-259	Nov. 8 - Nov. 14
38	260-266	Nov. 15 - Nov. 21
39	267-273	Nov. 22 - Nov. 28
40	274-280	Nov. 29 - Dec. 5
41	281-287	Dec. 6 - Dec. 12
42	288-294	Dec. 13 - Dec. 19
43	295-301	Dec. 20 - Dec. 26

[1]Climatic day 1 is March 1; climatic week 1 is March 1-7.

and forage conditions were within the ranges specified for acceptable products, the performance of the harvesting system was simulated. At the end of the harvesting season, the values of the system output variables were recorded, and the simulation was repeated for the next year.

To simulate random values for the variables, a mathematical distribution for the values of each variable had to be assumed. Three distributions were considered for each variable:

(1) normal, with mean and variance estimated from the data set;

(2) rectangular, with upper and lower bounds estimated from the data set;

(3) Weibull, with mean and variance estimated from the data set and with a value for the guaranteed life parameter, XO, chosen to minimize the value of the chi-square statistic.

The equation for the Weibull distribution function is

$$F(x) = 1 - e^{-\left(\frac{x - XO}{\theta}\right)^{B}} \qquad x \geq XO \qquad (8)$$

$$F(x) = 0 \qquad \text{elsewhere}$$

where F(x) = Weibull cumulative distribution function

XO = Weibull guaranteed life parameter

θ = Weibull characteristic life parameter

B = Weibull shape parameter

The data set for many of the variables in the model was not symmetric about a mean value, and the Weibull distribution was considered because of its ability to exhibit both positive and negative skewness, as well as symmetry (Weibull, 1951). Since the Weibull distribution described by equation 8 is a 3-parameter distribution, a whole family of distributions could be used to describe a data set if only the mean and variance were known. The guaranteed life parameter, XO, was chosen as the third independent variable describing the distribution, since its maximum value would be the smallest observation in the data set. The minimum value for XO was specified as the smallest permissible value for the random variable. A computer program was used to search over this range of XO and return the Weibull parameters for the distribution with the smallest value of the chi-square statistic. The class intervals for the chi-square test were chosen according to the method described in Appendix E. The values of the chi-square statistics for the three distributions (normal, rectangular, and Weibull) were compared, and the distribution having the smallest chi-square value was chosen to represent the data set. When the chi-square test indicated that the normal distribution could be assumed to represent a data set, the Kolmogorov-Smirnov test described by Lilliefors (1967) was used as an additional criterion for acceptance.

The final machine-crop system model consisted of several component models, each simulating the performance of a particular sub-system. The development of the component models will be described in the remainder of this chapter.

Crop Maturity

A set of initial conditions relating crop growth to time was required because the flow of time in the model of the machine-crop system did not begin with corn planting. Carpenter and Brooker (1970) and Morey (1971) specified a grain moisture content on September 1 as their initial condition and used the same value of grain moisture for each simulation. But grain moisture on any particular day is a random variable, so a constant value cannot be used for the starting day if each simulation represents a different crop year. Holtman et al. (1973) used known values of grain moisture and potential yield on October 15 as their initial conditions. But their model was year-specific, requiring historical weather data and known initial conditions for each year being simulated. They did not simulate weather and initial crop conditions.

One of the assumptions about the state of the system on August 29 was that the crop had grown and was approaching maturity. Therefore, maturity was selected as the particular stage of crop development that would be used as the link between crop growth and time.

The attainment of maximum grain dry weight, or of some specified grain moisture content, and time from silking have been used as indicators of maturity by many researchers (Hallauer, 1960; Kiesselbach, 1950; Newlin, 1953; Miles, 1956; Shaw, 1949; Shaw and Thom, 1951). In recent years, the formation of a black layer of collapsed cells at the base of the corn kernel has been found to be a better indicator of the arrival of maturity than time, kernel dry weight, or moisture content (Baker, 1971; Daynard and Duncan, 1969; Rench and Shaw, 1971). The black layer can be easily seen and usually develops at a kernel moisture content near 30 percent (Baker, 1971), although it may form prematurely when the plant is under a stress condition or during periods of cool temperatures (Baker, 1971; Daynard, 1972).

The relationship between the rate of growth of corn seedlings and ambient temperature was well documented by the early work of Lehenbauer (1914), and several relationships between temperature and rate of growth have been proposed to predict corn maturity. These relationships were based on the assumption that a particular stage of plant development would be reached when the plant had received a specific accumulation of heat units above some base, independent of the particular period of time involved (Aspiazu and Shaw, 1972). Heat units were usually computed from the mean daily temperature and corrected for high and low extreme values.

Gilmore and Rogers (1958) compared corn maturity to heat units calculated by 15 different methods. They found that the mean daily temperature minus 50°F. gave the least coefficient of variation when daily maximum temperatures above 86°F. were corrected to 86°F. and daily minimum temperatures below 50°F. were corrected to 50°F. The number of heat units required for silking was relatively constant for crops with different planting dates, although calendar days varied widely.

Mills (1964) used the method described by Gilmore and Rogers to predict optimum peanut harvesting time, and Bowen (1966) used the same method to predict germination of cotton seedlings. Newman et al. (1968) related corn growth to accumulated heat units using a formula that corrected maximum daily temperatures to 90°F. and Aspiazu and Shaw (1972) discussed other methods of calculating heat units that were being studied.

The necessary connection between climatic conditions and the use of black layer formation to define maturity was established in a meeting of seed-corn industry representatives at Ames, Iowa in February 1970 (Felch et al. 1972). They agreed to use the formation of a black layer as the criterion of corn maturity and to evaluate the maturity requirements for their varieties by calculating growing degrees (the accepted term today for heat units) with the formula being used by the Environmental Data Service (EDS) of the National Oceanic and Atmospheric Administration in Washington, D.C. With this formula, daily growing degrees are calculated as follows:

$$GD = \frac{TMAX + TMIN}{2} - 50°F. \qquad \begin{array}{l} TMAX \leq 86°F. \\ TMIN \geq 50°F. \end{array} \qquad (9)$$

where GD = daily growing degrees

TMAX = maximum daily temperature, °F. If the maximum temperature is greater than 86°F., TMAX is set equal to 86°F. before the calculation is made.

TMIN = minimum daily temperature, °F. If the minimum temperature is less than 50°F., TMIN is set equal to 50°F. before the calculation is made.

The seed-corn industry representatives also agreed to begin calculating varietal growing degree requirements at the time the corn was planted.

With this method of determining corn maturity, a farmer would add the number of growing degrees accumulated at the time he planted the corn to the number of accumulated growing degrees required for maturity by the particular variety he planted. The sum would be the total number of accumulated growing degrees required for the corn to reach black layer formation. By comparing this value to the climatological history of growing degrees for his geographic location, he could estimate the maturity date of the corn. By comparing the accumulated growing degrees at various times during the growing season to the climatological history of growing degrees, he could also assess whether the corn crop was developing at a normal rate, or not, and revise his estimate of maturity date.

The procedure described in the last paragraph for estimating the date of maturity was used in the corn maturity model of the simulation program. The input data required for initial conditions were the climatic week planting occurred and the number of accumulated growing degrees required for the crop to reach maturity. Grain moisture and potential grain yield were selected as parameters to describe the condition of the crop at maturity.

Felch et al. (1972) published the monthly mean values of accumulated growing degrees and the total accumulated growing degrees from various planting dates through the end of the growing season for 10 locations in Iowa, including Ames. Values of accumulated growing degrees were calculated from climatological data for the period 1941-70 using equation 9.

Because random values of accumulated growing degrees at any time during the harvesting season were needed for the maturity model, the original data for Ames were obtained from Felch. Mathematical distributions were fitted to the histograms of the 30 values of accumulated growing degrees at the end of each climatic week during April, May, August, September, and October by the procedure described at the beginning of this chapter. The distribution having the lowest value of the chi-square statistic was selected to represent the distribution of accumulated growing degrees at the end of each week.

Climatic weeks were chosen as the smallest time increment in the maturity model. Early in the planting season when the weekly accumulation of growing degrees was low, the number of days required for corn to germinate would be high. Later in the season when the weekly accumulation of growing degrees was higher, the number of days required for the corn to germinate would be lower. Therefore, any error introduced by using the value of accumulated growing degrees at the end of the week planting occurred instead of the value of accumulated growing degrees on the actual day planting occurred would be small, particularly if planting extended over a period of several days.

The numbers of accumulated growing degrees at the ends of two successive climatic weeks during the harvesting season were found to be highly correlated. If the value at the end of the first week was above normal, the value at the end of the next week was also likely to be above normal. Therefore, when the crop matured during the week, the climatic day of maturity was estimated by interpolating between the value of accumulated growing degrees at the end of the week and the value at the end of the previous week.

The parameters of the Weibull distributions of accumulated growing degrees at the end of each climatic week are listed in Table 47. Computed values of the chi-square statistic for the Weibull distributions were less than the tabulated value of 7.815 (three degrees of freedom, 5 percent significance level) for all weeks. The chi-square and Kolmogorov-Smirnov tests (Appendix E) indicated that the normal distribution should be rejected for the first three climatic weeks listed in Table 47. The computed values of the chi-square statistic for the normal distribution were smaller than the values for the Weibull distribution for the 5 weeks marked with an asterisk in Table 47. But the Weibull distributions for those weeks were used to simplify the model logic since the chi-square test did not indicate that they should be rejected.

The distributions of accumulated growing degrees at the ends of the climatic weeks ending on April 18 and April 25 are shown in Figure 43. These distributions had the smallest and largest values of the computed chi-square statistic for all climatic weeks during the planting season (Table 47). The distribution for the week ending April 18 clearly illustrates the nonsymmetrical distribution of

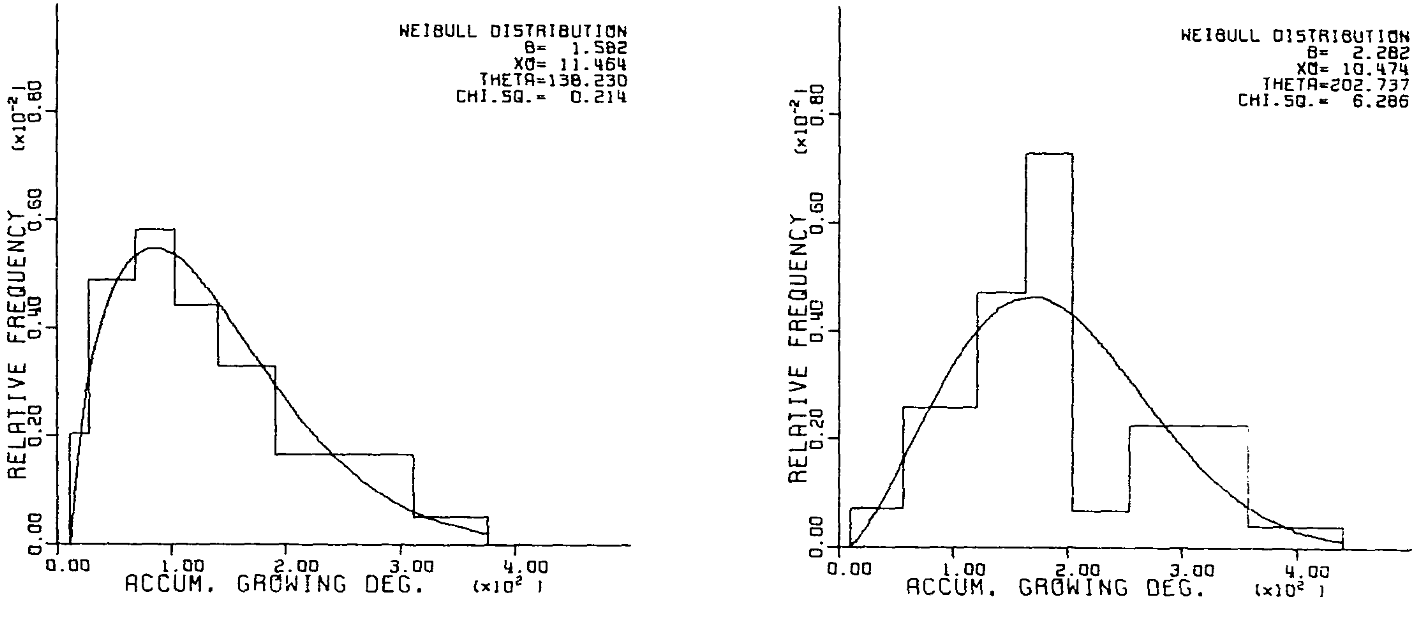
Table 47. Parameters of the Weibull distributions of accumulated growing degrees at the end of selected climatic weeks for Ames, Iowa (seven chi-square classes)

Week ending	$\bar{x}$	$\hat{\sigma}$	XO	θ	B	χ^2
3-28	36.80	37.84	0.000	36.356	0.973	4.786
4-04	61.93	58.16	0.000	63.484	1.065	4.000
4-11	91.30	65.98	6.845	91.302	1.290	0.571
4-18	135.53	80.24	11.464	138.230	1.582	0.214
4-25*	190.07	83.38	10.474	202.737	2.282	6.286
5-02	254.57	87.73	23.608	259.174	2.856	4.393
5-09	327.23	92.81	73.446	284.288	2.979	3.786
5-16	407.73	86.73	231.579	198.905	2.138	2.357
5-23*	499.90	93.04	313.112	210.901	2.110	4.714
5-30	603.17	93.76	379.980	251.410	2.552	3.643
8-29	2520.87	155.94	1946.743	632.115	4.146	2.357
9-05	2654.97	153.60	1967.873	747.181	5.135	0.929
9-12	2767.83	152.91	1999.775	829.251	5.826	0.214
9-19*	2866.93	161.44	2150.766	779.208	5.088	2.321
9-26	2951.90	165.80	2417.771	592.964	3.576	2.321
10-03	3028.77	172.71	2338.240	756.293	4.540	0.929
10-10*	3098.73	176.40	2441.447	723.127	4.201	2.321
10-17	3167.23	175.43	2535.822	696.187	4.043	4.464
10-24	3220.07	184.23	2593.204	693.601	3.799	3.036
10-31*	3257.50	184.47	2469.247	859.675	4.884	3.750

*Computed value of the chi-square statistic for the normal distribution was lower than the computed value of the chi-square statistic for the Weibull distribution listed in the last column.

values which was characteristic of most weeks during this time period.

The distributions of accumulated growing degrees at the ends of the climatic weeks ending on September 12 and October 17 are shown in



(a) (b)

Figure 43. Distributions of accumulated growing degrees at the end of two climatic weeks in the spring; (a) Week ending April 18, seven classes; (b) Week ending April, 25, seven classes

in Figure 44. These distributions had the smallest and largest values of the computed chi-square statistic for all climatic weeks during the harvesting season.

With some combinations of planting date and varietal growing degree requirements, corn may not reach maturity before frost terminates growth. Therefore, the climatic day of the first "killing frost", defined by Felch et al. (1972) as the occurrence of a temperature of 30°F. or below, was simulated in the maturity model. The climatic days on which the first frost occurred were obtained from climatological records for Ames, Iowa for the period 1941-70 (United States Department of Commerce, 1941-72), and mathematical distributions were fitted to the histograms of the 30 values. The histograms and density functions of the resulting normal and Weibull distributions are shown in Figure 45. The Weibull distribution described by the following parameters had the smallest value of the computed chi-square statistic:

$$\bar{x} = 230.300$$

$$\hat{\sigma} = 11.983$$

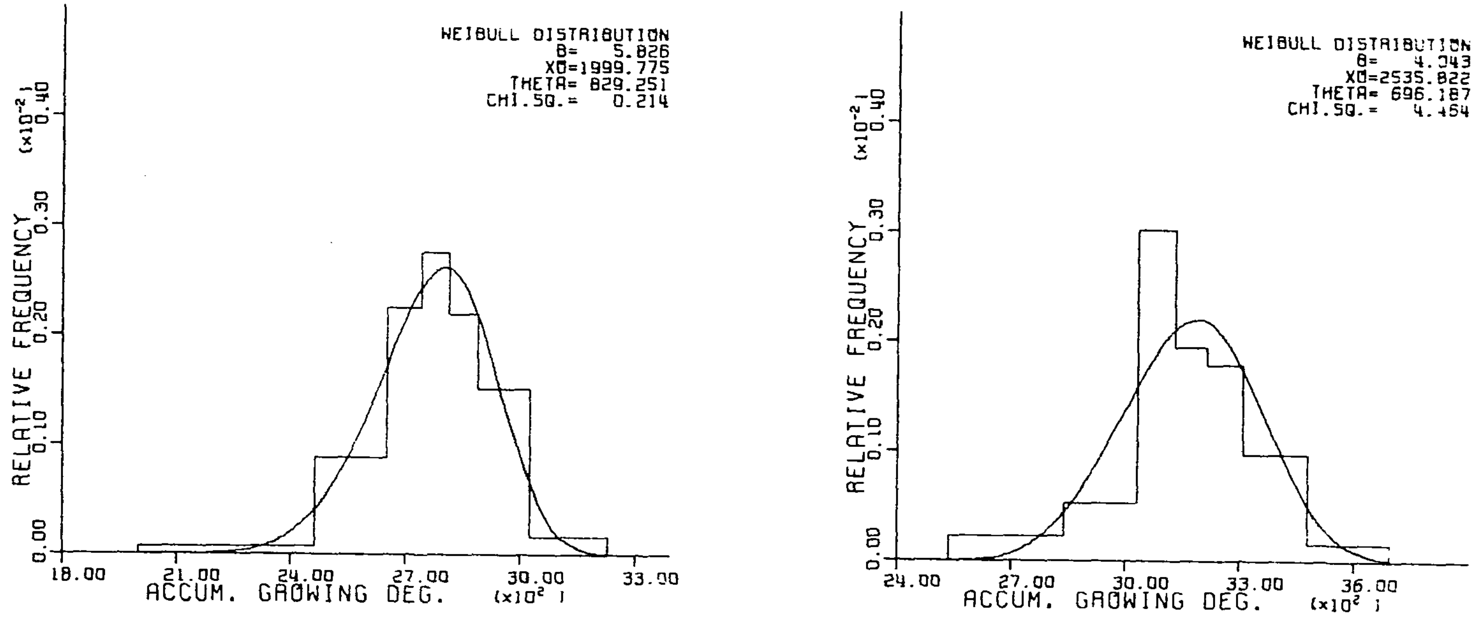
$$B = 2.386$$

$$XO = 203.441$$

$$\theta = 30.302$$

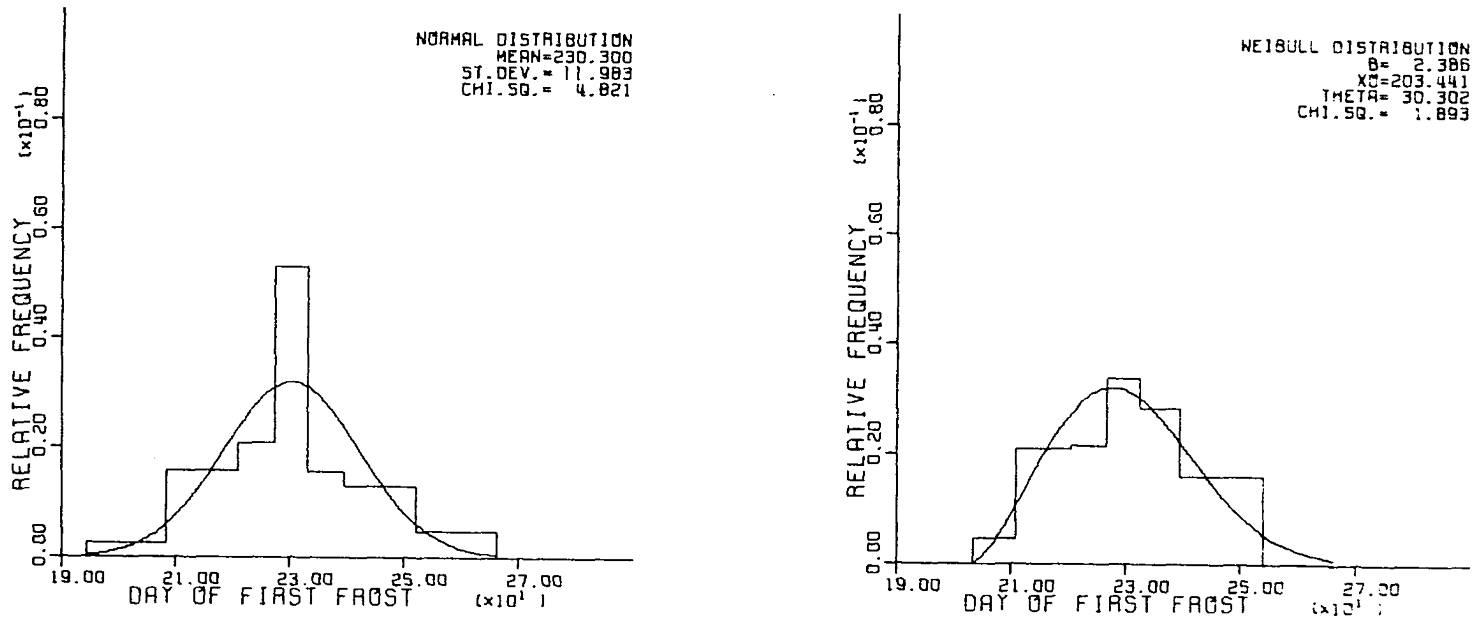
$$\chi^2 = 1.893$$

Rench and Shaw (1971) reported a range of grain moisture contents from 29.8 percent to 36.1 percent at black layer formation for hybrids with relative maturity ratings of 95-125 days. Therefore, if frost



(a) (b)

Figure 44. Distributions of accumulated growing degrees at the end of two climatic weeks in the fall; (a) Week ending September 12, seven classes; (b) Week ending October 17, seven classes



(a) (b)

Figure 45. Distribution of climatic days on which the first temperature of 30°F. or below occurred; (a) Normal distribution, seven classes; (b) Weibull distribution, seven classes

occurred before black layer formation, the grain moisture would be approaching this moisture content range from above. Schmidt and Hallauer (1966) reported an average grain moisture decrease of 0.76 percent per day when grain moisture was between 50 and 30 percent. The most likely time for the grain moisture to be in the range of 50-30 percent would be in September or early October. The average accumulation of growing degrees during the 28-day period from September 6 to October 3 was 13.35 growing degrees per day (Table 47). Dividing 0.76 percent moisture decrease per day by 13.35 growing degrees per day resulted in 0.0569 percent moisture decrease per growing degree. Therefore, when frost occurred before maturity, the grain moisture at frost was calculated with equation 10.

$$GMF = GMM + 0.0569(AGDT - AGDF) \qquad GMF \geq GMM \qquad (10)$$

where GMF = grain moisture content at frost, percent

GMM = grain moisture content at maturity, percent

AGDT = total accumulated growing degrees required to reach maturity

AGDF = accumulated growing degrees at frost

The procedure for estimating crop maturity in the model is described by the following steps:

1. A random value of accumulated growing degrees at planting was selected by Monte Carlo sampling from the Weibull distribution of accumulated growing degrees at the end of the specified climatic week during which planting occurred.

2. This value of accumulated growing degrees was added to the varietal growing degrees requirement to determine total accumulated growing degrees required to reach maturity.
3. A random value of the climatic day of first frost was selected by Monte Carlo sampling from the Weibull distribution of the climatic day on which a temperature of 30°F. or below occurred.
4. Beginning with climatic week 27, a random value of accumulated growing degrees at the end of each climatic week during the harvesting season was selected by Monte Carlo sampling from the Weibull distribution for each week. A single uniform (0,1) random number was generated at the beginning of each simulation and used for sampling each distribution because of the high correlation between values of accumulated growing degrees at the ends of two successive weeks.
5. If grain maturity was reached before frost occurred, the climatic day of maturity and the specified grain moisture content at maturity were returned to the main program.
6. If frost occurred before grain reached maturity, the climatic day of frost and the grain moisture content on that day were returned to the main program.

Grain Yield

The potential yield of grain available for harvesting on any day is usually assumed to increase to some maximum at maturity and then to decline if the crop is left unharvested. The maximum potential yield at maturity is primarily a function of variety and agronomic and environmental conditions during the growing season, although disease and insects may reduce the rate of dry matter accumulation in the grain or terminate it prematurely. The potential yield declines after maturity because of continued plant cell respiration, scavenger losses, and random effects of weather. This decline appears to be primarily a function of time and the rate of moisture loss from the grain. On any particular harvesting day, the yield recovered by a harvesting machine will be lower than the potential yield because of machine losses.

Carpenter and Brooker (1970) developed two equations for field loss of grain, one relating loss to grain moisture content and one relating loss to time. Total loss was the sum of two components, and was subtracted from an assumed potential yield to determine yield recovered by the harvesting machine.

Morey (1971) developed a single recoverable yield function for a combine which included maximum potential yield, time, and grain moisture as variables. Recoverable yield was a function of maximum potential yield and grain moisture prior to November 1, increasing to a maximum at a grain moisture of approximately 27 percent and then declining as the grain dried. After November 1, recoverable yield decreased an additional 0.2666 percent per day because of time.

Holtman et al. (1973) specified a maximum potential yield on October 15 for each year being simulated, and then calculated preharvest loss and machine losses for each harvesting day. Lodging was related to the number of days after September 15, and preharvest loss was assumed to be 0.07 times lodging percent.

For the simulation model discussed in this dissertation, separate models of potential yield and of harvesting machine losses were developed because (1) the potential yield available for harvesting on any day during the harvesting season is independent of the particular harvesting machine to be used, and (2) different machine loss models could be used for each harvesting system without affecting the model of potential yield. Machine loss models will be discussed in a later section of this chapter.

During a study of the rate of grain moisture loss after silking, Schmidt (1968a) obtained extensive data on the accumulation of dry matter in the cob and kernels for one variety of corn. Because comparable data for other varieties could not be found, Schmidt's data were used to develop the basic model of potential grain yield.

Schmidt (1968a) found that dry matter per kernel of grain increased to a maximum at a grain moisture content of approximately 31 percent and then declined as the grain dried. But when the dry matter of all kernels from a single ear was added, the maximum value occurred at a moisture content below 31 percent. Grain dry matter per ear of corn was believed to be a better measure of the potential yield of grain available for harvesting than dry matter per kernel because the ear was the part of the plant actually removed by the machine. A polynomial regression of grain dry matter per ear of corn on grain moisture content was calculated, and the regression curve is shown in Figure 46a. The regression equation is

$$Y = (43.629,\ 13.616) + (10.259,\ 0.977)x - (0.248,\ 0.021)x^2 + (0.0014,\ 0.0001)x^3$$

where Y = grain day matter per ear of corn, grams

x = grain moisture content, percent

The first number in each parentheses is the value of the regression coefficient and the second number is its standard deviation. The value of the coefficient of determination (R^2) for this regression was 0.973, and the analysis of variance (Table C23, Appendix C) indicated that the reduction in variance due to regression was highly significant ($P > 0.01$).

To have an expression that could be used over a range of maximum potential yields, the regression equation was transformed into an expression relating potential yield, as a percent of the maximum, to grain moisture content. The maximum calculated value of grain dry matter per ear, 168.4 grams, occurred at a grain moisture content of 27.1 percent. Dividing the regression equation by this maximum value, and multiplying by 100, resulted in the following expression:

$$Z = (25.913,\ 8.087) + (6.093,\ 0.580)x - (0.147,\ 0.012)x^2 + (0.00086,\ 0.00008)x^3 \qquad (11)$$

where Z = potential grain yield, percent of maximum potential grain yield x = grain moisture content, percent

The first number in each parentheses is the value of the regression coefficient, and the second number is its standard deviation.

Rench and Shaw (1971) reported that later maturing varieties reached black layer formation at higher moisture contents than earlier maturing varieties, and that all the varieties tested reached black layer formation at higher moisture contents when they were planted later. To extend the usefulness of the model, the potential yield curves shown in Figure 46b and given by equations 12-14 were derived graphically. The maximum potential grain yields predicted by equations 12-14 occurred at grain moisture contents of 29.3, 31.2, and 32.9 percent, respectively. Since these expressions were derived, the standard deviations of the coefficients were meaningless.

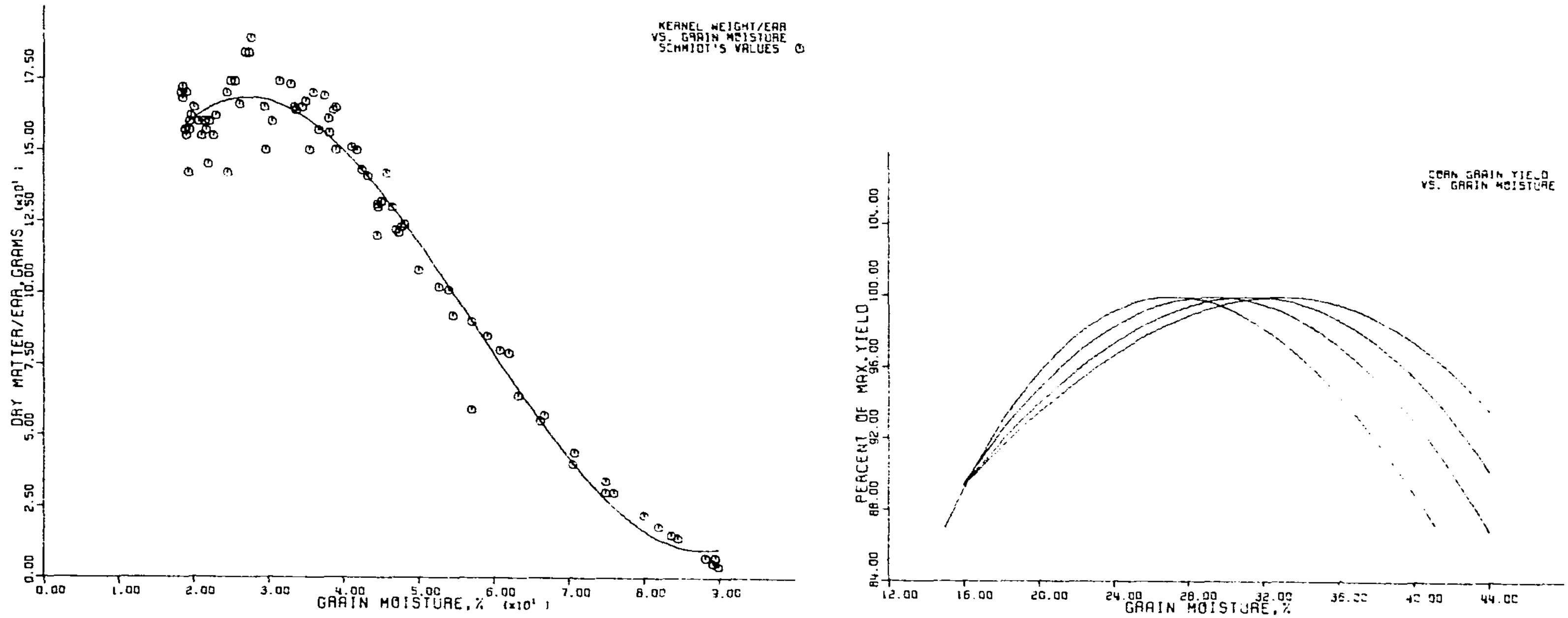
$$Z = 48.941 + 3.471x - 0.058x^2 - 0.00002x^3 \quad (12)$$

$$Z = 63.179 + 1.871x - 0.0065x^2 - 0.0005x^3 \quad (13)$$

$$Z = 69.038 + 1.309x + 0.0062x^2 - 0.00053x^3 \quad (14)$$

Grain Moisture Content

Schmidt and Hallauer (1966) partitioned the range of grain moisture contents between 88 and 20 percent into five arbitrary moisture intervals. They reported that the average daily rate of moisture loss between 88 and 75 percent was not related to any of the weather factors



(a) (b)

Figure 46. Grain yield vs. grain moisture content; (a) Regression of grain dry matter per ear of corn on grain moisture content; (b) Potential grain yield for four values of grain moisture content at maturity

studied. Between 75 and 50 percent, and between 50 and 30 percent, daily rates of moisture loss were significantly correlated with air temperature. Between 30 and 25 percent, and between 25 and 20 percent, moisture loss per day was significantly correlated with wet bulb depression. They concluded that the reduction in moisture before maturity was largely a physiological process, whereas after maturity, moisture reduction was a drying process.

Carpenter and Brooker (1970) and Holtman et al. (1973) used the results of Schmidt and Hallauer (1966) to relate grain moisture reduction per day to known values of temperature and wet bulb depression for each year being simulated. Carpenter and Brooker (1970) derived an expression relating the daily reduction in grain moisture, for moisture contents below 20 percent, to the number of days after grain moisture content reached 20 percent. The constant in their expression was chosen so that grain would dry to 16 percent by the end of December in an average year.

Morey (1971) assumed that the rate of moisture loss from grain in the field was proportional to the difference between the grain moisture content and the equilibrium moisture content of the grain with air. He used the following equation to relate this drying rate to time:

$$\frac{dm}{dt} = B(t)[M - M_e(t)] \qquad (15)$$

where M = grain moisture content in the field, percent

$M_e(t)$ = equilibrium moisture content of grain with air, percent

$B(t)$ = drying constant, $time^{-1}$

Morey assumed a constant value of 0.06 per day for B and that $M_e(t)$ increased linearly with time, from a value of 15 percent on September 1 to 18 percent on November 30. These assumptions resulted in an expression for expected grain moisture content that yielded higher drying rates earlier in the season and negative drying rates, or increasing moisture contents, later in the season for grain that was approaching the equilibrium moisture content.

In an unpublished report of the research by Schmidt and Hallauer (1966), Schmidt (1965) described a detailed study during two years in which samples were taken at regular intervals of a few days. He reported that the correlations between daily rates of moisture loss and average temperatures between samplings were consistently low and nonsignificant when grain moisture was between 75 and 30 percent, indicating that the influence of daily temperature changes on daily rates of moisture loss was small. However, the within year regression coefficients were comparable to the regression coefficients for the 12 years reported by Schmidt and Hallauer (1966). Schmidt (1965) concluded,

> Assuming that the above results from these individual year studies and their comparison to average results are true, one concludes, then, that the effect of daily fluctuations of temperature (weather) on the reduction rate is not great, and that only long periods of adverse weather affect the rate of reduction of corn moisture in the field to any significant amount.

Sufficient data were not available to make studies of the influence of daily wet bulb depression changes on the rate of moisture loss below 30 percent moisture, but Schmidt stated that similar results would be expected.

This discussion suggests that predicting daily rates of moisture loss from daily climatological data, as Carpenter and Brooker (1970) and Holtman et al. (1973) did, could introduce an error into the predictions because of daily fluctuations in the predicted rate of moisture loss that would not occur under field conditions. Over a long period of time, daily errors might be cumulative, causing the predicted value to be consistently high or low.

Based on the discussion in the last three paragraphs, the following decisions were made:

1. The range of grain moisture values from 75 percent moisture to equilibrium moisture would be partitioned into five intervals. The range from 75 to 20 percent would be partitioned into the same four intervals used by Schmidt and Hallauer (1966), and the fifth interval would extend from 20 percent to equilibrium.
2. For the first four intervals, the number of days for grain moisture to pass through an interval would be simulated rather than the daily rate of moisture loss for the interval.
3. A single random value of the number of days for grain moisture to pass through an interval would be selected at the beginning of the interval each year and used to calculate the daily moisture loss for the interval. This daily moisture loss would be used, without regard to weather, for each day that grain moisture was in the interval.

4. Equation 15 would be used to predict grain moisture in the interval from 20 percent to equilibrium.

Schmidt's (1965) original data was obtained, and values from Schroeder (1968b), Hitzhusen (1969), and Marley and Ayres (1972), and data collected for this dissertation were added. Mathematical distributions were fitted to the histograms of the number of days in each moisture interval by the procedure described at the beginning of this chapter. For the number of days in the 75-50 percent moisture interval, the normal and Weibull distributions had equal values of the computed chi-square statistic, so the normal distribution was selected for the model. For the number of days in the 50-30 percent moisture interval, the normal distribution had the smallest value of the computed chi-square statistic. For the 30-25 percent and 25-20 percent moisture intervals, the Weibull distributions had the smallest values of the computed chi-square statistic. The means, standard deviations, and computed chi-square statistics for the two normal distributions, and the means, standard deviations, computed chi-square statistics, and parameters for the two Weibull distributions are listed in Table 48. The four histograms and density functions are shown in Figures 47 and 48.

To use equation 15 to represent grain moisture as a function of time in the interval from 20 percent moisture to equilibrium moisture, expressions for $M_e(t)$ and B(t) were needed for central Iowa. Schmidt (1966) reported that corn left standing in the field over winter would approach a moisture content of 16 percent in central

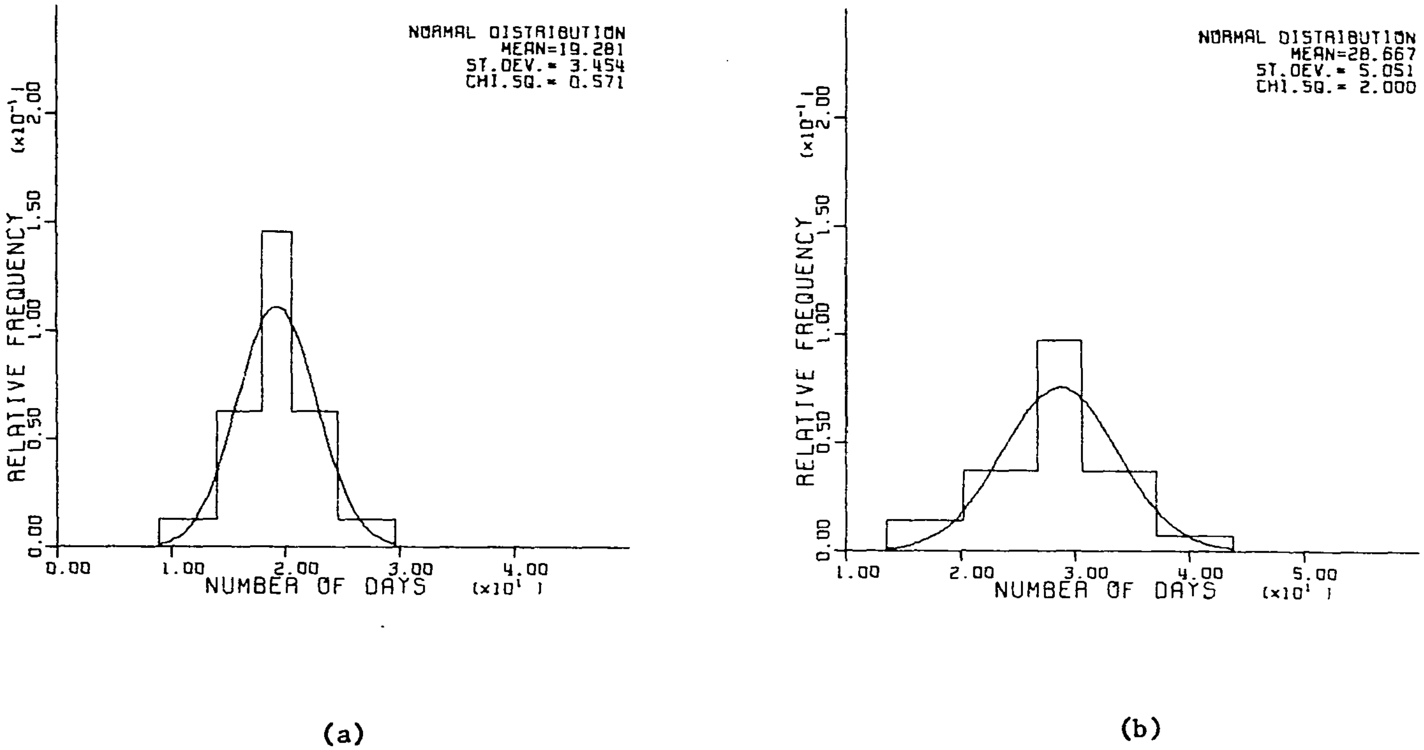
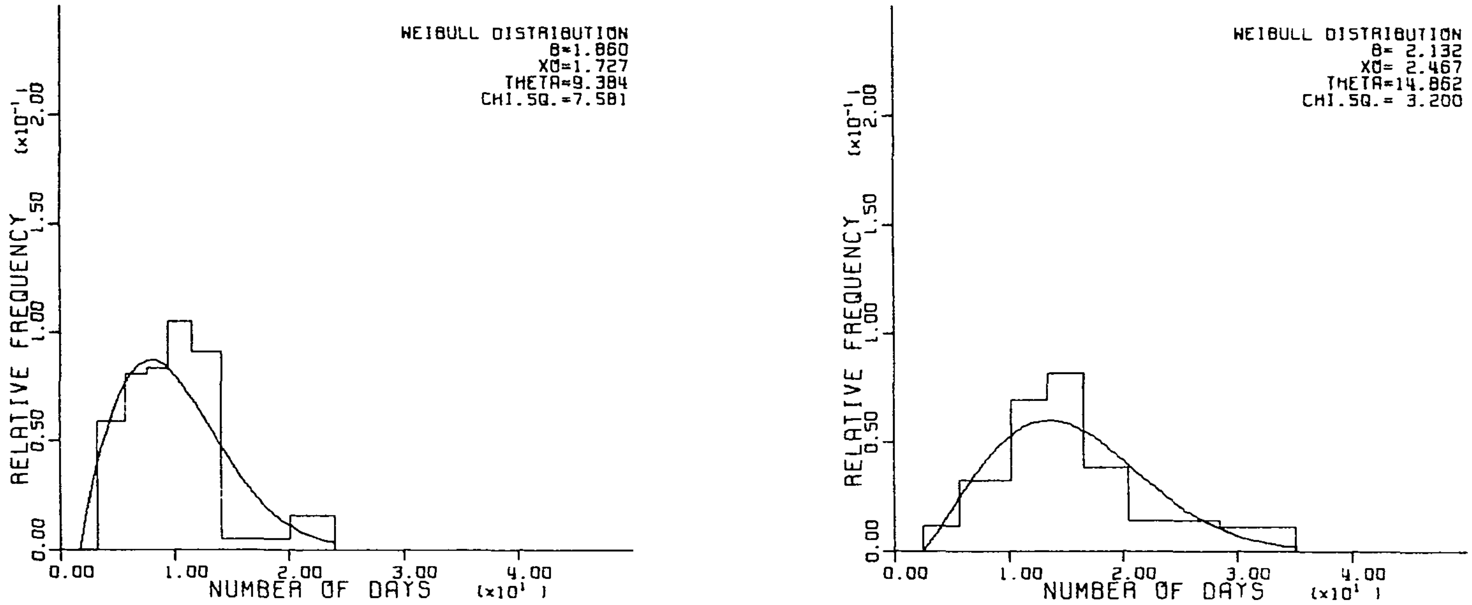


Figure 47. Distributions of the number of days for grain moisture to pass through two moisture intervals; (a) 75-50 percent moisture, five classes; (b) 50-30 percent moisture, five classes



(a) (b)

Figure 48. Distributions of the number of days for grain moisture to pass through two moisture intervals; (a) 30-25 percent moisture, eight classes; (b) 25-20 percent moisture, seven classes

Table 48. Parameters of the distributions of the number of days for grain moisture to pass through four moisture intervals

Moisture interval	$\bar{x}$	$\hat{\sigma}$	XO	θ	B	χ^2
75-50%	19.28	3.454				0.571
50-30%	28.67	5.051				2.000
30-25%	10.06	4.652	1.727	9.384	1.860	7.581
25-20%	15.63	6.495	2.467	14.862	2.132	3.200

Iowa. Ayres et al. (1972) obtained two samples of shelled corn from combines operating in central Iowa in 1971 that had moisture contents below 14 percent. Because measured values of corn equilibrium moisture content throughout the harvesting season could not be found in the literature, an expression for average equilibrium moisture content as a function of time was derived from weather data.

Sorption isotherms for hygroscopic materials are usually represented by empirical equations expressing equilibrium moisture as a function of air (or material) temperature and relative humidity (Chen, 1971; Chen and Clayton, 1971). Relative humidity values are not available for Ames, Iowa, but both relative humidity and wet bulb depression data are available for the municipal airport in Des Moines. It was believed that wet bulb depression would have less variation between Des Moines and Ames than relative humidity, so average wet bulb depression values were calculated for Des Moines on the first and 15th of each month from September-December. These average wet bulb depression values and average dry bulb temperature values for Ames on the same dates were used to determine average values of relative humidity from a psychrometric chart.

The values of relative humidity and dry bulb temperature were then used to calculate average equilibrium moisture content values for each of the eight dates with the following four-parameter desorption equation for corn developed by Chen and Clayton (1971):

$$Rh = \exp(-1.0034(10)^{3}T^{-0.8245}\exp(-0.5671(10)^{-5}T^{2.3768}x)) \quad (16)$$

where Rh = air relative humidity, decimal

T = absolute temperature (of air or material), °R.

x = moisture content, dry basis, decimal

The values of equilibrium moisture content were converted to wet basis moisture content, and equation 17 was derived to relate equilibrium moisture content to the number of climatic days after August 31 (climatic day 184).

$$M_e(t) = (14.45, 0.71) - (0.076, 0.062)t_e + (0.0022, 0.0014)t_e^2$$
$$-(0.00001, 0.000009)t_e^3 \quad (17)$$

where $M_e(t)$ = corn equilibrium moisture content, wet basis, percent

t_e = number of days after August 31

t = climatic day

The first number in each parentheses is the value of the regression coefficient and the second number is its standard deviation.

The curve of corn equilibrium moisture content as a function of time, described by equation 17, is shown in Figure 49a.

Actual values of corn equilibrium moisture content in any year might vary considerably from the calculated values.

An expression for B(t) could not be estimated from the few values of grain moisture content below 20 percent that were available, so B was assumed to be constant for a particular year. The arbitrary division of the range of grain moisture values into five intervals permitted discontinuities at each transition moisture content, but a value of B was desired so that the slopes on either side of 20 percent moisture would be comparable in an average drying year. The mean value of the number of days for corn to dry from 25-20 percent moisture was 15.63 days (Table 48), resulting in an average slope of 0.32 percent per day above 20 percent moisture.

The earliest date of frost that could be selected from the Weibull distribution in Figure 45b was September 19. Medium and full season varieties usually produce the highest yields of grain (Duncan, 1968) and mature at moisture contents slightly higher than 30 percent (Rench and Shaw, 1971). If they were planted to mature a few days prior to September 19, grain might reach 30 percent moisture on September 20-22. In an average drying year, 25.7 days would be expected for grain to dry from 30-20 percent moisture (Table 48), so that 20 percent moisture would be reached on October 16-18.

Average equilibrium moisture on October 17, calculated from equation 17, would be 14.67 percent. Using this value, a grain moisture content value of 20 percent, and a slope of 0.32 percent per day, equation 15 was solved for B, resulting in a value of 0.06 per day, in agreement with Morey (1971).

In 1971, grain moisture early in the harvesting season was below normal. In 1972, grain in many fields failed to dry below 20 percent until late in December. To simulate a range of drying rates, a normal distribution was assumed for B, with a mean value of 0.06 and a standard deviation of 0.015. A random value of B was selected from this distribution on the first day that grain reached a moisture content of 20 percent or less each year and used for all remaining days in that year.

The general solution for equation 15 for constant B (Wylie, 1960) is

$$M(t) = e^{-Bt} \int e^{Bt} BM_e(t)\,dt + Ce^{-Bt} \tag{18}$$

The variable t in equation 18 represents elapsed time from an earlier time when the moisture content was known. In equation 17, t_e represents elapsed time from August 31. Therefore, equation 17 was rewritten as

$$M_e(t) = q + r(t + t_o) + s(t + t_o)^2 + u(t + t_o)^3 \tag{19}$$

where t_o = climatic day when moisture content is known - 184

t = climatic day - climatic day when moisture is known

$q = 14.45$

$r = -0.0763$

$s = 0.00224$

$u = -0.000011$

Substituting equation 19 for $M_e(t)$ in equation 18 and integrating yields

$$M(t) = q + rt_o + st_o^2 + ut_o^3 + \frac{1}{B}(r + 2st_o + 3ut_o^2)(Bt - 1)$$
$$+ \frac{1}{B^2}(s + 3ut_o)(B^2t^2 - 2Bt + 2)$$
$$+ \frac{u}{B^3}(B^3t^3 - 3B^2t^2 + 6Bt - 6) + Ce^{-Bt} \quad (20)$$

Applying the initial condition

$$M(o) = M_o,$$

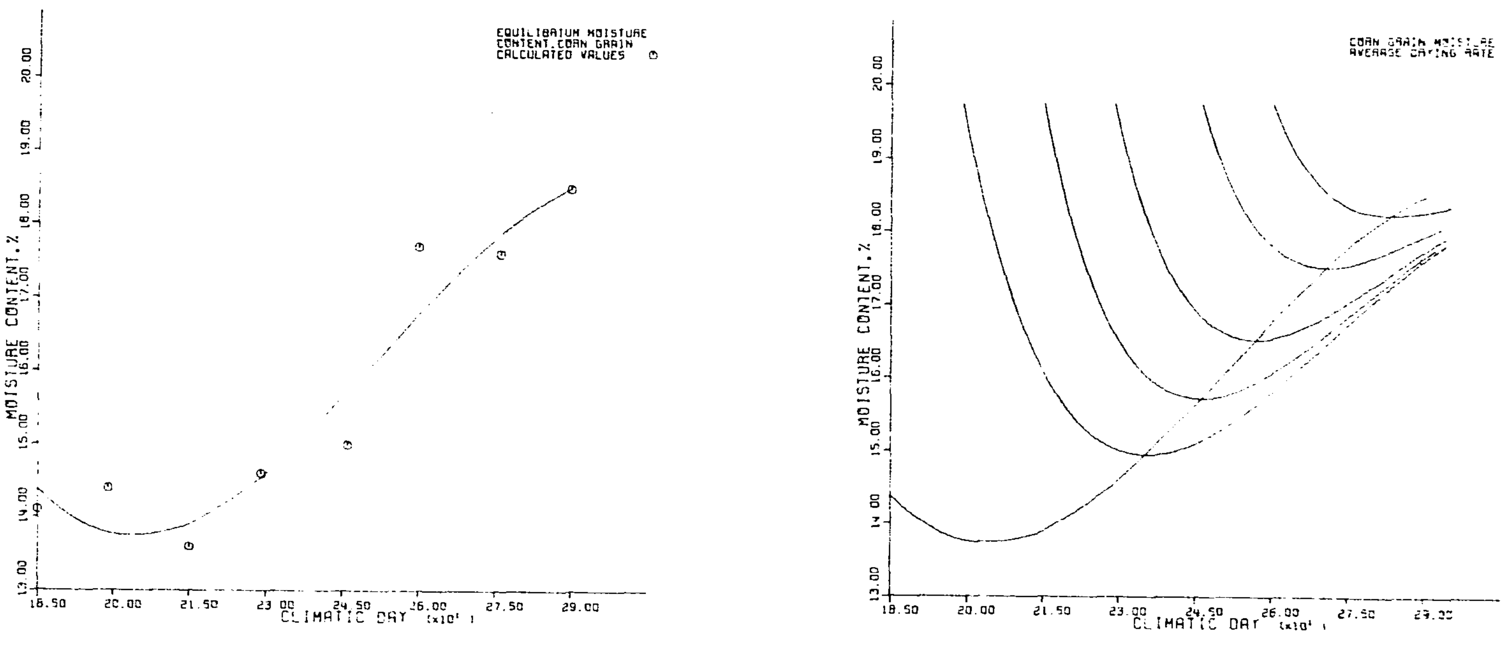
the following expression for the constant C is obtained:

$$C = M_o + \frac{1}{B}(r + 2st_o + 3ut_o^2) - \frac{2}{B^2}(s + 3ut_o)$$
$$+ \frac{6u}{B^3} - q - rt_o - st_o^2 - ut_o^3 \quad (21)$$

Substituting this expression for C into equation 20, the complete solution is

$$M(t) = q + rt_o + st_o^2 + ut_o^3 + \frac{1}{B}(r + 2st_o + 3ut_o^2)(Bt - 1)$$
$$+ \frac{1}{B^2}(s + 3ut_o)(B^2t^2 - 2Bt + 2)$$
$$+ \frac{u}{B^3}(B^3t^3 - 3B^2t^2 + 6Bt - 6)$$
$$+ [M_o + \frac{1}{B}(r + 2st_o + 3ut_o^2) - \frac{2}{B^2}(s + 3ut_o)$$
$$+ \frac{6u}{B^3} - q - rt_o - st_o^2 - ut_o^3]e^{-Bt} \quad (22)$$

Curves of M(t) are shown in Figure 49b for $B = 0.06$ and $M_o = 19.76$ percent on September 15, October 1, October 15, November 1, and November 15. The equilibrium moisture curve is also shown to illustrate the zero slope of each M(t) curve when the equilibrium moisture content is



(a)

(b)

Figure 49. Corn grain moisture content vs. time; (a) Average equilibrium moisture content for central Iowa; (b) moisture content for average drying rates

reached and the increasing grain moisture after that time.

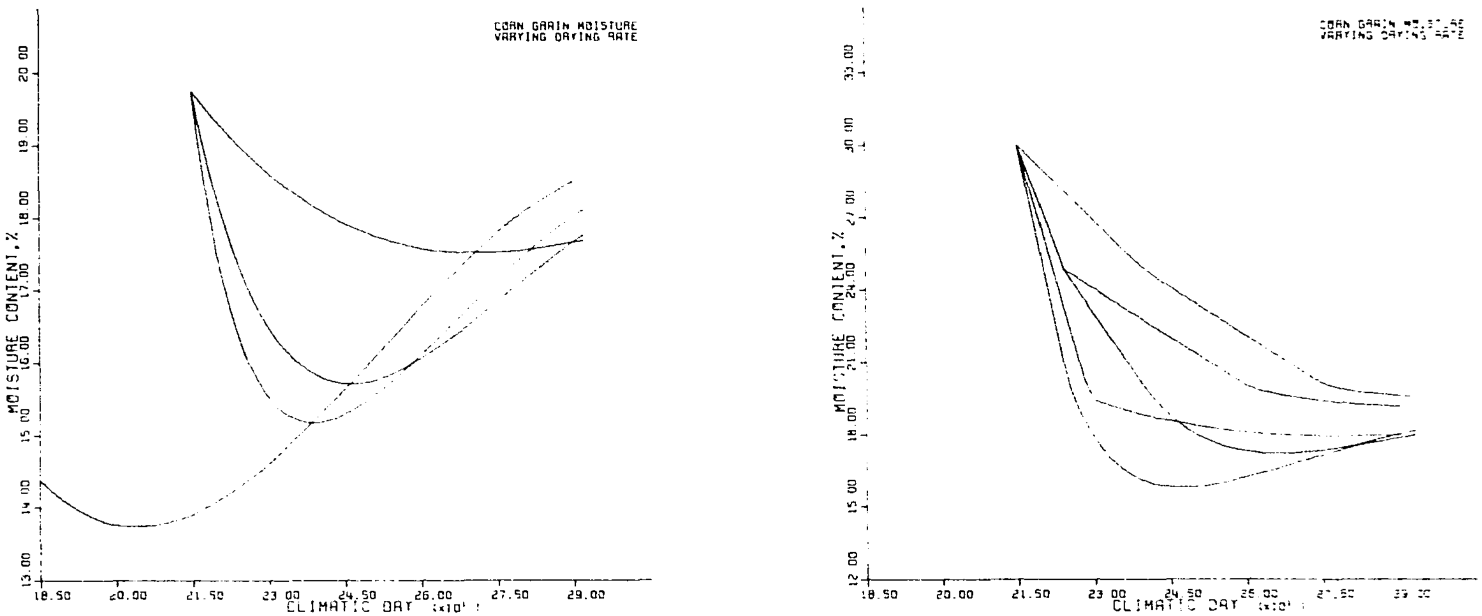
Curves of M(t) for B = 0.015, 0.06, and 0.10, and for M_o = 19.76 percent on October 1, and the equilibrium moisture curve, are shown in Figure 50a to illustrate slow, average and fast drying years.

The grain moisture curves in Figure 50b illustrate five of the many types of drying conditions that might be simulated with the final grain moisture model. All curves start with a grain moisture content of 30 percent on October 1. The upper curve represents a slow-drying year, in which 24 days were required for grain to dry from 30-25 percent moisture, 35 days were required to dry from 25-20 percent moisture, and B = 0.015. The next curve represents a normal rate of drying to 25 percent moisture, and below normal rates of drying after that, approximately the drying conditions observed during 1972. The middle curve represents an average drying year. The second curve from the left represents above normal drying rates to 20 percent moisture and slow drying below 20 percent moisture (B = 0.015). The bottom curve represents above normal drying rates throughout the harvesting season, with only 10 days required to dry from 30-20 percent moisture, and B = 0.10.

Forage Yield

Refuse and husklage dry matter yields were calculated from equations 23 and 24, which are the equations for the linear regressions in Figures 18b and 21a.

$$Y_r = 2576 + 22.61x \qquad (23)$$



(a) (b)

Figure 50. Corn grain moisture content vs. time for varying drying rates

where Y_r = refuse dry matter yield per acre, pounds

x = grain yield per acre, bushels

$$Y_h = 981 + 7.88x \tag{24}$$

where Y_h = husklage dry matter yield per acre, pounds

x = grain yield per acre, bushels

A regression of stalklage dry matter yield on grain dry matter yield could not be calculated from the data obtained during the harvesting studies. Therefore, equations for stalklage yield as a function of grain yield were derived for five different operating policies: harvesting only the two center rows behind 4-, 6-, and 8-row combines without straw spreaders, harvesting all rows behind a combine with a straw spreader, and harvesting all rows behind a combine without a straw spreader.

Estimates of the forage recovery by harvesting stalklage with each of the five operating policies are listed on the last line of Table 49. The numbers in the second column of Table 49 are the percentages of refuse dry matter contributed by each plant part. They were calculated from the values in the column under 25 percent kernel moisture in Table 17. The values in the last five columns of Table 49 are estimates of the fraction of each plant part that would be recovered by a flail-type harvesting machine if corn rows were not excessively ridged during cultivation. The values in the last three columns were based on those in column four, adjusted for the fractions of stalks and leaves available when only two rows were harvested.

Table 49. Estimated dry matter recovery of corn plant parts by a harvesting machine with a flail-type gathering attachment

Corn plant part	Percent of refuse dry matter[1]	All rows spreader	Dry matter recovery multiplier			
			All rows no spreader	2 of 4 rows	2 of 6 rows	2 of 8 rows
Stalk	40.1	0.80	0.80	0.5x0.80	0.333x0.80	0.25x0.80
Cob	23.2	0.25	0.40	0.40	0.40	0.40
Husks	17.7	0.40	0.80	0.5x0.80	0.333x0.80	0.25x0.80
Leaves	19.0	0.40	0.40	0.40	0.40	0.40
Total recovery, %		52.6	63.2	43.3	36.7	33.4

[1] Calculated from values listed in Table 17 for a grain moisture of 25 percent.

The estimates of total forage recovery at the bottom of Table 49 were calculated by multiplying the values in column two by the values in each of the other columns and adding the products. The only recovery estimate that could be verified directly with the measured yields in Table 12 was the value of 36.7 percent for harvesting the two center rows behind a 6-row combine. Dividing each of the values of stalklage yield in the last four lines of Table 12 by the refuse yields for the same yields of grain, calculated with equation 23, resulted in an average stalklage dry matter recovery of 36.6 percent.

The value of 52.6 percent recovery (Table 49) for harvesting all rows behind a combine equipped with a straw spreader is also comparable to the 53.5 percent recovery reported by Berge.[1] The recovery estimates for the other three operating policies looked reasonable compared to 36.7 and 52.6 percent, and they were used without verification.

The dry matter yield of stalklage was calculated with equation 25.

$$Y_s = \frac{r}{100}(2576 + 22.61x) \qquad (25)$$

where Y_s = stalklage dry matter yield per acre, pounds

r = appropriate value of percent recovery from Table 49

x = grain yield per acre, bushels

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[1]Berge, Orrin I. 1970. Department of Agricultural Engineering, University of Wisconsin, Madison, Wisconsin. Harvesting corn stalklage with a Fox forage harvester. Private communication.

Forage Moisture

Refuse and husklage moisture contents were calculated from equations 26 and 27, which are the equations for the linear regressions in Figure 20 and 21b.

$$M_r = 9.94 + 1.70\ M_g \qquad (26)$$

where M_r = refuse moisture content, percent

M_g = grain moisture content, percent

$$M_h = -14.77 + 2.03M_g \qquad (27)$$

where M_h = husklage moisture content, percent

M_g = grain moisture content, percent

Regressions of stalklage moisture content on grain moisture content could not be calculated with the small number of values obtained during the harvesting studies. Therefore, equations expressing stalklage moisture content as a linear function of grain moisture content were derived from the dry matter distributions in Table 49 and data reported by Schroeder (1968b). The coefficients for the five equations are listed in Table 50.

The distribution of dry matter among the four plant parts for stalklage harvested with each operating policy was calculated by multiplying the values in column two of Table 49 by the values in each of the other columns. Schroeder (1968b) calculated linear regressions of the moisture content of each plant part on grain moisture content. His regression equations were used to calculate the distribution of wet weight among the four parts for all stalklages.

Table 50. Coefficients of linear equations[1] relating stalklage moisture content to grain moisture content

Operating policy	c_1	c_2
Combine with straw spreader, all rows	17.94	1.40
Combine without straw spreader		
All rows	14.26	1.46
2 of 4 rows	8.94	1.54
2 of 6 rows	5.99	1.58
2 of 8 rows	3.85	1.61

[1] $Y = c_1 + c_2 x$, where Y = stalklage moisture content, percent, and x = grain moisture content, percent

A dry matter percentage was calculated for each stalklage by dividing the total dry weight by total wet weight, and converted to moisture content. Calculations were made at two levels of grain moisture content to calculate each c_1 and c_2. Equation 28 was used to calculate stalklage moisture content in the model.

$$M_s = c_1 + c_2 M_g \tag{28}$$

where M_s = stalklage moisture content, percent

c_1, c_2 = appropriate coefficients from Table 50

M_g = grain moisture content, percent

Vehicle Mobility

Vehicle mobility was defined as the ability of a machine to operate in a field and perform its primary function. The determination of vehicle mobility in the model was reduced to a binary decision; a machine could operate in a field or it could not.

The criteria defining vehicle mobility are the field conditions that result in satisfactory machine performance. They determine the days on which a field operation can be performed during any period of time. For example, if corn grain reaches a moisture content of 30 percent on September 20, and if the grain can be stored as high moisture corn at a moisture content of 30 percent or less, harvesting can begin any time after September 20. If harvesting should be completed by November 1, to allow time for subsequent field operations, the harvesting season comprises the 41 days between September 20 and November 1. But the vehicle mobility on each day during this period determines which days are suitable for harvesting, and there will usually be fewer than 41 potential harvesting days. The number of potential harvesting days on which harvesting is actually performed will be determined by the reliability of the machinery system, and the system output will be the sum of the man-machine productivities on each harvesting day.

Consequently, the field conditions defining vehicle mobility, and the probability of their occurrence in the proper combinations, determine the minimum daily man-machine productivity that will allow completion of a field operation within allowable time limits. All machines with daily man-machine productivities equal to or greater than this minimum value will have the desired, or higher, completion probability. The particular machine selected, and the method of acquiring it, are economic decisions.

In this context, vehicle mobility is not the same as soil trafficability. Gill and Vanden Berg (1967) define soil trafficability as "the capacity of a soil to support and withstand traffic". Soil trafficability is only a measure of the ability of a soil to withstand the forces applied to it by a traction device without allowing the traction device to become mired. Vehicle mobility requires not only that the soil be trafficable, but also that the functional performance of the machine be satisfactory. Therefore, classifying days as good or bad for field operations on the basis of vehicle mobility will usually result in fewer good days than classifying them on the basis of soil trafficability alone.

Link (1962) calculated the probabilities of suitable field days from information in the personal diary of the manager of the old Agronomy Farm at Ames, Iowa for the years 1932-1939 and 1941-1961. Each day that field work had been performed was classified as a good day, and a binomial distribution was fitted to the occurrence of good and bad days during each climatic week. The binomial distribution permitted the calculation of the probabilities of having from zero to six suitable field days during each climatic week (Sundays were excluded in the diary). Frisby (1965) and Marley (1965) also used these binomial probabilities in their studies of machinery systems for corn production. Morey et al. (1972) used data reported by field observers in central Indiana to classify days as good or bad for field work.

Carpenter and Brooker (1970) determined vehicle mobility from historical climatological records. A day suitable for harvesting was defined by a relationship between precipitation and average temperature, snowfall less than 1 inch, and a depth of snow on the ground less than 1 inch. They assumed that soil would be frozen on any day with an average temperature less than 20°F., and classified such days as suitable for harvesting regardless of precipitation if snowfall and depth of snow were both less than 1 inch.

Several vehicle mobility models have also included soil moisture content as a criterion of vehicle mobility. Shaw (1965a) used a soil moisture budgeting technique to estimate the moisture content in the top 6 inches of the soil profile from daily precipitation and evaporation. He calculated evaporation from temperature and cloud cover, and specified several combinations of temperature and precipitation that would cause either freezing or thawing of the soil. He assumed that soil was workable any day when it was not frozen and the available soil moisture in the top 6 inches of the profile was less than or equal to 0.75 inch. He considered a day prior to May 1 suitable for field operations if the soil was workable and less than 0.20 inch of precipitation occurred. After May 1, he considered a day suitable if soil was workable and less than 0.30 inch of precipitation occurred. If rain occurred at night, he considered the suitability of the next day to be a function of the amount of rain and available soil moisture.

Shaw compared the number of predicted days suitable for field operations to the record of days suitable for field operations from the old Agronomy Farm, Ames, Iowa (Link, 1962). The correlations between the observed and predicted number of days during March, April, and May ranged from 0.87-0.93. Excluding cloud cover from the calculation of evaporation did not change the correlations significantly. Shaw concluded that additional information about specific field operations performed during these months would improve the predictions.

Bolton et al. (1968) developed a soil moisture accounting technique to estimate the soil moisture content on any day from records of rainfall and pan evaporation. From a 2-year record of days suitable for field operations at the Delta Branch Experiment Station, Stoneville, Mississippi, they determined that a soil moisture content of 78-80 percent of the maximum soil moisture was the limiting value for vehicle mobility.

Link (1968) used a similar moisture budgeting technique to estimate daily soil moisture contents. He proposed the plastic limit as the maximum value of soil moisture content 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. He also stated that the rapidly changing binomial probabilities during the weeks in spring and fall, and the persistence effects in rainfall phenomena, may have invalidated the assumptions required to represent vehicle mobility with a binomial distribution as he had done previously (Link, 1962).

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 the 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, except during the months when snow occurred, when a maximum soil moisture content of 99.5 percent of field capacity in the top three moisture zones was used as the criterion of vehicle mobility. The correlation was improved when 95 percent of field capacity was used as the maximum soil moisture content in the top three moisture zones and the restriction of no snow on the ground was included. They also reported that the probability of any day being suitable for tillage was dependent on the suitability of the previous day, indicating a persistence effect of vehicle mobility.

Holtman et al. (1973) used a combination of the soil moisture budgets developed by Shaw (1963a) and Baier and Robertson (1966) to estimate available soil moisture in the top 6 inches of soil profile. They defined a day as suitable for harvesting if the percent available moisture in the upper 3 inches of the soil profile was below 95 percent on light soils. For heavier well-drained soils, percent available moisture in the second 3 inches of the soil profile had to be below 98-99 percent also. They did not determine vehicle mobility when soil was frozen.

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 the soil moisture budget developed by Shaw (1963a) to estimate soil moisture contents from historical records. 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 0.1 inch. Frisby used a Markov chain model to account for persistence of good and bad days, and calculated initial and transition probabilities for successive 5-day intervals.

Morey (1971) used a similar procedure to estimate the number of days suitable for harvesting corn in central Indiana. A suitable day was defined as one having less than 0.1 inch of precipitation and a moisture content less than 95 percent of available capacity in the top 6 inches of the soil profile. Morey also used a Markov chain model to account for persistence and calculated initial and transition probabilities for successive 7-day intervals corresponding to climatic weeks. He compared the probabilities of zero to seven good days calculated with the Markov chain model to the probabilities of the same numbers of good days given by the binomial distribution and verified that persistence did exist and should be included in a vehicle mobility model.

This review of attempts to relate climatological variables, field conditions, and machine performance indicated that (1) the relationships between them have not been defined will enough to be used without verification, and that (2) a model of vehicle mobility should include the effects of persistence of good and bad days. The lack of data verifying the criteria used to define vehicle mobility was evident in the models for corn harvesting machines. Carpenter and Brooker (1970) reported no verification of their criteria defining suitable field conditions for harvesting. Morey (1971) and Holtman et al. (1973) reported that their choice of 95 percent of field capacity for the limiting value of soil moisture was based on the work of Rutledge and McHardy (1968). But Rutledge and McHardy estimated this value for tillage. Therefore, in view of the importance of vehicle mobility for the simulation of machine performance, a vehicle mobility model was developed for corn harvesting in central Iowa.

Soil trafficability tests have been conducted with many types of wheeled and tracked vehicles at the U.S. Army Engineer Waterways Experiment Station (Knight and Freitag, 1962; Gill and Vanden Berg, 1967; Rush, 1968, 1969). These tests have been conducted on very wet, fine-grained soils and wet sands. Relationships have been developed between soil strength and soil trafficability that have been used successfully to predict the ability of a vehicle to complete 50 passes over the soil in the same path. Knight and Freitag (1962) and Rush (1969) reported that the best correlation between predicted and observed performance for most vehicles up to 50,000 pounds gross weight was obtained when the soil strength was measured in the layer 6-12 inches below the soil surface. For light vehicles, the critical layer is 3-9 inches below the surface, and for very heavy vehicles, (over 50,000 pounds gross weight) the critical layer is 9-15 inches below the surface. For wet sand, the critical layer is 0-6 inches below the surface for all vehicles.

The minimum index of soil strength required for a vehicle to complete a single pass over the soil has been found to be approximately one-half of the minimum index required for the vehicle to complete 50 passes. Rush (1969) reported that the critical layer of soil for predicting single pass vehicle performance can be either 0-6 inches or 6-12 inches below the soil surface.

Aldabagh (1971) found that soil strength increased significantly as soil moisture content decreased for agricultural soils at two locations near Ames, Iowa. He measured soil strength using the procedures developed at the Waterways Experiments Station, and his data indicate that soil strength at a depth of 6 inches was adequate to support 50 passes of most agricultural vehicles.

Corn harvesting equipment would make only one pass over the soil and would not be as heavy as many of the military vehicles tested. Therefore, a vehicle mobility model that included the soil conditions in the layer 0-6 inches below the surface should be adequate for corn harvesting machinery.

To be useful to farm managers and extension personnel working in the area of machinery management, a vehicle mobility model should require only input data that is generally available. Soil moisture content was selected as the variable to describe soil conditions in the upper 6-inch layer of the profile, based on the previous models reviewed, and because a historical record of soil moisture was available for many locations in Iowa. Shaw et al. (1972) published historical records of average soil moisture on selected dates for 22 locations in Iowa. The soil moisture sampling program was started at 10 locations in Iowa in 1954 and expanded to 22 locations by 1959.

Soil moisture samples were taken from corn and meadow rotations and the soil moisture budgeting techniques develped by Shaw (1963a, 1964) were used to estimate available soil moisture between sampling dates. Samples were taken in early April, early June, late July-early August, and early November through 1961. The June sample was discontinued in 1962 and the July-August sample was discontinued in 1965 because of the high correlations between predicted and measured values in November. In some dry years, late July-early August samples were obtained to check the predicted values.

Ames was one of the 10 original sampling locations, and samples were obtained from a Webster silty-clay loam with a water-holding capacity of 1.0 inch of plant-available water in the upper 6 inches of the soil profile at field capacity. Values of available soil moisture in the upper 6 inches of soil under corn were obtained for each day after August 30 for the period 1954-1971 from the Climatology and Meteorology office at Iowa State University. For each day between the final sampling each year and December 26, available soil moisture was estimated with soil moisture budgeting techniques developed by Shaw (1963a, 1965b). Daily value of maximum and minimum temperature, precipitation, snowfall, and depth of snow on the ground for Ames during the same 1954-1971 period were obtained from climatological records (United States Department of Commerce, 1941-1972).

Because the field conditions that would cause a day to be unsuitable for harvesting had not been measured, the records of good and bad field days from the old Agronomy Farm at Ames (Link, 1962, 1968) were used to select the values of the parameters in the vehicle mobility model. This record and the record of soil moisture values were both available for the period 1954-1961, so only those 8 years were used to develop the model.

To use the record of observed suitable days, the assumption had to be made that the field operations performed on the Agronomy Farm during the fall were typical of other farms in the area. This assumption can be challenged because the operations on the Agronomy Farm were performed in small research plots rather than on a field basis, and machinery may have been smaller than the machinery generally used by farmers. Frisby (1963) reported that two more suitable days were recorded at the Agronomy Farm during the 1961 harvesting season than were recorded by the University Farm Service department, and attributed the discrepancy to the heavier machinery used by University Farm Service. This author has observed that university researchers are at least as eager to complete the harvest as most farmers, and occasionally operate machinery under conditions that are marginal for good performance. Therefore, the number of suitable days predicted by the model probably should not be any greater than the number of suitable days recorded at the Agronomy Farm.

Three other criticisms of using the records of observed good and bad days can also be made. No records were kept after 1961, and farming practices today are not the same as they were prior to 1961. Using records of general observations of good and bad days means that the model will not represent vehicle mobility for a specific machine, such as a combine or forage harvester. Finally, using observations of days in which suitable field conditions occurred instead of measured values of those conditions means that the validity of using the model in areas away from Ames will be unknown until the parameters are verified with field measurements.

Freezing and thawing of soil was estimated with the conditions reported by Shaw (1965a, 1965b). The soil was assumed to be frozen after (a) a minimum air temperature less than 20°F. occurred, or (b) both minimum and maximum air temperatures were less than 32°F. for 2 consecutive days. The soil was assumed to remain frozen until no measurable depth of snow was recorded and (a) both maximum and minimum air temperatures were greater than 32°F. for 2 consecutive days, (b) a maximum air temperature greater than 70°F. occurred,

(c) a maximum air temperature greater than 60°F. and a minimum air temperature greater than 32°F. occurred, or (d) both maximum and minimum air temperature were greater than 32°F. and 0.5 inch or more precipitation occurred. The soil was assumed to have thawed on the day when any of these conditions occurred.

It was assumed that harvesting could be performed when soil was frozen if precipitation, snowfall, or the depth of snow on the ground were not too great. Therefore, available soil moisture was not checked on days when soil was frozen. This assumption limited the model to field operations other than tillage. To predict days suitable for fall tillage operations, the model would have to be changed to classify a day as unsuitable when soil became frozen at some critical depth.

Days suitable for field operations were predicted with 35 combinations of parameter values. The ranges of values checked were: (a) available soil moisture, 0.95-1.05 inch; (b) maximum precipitation, 0.10 to 0.50 inch; (c) maximum precipitation on preceding day, 0.40-0.90 inch. Values of the parameters on the preceding day were not included in many of the combinations. But a comparison between predicted and observed suitable days showed that the number of suitable days was consistently overestimated. On many of the days that were classified as being suitable but were observed to be unsuitable, the values of the parameters were less than the values required to classify a day as being unsuitable, indicating a persistence effect from conditions on the preceding day. Several combinations of parameters for both the day being evaluated and the preceding day were tested, but the only combination that improved the prediction included precipitation as the only parameter for the preceding day.

The values of the parameters in the models that had the best agreement with the 8-year observations are listed in Table 51. Model 1 did not include any parameters for the preceding day, and model 2 included only precipitation on the preceding day. The other parameters were the same for both models.

The values of maximum precipitation when soil was not frozen and of maximum available soil moisture in the 0- to 6-inch layer for a day to be classified as suitable for field operations were determined from the record of observations of good days. The maximum allowable precipitation when the soil was frozen could not be determined from the record of observations because days when soil was frozen were recorded as being unsuitable for field observations. Because precipitation would not percolate into a frozen soil profile, the value of 0.10 inch was assumed to be near the limit for soil trafficability. Observations during the 1972 harvesting season indicated that a snowfall or a depth of snow on the ground less than 1.0 inch would not interfere with normal harvesting.

The total number of days recorded as being suitable for field operations during climatic weeks 27-38 over the 8-year period, and the number of suitable days predicted with each model, are listed in Table 52. A total of 96 weeks occurred during this period, but records were not available for 9 weeks (Link, 1962, 1968). Therefore, the

Table 51. Parameters defining field conditions suitable for field operations, except tillage, in the fall

Parameter (inches)	Model 1	Model 2A	Model 2B
Maximum precipitation yesterday	-	0.54	0.54
Maximum precipitation today			
Unfrozen soil	0.27	0.27	0.27
Frozen soil	0.10	0.10	0.10
Maximum available soil moisture, 0-6 inches	1.05	1.05	1.05
Maximum snowfall	1.00	1.00	1.00
Maximum depth of snow on ground	1.00	1.00	0.00

predicted values for those weeks were not included in the figures listed in Table 52. Sundays were also excluded because they had not been included in the Agronomy Farm records. A comparison between observed and predicted values was not made for climatic weeks after week 38 because only 1 day was recorded as being suitable for field operations after week 38 during the period 1954-1961.

Model 1, which did not include a parameter for the preceding day, overestimated the total number of suitable days by 16 days. Disagreement between observed and predicted numbers of suitable days occurred for 31 of the 87 weeks, with 13 weeks having fewer good days predicted than observed, and 18 weeks having more good days predicted than observed.

Model 2 included the precipitation on the preceding day as a parameter. When the maximum allowable depth of snow on the ground

Table 52. Total number of days[1] suitable for field operations for the period 1954-1961, excluding Sundays

Climatic week	Observed	Model 1	Model 2A	Model 2B
27	40	42	38	38
28	37.5	37	36	36
29	35.5	38	37	37
30	35.5	33	32	32
31	36	37	37	37
32	33.5	43	41	41
33	45.5	42	41	41
34	39	39	39	39
35	39.5	38	38	38
36	39.5	40	39	38
37	34	38	38	38
38	19.5	24	23	21
Total	435	451	439	436
χ^2		5.022	3.882	3.420

[1] A record of observed days was available for only 87 weeks during this period. Therefore, the suitable days predicted for the other 9 weeks were not included in the last three columns of the table.

was set at 1.0 inch (model 2A), the total number of suitable days was overestimated by only 4 days. Disagreement between observed and predicted numbers of suitable days still occurred for 31 of the 87 weeks, but 15 weeks had fewer good days predicted than observed, and only 16 weeks had more good days predicted than observed.

Carpenter and Brooker (1970) assumed that corn harvesting equipment could be operated satisfactorily with up to 1.0 inch of snow on the ground. Observations during the 1972 harvesting season confirmed this assumption, and indicated that even deeper snow could be present if the corn was standing well so that the gathering chains on a cornhead could be operated above the snow. However, snow between rows of standing corn melted more slowly than snow in the open at the weather station, and snow remained in the cornfields for several days after no measurable snow was recorded in the climatological records. Because of the slower rate of melting, snow was deeper between rows of standing corn than at the weather station during the melting period.

Because climatological records of snow depth were used in the vehicle mobility model, a limiting value of zero was specified in the final model (model 2B). The overestimation of suitable days was reduced to only a single day during climatic weeks 27-38 (Table 52).

The probabilities of any day being suitable for field operations other than tillage are listed in Table 53 for climatic weeks 27-43. The binomial probabilities are those computed by Link (1962). The effect of specifying a zero depth of snow on the ground can be seen in the lower probabilities for weeks 36 and 38-43.

Model 2B was used in the simulation model. Varying the values of the parameters listed in Table 51 did not improve the predictions. For many weeks when predicted and observed numbers of suitable days

Table 53. Probability of any day being suitable for field operations except tillage, for the period 1954-1971

Climatic week	Binomial[1]	Model 2A	Model 2B
27	0.8590	0.7857	0.7857
28	0.8910	0.8016	0.8016
29	0.9135	0.8254	0.8254
30	0.8653	0.7857	0.7857
31	0.8547	0.8095	0.8095
32	0.8087	0.8413	0.8413
33	0.9198	0.8651	0.8651
34	0.9103	0.9127	0.9127
35	0.9423	0.8492	0.8492
36	0.8270	0.8730	0.8651
37	0.8467	0.8571	0.8571
38	0.7028	0.7619	0.6905
39	0.2937	0.7937	0.7778
40	0.1450	0.8810	0.8333
41	0.0278	0.7063	0.6825
42	-	0.6825	0.5714
43	-	0.6667	0.5159

[1] From Link (1962).

were different, no reasons for the disagreement could be determined from the climatological and soil moisture values. Several days were recorded as being unsuitable when no precipitation occurred and available soil moisture was low. Other days were recorded as being suitable for field operations when 1.0-1.5 inches of precipitation occurred the previous day and available soil moisture was at field capacity.

These discrepancies appeared to result from not including a parameter for the time during which precipitation occurred. A day might be suitable for field operations if 0.5 inch of precipitation occurred at 8 p.m. the previous evening, but not if the precipitation occurred at 8 a.m. in the morning. Since weather observations at the Agronomy Farm were made at 7 p.m. each day, precipitation occurring after that time was recorded as having occurred the next day.

Rutledge and McHardy (1968), Frisby (1970), and Morey (1971) reported that days suitable for field operations exhibited a persistence effect from one day to the next. The use of a first order Markov chain model to approximate the probabilities of climatological events exhibiting persistence has been well-documented in the literature (Caskey, 1963; Miller, 1964; Weiss, 1964; Feyerherm and Bark, 1965; Feyerherm et al., 1965; Jones et al., 1972). Hillier and Lieberman (1967) state that a stochastic process is said to have the Markovian property if the conditional probability of any future event, given any past event and the present state, is independent of the past event and depends only on the present state of the process. A stochastic process is said to be a finite-state Markov chain if it has the Markovian property, a finite number of states, stationary transition probabilities, and a set of inital probabilities for all states. Since vehicle mobility has two states, good or bad, and if the probability of any day during a climatic week being good is dependent only on the state of the previous day, ignoring all earlier days, vehicle mobility each week can be approximated with a first order Markov chain.

The probability of a good day, and the probability of a good day given that the previous day was good, were calculated for each climatic week from the record of good and bad days predicted with model 2B for the period 1954-1971. The remaining probabilities were calculated with the following equations:

$$P(B) = 1.0 - P(G) \tag{29a}$$

$$P(B/G) = 1.0 - P(G/G) \tag{29b}$$

$$P(G/B) = P(G)P(B/G)/P(B) \tag{29c}$$

$$P(B/B) = 1.0 - P(G/B) \tag{29d}$$

where P(G) = the initial probability of a good day

P(B) = the initial probability of a bad day

P(G/G) = the transition probability of a good day given that the previous day was good

P(B/G) = the transition probability of a bad day given that the previous day was good

P(G/B) = the transition probability of a good day given that the previous day was bad

P(B/B) = the transition probability of a bad day given that the previous day was bad

The initial and transition probabilities for each climatic week are listed in Table 54. By comparing the values of P(G), P(G/G), and P(G/B) for each week, the persistence of good and bad days is evident throughout the season.

The number of days suitable for field operations during each

Table 54. Initial and transition probabilities of days being suitable for field operations other than tillage

Climatic week	P(G)	P(B)	P(G/G)	P(B/G)	P(G/B	P(B/B)
27	0.7857	0.2143	0.8454	0.1546	0.5670	0.4330
28	0.8016	0.1984	0.8614	0.1386	0.5600	0.4400
29	0.8254	0.1746	0.9038	0.0962	0.4545	0.5455
30	0.7857	0.2143	0.8367	0.1633	0.5986	0.4014
31	0.8095	0.1905	0.8835	0.1165	0.4951	0.5049
32	0.8413	0.1587	0.8972	0.1028	0.5449	0.4551
33	0.8651	0.1349	0.9159	0.0841	0.5393	0.4607
34	0.9127	0.0873	0.9298	0.0702	0.7337	0.2663
35	0.8492	0.1508	0.9083	0.0917	0.5167	0.4833
36	0.8651	0.1349	0.9346	0.0654	0.4195	0.5805
37	0.8571	0.1429	0.9189	0.0811	0.4865	0.5135
38	0.6905	0.3095	0.8977	0.1023	0.2281	0.7719
39	0.7778	0.2222	0.9175	0.0825	0.2887	0.7113
40	0.8333	0.1667	0.9519	0.0481	0.2404	0.7596
41	0.6825	0.3175	0.8352	0.1648	0.3544	0.6456
42	0.5714	0.4286	0.8889	0.1111	0.1481	0.8519
43	0.5159	0.4841	0.8923	0.1077	0.1148	0.8852

climatic week is listed in Table 55 for seven probability levels. They were calculated from the initial and transition probabilities for each week (Table 54) by a 3-step procedure. The probabilities of exactly 0-7 suitable days were calculated for each week with the expressions listed in Appendix F. Since the probabilities of exactly 0-7 suitable days are mutually exclusive,

$$P_j(i \geq k) = \sum_{i=k}^{7} P_j(i) \qquad 1 \leq k \leq 7 \quad (30)$$

where $P_j(i \geq k)$ = probability of at least k suitable days during week j

$P_j(i)$ = probability of exactly i suitable days during week j

The probabilities of at least 1-7 suitable days during each climatic week were calculated with equation 30, and the numbers of days with a probability equal to or greater than the probabilities listed in Table 55 were selected.

The Figures in Table 55 are the maximum numbers of suitable days expected at the indicated probability level. During climatic week 27, for example, at least 4 suitable days would be expected with a probability of 90 percent; in approximately 10 percent of the years, fewer than 4 suitable days would be expected. At least 5 suitable days would be expected in 3 years out of 4, and 6 suitable days would be expected to occur in approximately one-half of the years.

After selecting the desired probability level (or risk), Table 55 can be used to estimate the number of days suitable for field

Table 55. Expected numbers of days[1] suitable for field operations other than tillage at selected probability levels

Climatic week	Calendar dates	Probability level						
		0.98	0.95	0.90	0.85	0.80	0.75	0.50
27	Aug. 30-Sept. 5	2	3	4	4	4	5	6
28	Sept. 6-Sept. 12	2	3	4	4	5	5	6
29	Sept. 13-Sept. 19	2	3	4	4	5	5	6
30	Sept. 20-Sept. 26	2	3	4	4	4	5	6
31	Sept. 27-Oct. 3	2	3	4	4	5	5	6
32	Oct. 4-Oct. 10	2	3	4	5	5	5	6
33	Oct. 11-Oct. 17	3	3	4	5	5	5	7
34	Oct. 18-Oct. 24	4	5	5	6	6	6	7
35	Oct. 25-Oct. 31	2	3	4	5	5	5	6
36	Nov. 1-Nov. 7	2	3	4	5	5	5	7
37	Nov. 8-Nov. 14	2	3	4	5	5	5	7
38	Nov. 15-Nov. 21	0	0	1	2	3	3	5
39	Nov. 22-Nov. 28	0	1	2	3	4	4	6
40	Nov. 29-Dec. 5	0	1	3	4	5	5	7
41	Dec. 6-Dec. 12	0	1	2	3	3	4	5
42	Dec. 13-Dec. 19	0	0	0	0	1	2	4
43	Dec. 20-Dec. 26	0	0	0	0	0	1	4

[1] Sundays included in expected number of days.

operations, except tillage, that would be expected during any specific period of time. The minimum daily man-machine productivity required to complete the field operations within this period of time can be estimated by dividing the number of acres on which the field operations will be performed by the expected number of suitable days.

The values of P(G), P(G/G), and P(G/B) from Table 54 were used in the vehicle mobility model for each climatic week. A uniform (0,1) random number was generated for each day after harvesting began and compared to the appropriate probability for the week during which the day occurred. On the initial day, the random number was compared to P(G). On all other days, the random number was compared to either P(G/G) or P(G/B), depending on the classification of the previous day. If the random number was less than or equal to the appropriate probability, the day was classified as suitable for field operations.

Man-machine Performance

Man-machine performance is a random variable affected by crop yield, field conditions, operator capabilities, mechanical reliability, and many other factors. Sufficient data were not obtained during the harvesting studies to relate these factors to man-machine performance. Only a few observations of each machine were made to estimate an average rate of performance with one operator in one or two fields.

Therefore, man-machine performance was treated as a function of two variables; an average rate of performance per hour, and the hours of potential operating time per day (Figure 33). The average rate of performance was expressed as acres per hour, and was the product of man-machine activity and man-machine productivity. Initial values of man-machine activity and man-machine productivity were taken from Table 25. Other values were used to study the effects of changes in the operation of the machines, and they were calculated from the initial values with the activity ratios developed by Von Bargen and Cunney (1972).

Machine harvesting losses are a function of the variety and condition of the corn, field conditions, machine condition, operating policy of the harvesting machine, and many other factors. Harvesting losses are usually assumed to decrease to a minimum level as grain dries and then to increase as grain continues to dry (Herum, 1954; Johnson and Lamp, 1966).

Carpenter and Brooker (1970) and Morey (1971) developed expressions relating harvesting loss to grain moisture content and time. Holtman et al. (1973) developed expressions relating harvesting losses to variety, lodging, row spacing, grain moisture, and time. Parsons et al. (1971) used the same expressions, with the addition of travel speed and cornhead speed as variables.

Ayres et al. (1972) reported the results of a survey of corn harvesting losses from 84 combines operating in central Iowa during 1971. A polynomial regression of total machine loss on grain moisture content was calculated from their data. The regression curve is shown in Figure 51a, and the regression equation is given by equation 31:

$$L = (14.82,\ 10.47) - (1.04,\ 1.19)x + (0.024,\ 0.033)x^2 \qquad (31)$$

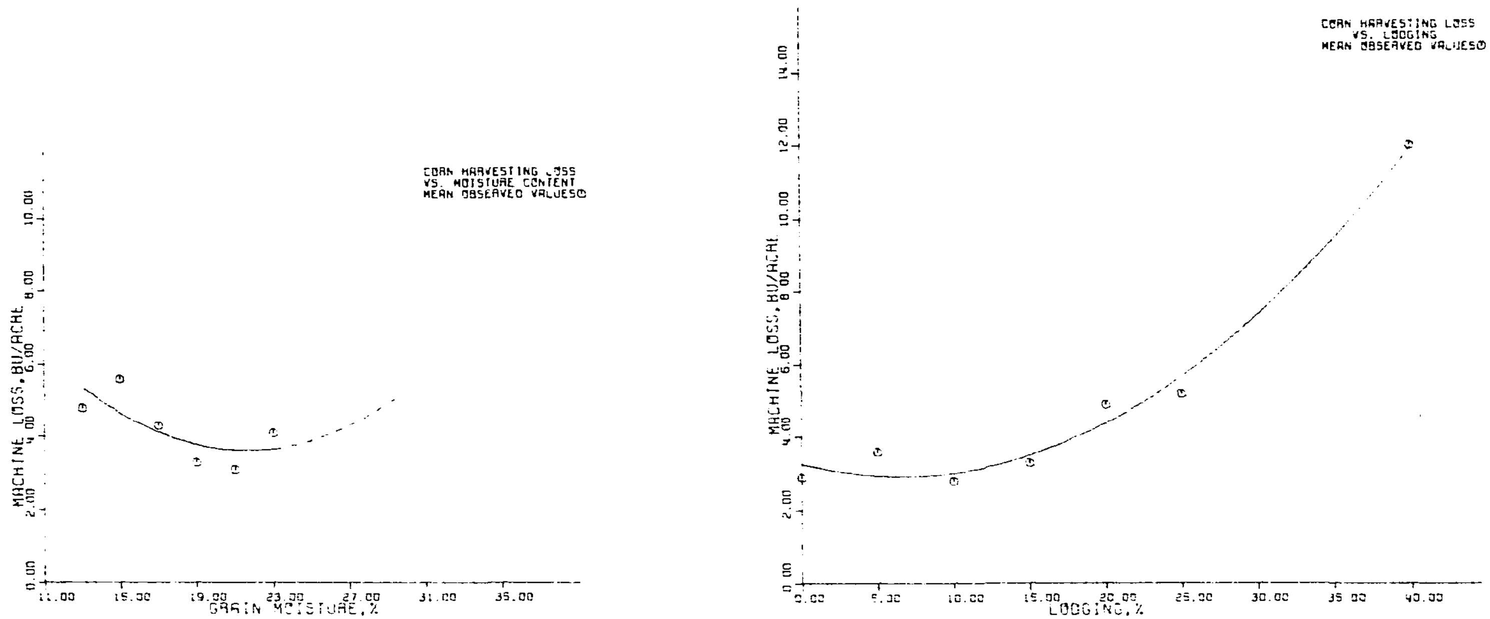
where L = total machine harvesting loss, bushels per acre

x = grain moisture content, percent

The first number in each parentheses is the value of the regression coefficient and the second number is its standard deviation.

Ayres et al. (1972) did not report values of harvesting loss for grain moisture contents above 24 percent, but losses reported by others (Herum, 1954; Johnson and Lamp, 1966) increased at higher moisture contents. Therefore, equation 31 was extrapolated beyond the range of data, as shown in Figure 31a, to estimate harvesting loss at higher moisture contents.

The values of harvesting loss predicted by equation 31 were average values for combines operating in central Iowa. To account for other than average conditions, the values calculated with equation 31 were adjusted by multiplying them by a grain loss modifier. For example, Ayres et al. (1972) reported that an average of 7 percent of the plants were lodged, and that harvesting loss increased as lodging increased, Figure 51b. Therefore, a value of the grain loss modifier greater than 1.0 was used to simulate harvesting loss in a field with more than 7 percent of the stalks lodged. Values greater than 1.0 were also used to simulate harvesting loss for a below-average operator, a weedy field, etc.



(a) (b)

Figure 51. Average corn harvesting machine loss for combines operating in central Iowa; (a) Loss vs. grain moisture content; (b) Loss vs. lodging

Machinery Costs

The purchase of farm machinery involves a relatively large capital investment and a series of nonuniform future operating costs. Alternative methods of acquiring the use of machinery, such as a long-term lease, a short-term rental, or custom hire, may involve a series of smaller annual capital investments and a different series of operating costs. Because these costs are not uniform over the economic life of a machine, the time value of money must be considered when comparing alternative machines and methods of acquiring them. Equations 32, 33, and 34 were used to convert nonuniform annual machinery costs to a series of uniform annual equivalent costs over the economic life of the machine.

$$(a/p)_n^i = \frac{i(1 + i)^n}{(1 + i)^n - 1} \qquad i > 0 \qquad (32)$$

$$(a/f)_n^i = \frac{i}{(1 + i)^n - 1} \qquad i > 0 \qquad (33)$$

$$(p/f)_m^i = \frac{i}{(1 + i)^m - 1} \qquad i > 0 \qquad (34)$$

where $(a/p)_n^i$ = uniform series worth of a present sum (capital recovery factor)

$(a/f)_n^i$ = uniform series worth of a future sum (sinking fund factor)

$(p/f)_m^i$ = present worth of a future sum

i = rate of return, or interest rate

n = economic life of machine, years

m = age of machine, years ($m \leq n$)

The following costs were estimated for each machine, assuming that all machines were purchased:

1. Fixed costs
   a. Annual equivalent cost of capital
   b. Annual equivalent cost of taxes and insurance
   c. Annual cost of housing and maintenance facilities
2. Variable costs
   a. Repairs and maintenance
   b. Fuel and lubricants
   c. Labor
   d. Tractor, except for self-propelled machines

The annual equivalent cost of capital includes recovery of the capital invested in the machine and a return on the invested capital during the economic life of the machine. The annual equivalent cost of capital for each machine was calculated with equation 35 from Smith (1968):

$$AEC = C(a/p)_n^i - S(a/f)_n^i \qquad (35)$$

where AEC = annual equivalent cost of capital, dollars

C = initial (first) cost of the machine, dollars

S = salvage value of the machine at the end of its economic life, dollars

The remaining value of a machine at the end of each year was calculated with equations published by the American Society of Agricultural Engineers (1972). These equations relate the remaining on-farm value of tractors and farm implements to the list price of the machine and its age, and can be represented by equation 36:

$$(RV)_m = Pa(b)^m \qquad m \geq 1 \qquad (36)$$

where $(RV)_m$ = remaining on-farm value of a machine at the end of year m, dollars

P = list of price of the machine, dollars

a,b = constants for a particular machine

m = age of machine, years

The salvage value in equation 35 was calculated from equation 36 by setting m equal to the economic life of the machine.

Taxes and insurance costs were calculated as a percentage of the remaining on-farm value of a machine at the beginning of each year. They were combined into a single cost, and the annual equivalent cost of taxes and insurance was calculated with equation 37:

$$AETI = (a/p)_n^i \sum_{m=1}^{n} t(RV)_{m-1}(p/f)_m^i \qquad m \geq 1 \ (37)$$

where AETI = annual equivalent cost of taxes plus insurance, dollars

t = annual rate for taxes plus insurance, decimal

$(RV)_{m-1}$ = remaining on-farm value of a machine at the beginning of year m (end of year m - 1), dollars

The annual cost of housing and maintenance facilities represents recovery of a share of the capital invested in machinery storage structures and maintenance facilities for the machinery system. This cost was assumed to be constant over the economic life of the machine, and was calculated as a constant percentage of the list price of the machine each year.

The cost of repairs and maintenance per unit of machine use are usually assumed to be low when the machine is new and to increase at an increasing rate over the life of the machine. Bowers and Hunt (1970) developed equations for the average total accumulated cost of repairs and maintenance during the life of farm machines from farm surveys conducted in Illinois and Indiana. Their equations can be represented by equation 38:

$$(TAR)_L = Pr_1r_2(L)^{r_3} \tag{38}$$

where $(TAR)_L$ = average total accumulated cost of repairs and maintenance at L, dollars

P = list price of machine, dollars

r_1, r_2, r_3 = constants for a particular machine

L = age of machine, percent of expected wearout hours

The expected total numbers of hours to reach wearout life for several types of farm machines are listed in Bowers (1968) and Bowers and Hunt (1970). The value of L at any time during the life of the machine is calculated by dividing the accumulated hours of operation to that time by the expected total hours of operation to wearout, and multiplying by 100.

The total accumulated cost of repairs and maintenance at the end of each year during the economic life of a machine was calculated with equation 38 for each rate of annual use. The total cost of repairs and maintenance during the year was calculated by subtracting the total accumulated cost at the end of the previous year. Because these annual costs were not equal, the annual equivalent cost of repairs and maintenance over the economic life of the machine was calculated from equation 39:

$$AERM = (a/p)^{i}_{n} \sum_{m=1}^{n} (RM)_m (p/f)^{i}_{m} \qquad m \geq 1 \qquad (39)$$

where AERM = annual equivalent cost of repairs and maintenance, dollars

$(RM)_m$ = total cost of repairs and maintenance during year m, dollars

The annual equivalent cost of repairs and maintenance was divided by the total units of machine use over its economic life to determine the cost of repairs and maintenance per unit of use.

Persson (1969) developed equations relating tractor fuel consumption to engine speed and load. His equation for an average tractor was

$$F = C_1\left(1 + \frac{C_2 N^2}{M}\right)H \qquad 0 \leq M \leq 1 \quad 0.5 \leq N \leq 1 \qquad (40)$$

where F = fuel consumption, gallons per hour

C_1 = 0.059 for gasoline engine tractors

= 0.047 for diesel engine tractors

C_2 = 0.51 for gasoline engine tractors

= 0.37 for diesel engine tractors

N = ratio of engine speed (rpm) to rated engine speed

M = ratio of PTO horsepower being used to maximum PTO horsepower

H = PTO horsepower being used

Equation 40 was used to calculate the fuel consumption for tractors and self-propelled machines when an average value of M could be estimated. When an average value of M could not be estimated, equations 41 and 42 were used to estimate an average value of fuel consumption (American Society of Agricultural Engineers, 1972):

$$F_g = 0.06(H_m) \tag{41}$$

$$F_d = 0.044(H_m) \tag{42}$$

where F_g = average fuel consumption of gasoline engine tractors, gallons per hour

F_d = average fuel consumption of diesel engine tractors, gallons per hour

H_m = maximum tractor PTO horsepower

With either method of calculating fuel consumption, fuel consumption was multiplied by the cost of fuel per gallon and divided by the man-machine performance per hour to determine fuel cost per unit of machine use.

Lubricant (oil, grease, filters) cost was assumed to be 15 percent of fuel cost (American Society of Agricultural Engineers, 1972). Labor was assumed to be a fixed amount per hour.

Program Structure

The structure of the simulation and cost analysis programs is shown in Figure 52. Machinery costs were calculated with a separate program after all simulations were completed.

Each program consisted of an executive program to control input and output data operations and to call the appropriate subroutines. Each of the subsystem models discussed in this chapter were programmed as one or more separate subroutines. This allowed them to be tested and used independently, and will permit a particular subsystem model to be changed at some future date without altering the subroutines for the other models. The documentation for the executive programs and for each subroutine in Figure 52 is listed in Appendix G.

The flexibility of this program structure will also allow expansion of the model in the future:

1. Stochastic man-machine performance, and mechanical reliability can be included by adding appropriate subroutines and changing only the HARVST subroutine.
2. A search program can be added between the executive program and subroutine HARVST to return the optimum machine size for a given acreage and corn variety, or to return the optimum corn acreage for a given machine size.
3. Subroutines for modeling soybean maturity and moisture content can be added by changing only the executive program. A search program can also be included to return the optimum machine size for a given acreage of soybeans and corn, or to return

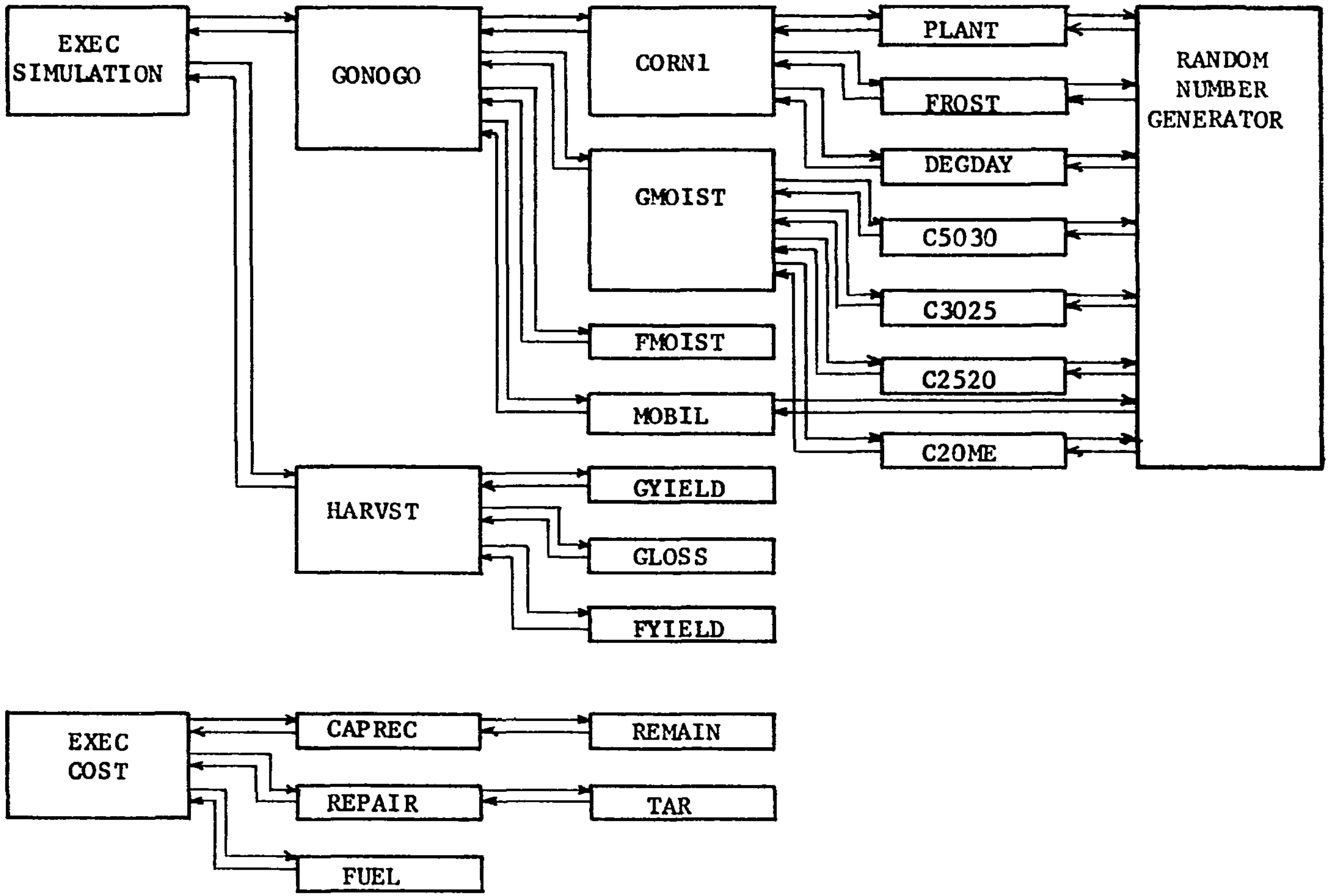


Figure 52. Structure of the computer programs for harvesting simulation and cost analysis

the optimum acreage of soybeans and corn for a given machine size.

4. Fall tillage, either after grain harvesting is completed or in parallel with grain harvesting, can be simulated by adding a subroutine for man-machine performance with tillage machines and changing the executive program.

RESULTS AND DISCUSSION OF SIMULATED HARVESTING PERFORMANCE

The simulation model was used to determine the expected number of harvesting days in central Iowa for corn refuse, husklage, and stalklage. The values of the crop parameters listed in Table 56 were used for all simulation experiments, and the values of the economic parameters listed in Table 57 were used to calculate machinery costs for all harvesting systems.

Table 56. Crop parameters used for all simulation experiments

Parameter	Value
Climatic week of planting	8
Accumulated growing-degrees to reach maturity	2700
Grain moisture content at maturity, percent	30
Maximum potential grain yield at maturity, bu./acre	140

Table 57. Economic parameters used for all harvesting systems

Parameter	Value
Economic life of machine, years	8
Annual cost of capital (interest rate), percent	8
Annual cost of taxes plus insurance, percent	2
Annual cost of housing and maintenance facilities, percent	1
Cost of gasoline, dollars per gallon	$0.22
Cost of diesel fuel, dollars per gallon	$0.20
Cost of labor, dollars per hour	$3.00
Total annual hours of tractor use, first tractor	600
other tractors	400

The expected number of harvesting days was a function of the combined effects of several random variables for each simulation trial. Therefore, trial runs were made for two of the harvesting systems to determine the number of simulation trials required for convergence of the simulated number of days. The results are shown in Figures 53 and 54.

For a combine (Figure 53), the mean value and standard deviation of the total number of harvesting days approached a steady-state condition after 40 simulation trials. After 100 simulation trials, the values of the statistics shown in Figure 53 were

$$\bar{x} = 70.25$$

$$s = 12.83$$

$$\frac{ts}{\sqrt{n}} = 2.55$$

so that the 95 percent confidence interval for the mean number of harvesting days was

$$67.7 \leq \mu \leq 72.8 \qquad (43)$$

For the Beefmaker (Figure 54) the mean value and standard deviation of the total number of harvesting days approached a steady-state condition after 50 simulation trials. After 100 simulation trials, the values of the statistics shown in Figure 54 were

$$\bar{x} = 21.93$$

$$s = 7.06$$

$$\frac{ts}{\sqrt{n}} = 1.40$$

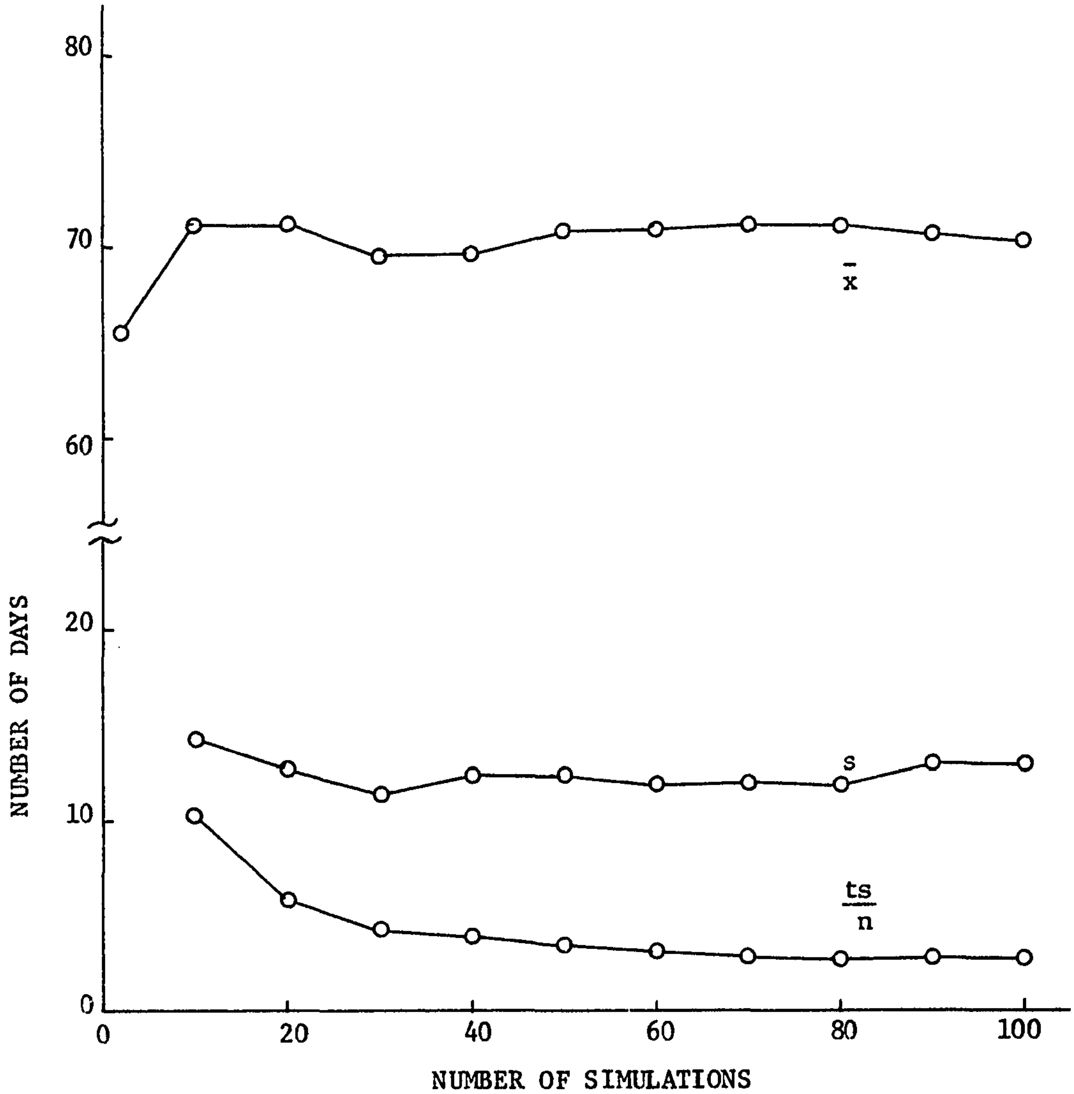


Figure 53. Mean, standard deviation, and 95 percent confidence interval for the simulated total number of harvesting days with a combine

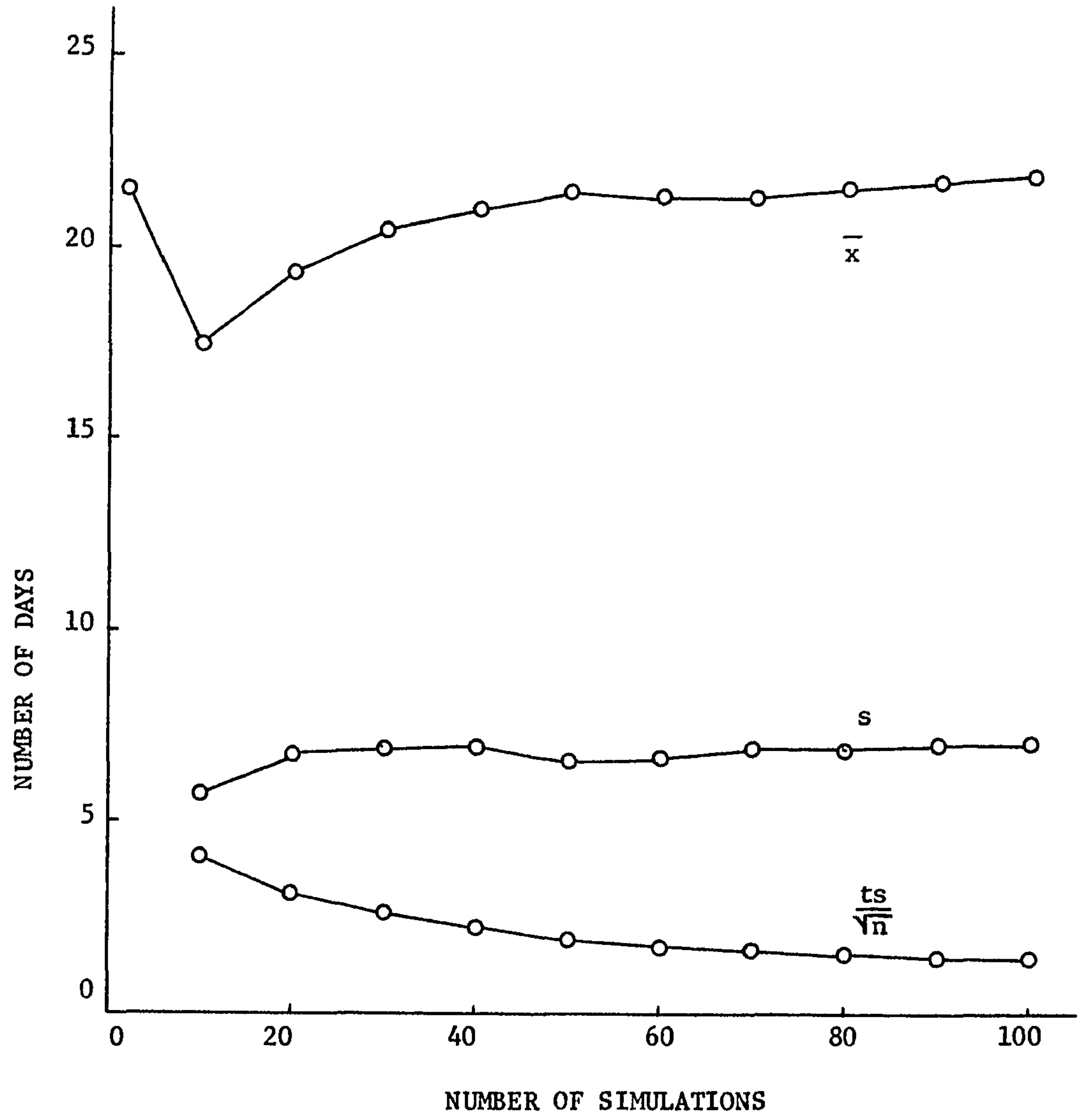


Figure 54. Mean, standard deviation, and 95 percent confidence interval for the simulated total number of harvesting days with the Beefmaker

so that the 95 percent confidence interval for the mean number of harvesting days was

$$20.53 \leq \mu \leq 23.33 \qquad (44)$$

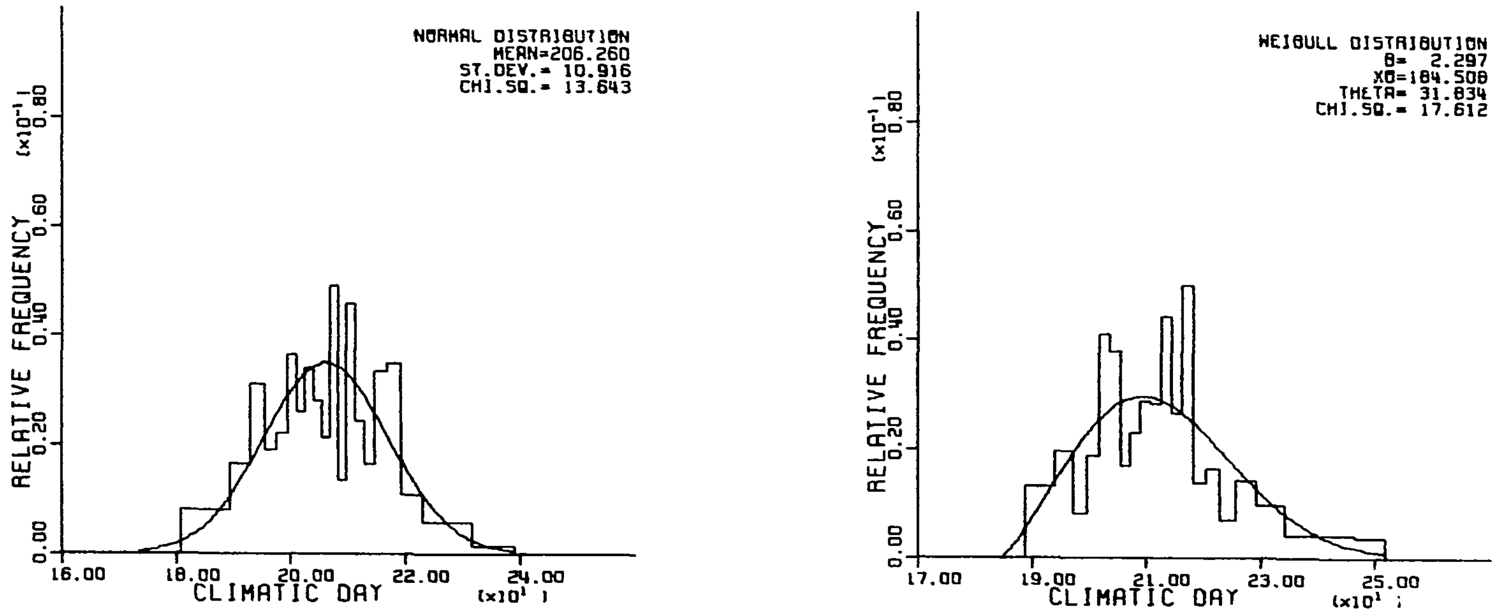
As shown in Figures 53 and 54, the width of the 95 percent confidence interval about the mean decreased very slowly as the number of simulation trials increased over 100, and small reductions could be obtained only with a significant increase in computer time. Therefore, 100 simulation trials were run for all simulation experiments.

Because the crop parameters listed in Table 56 were used for all simulation experiments, the distribution of the climatic day on which grain reached maturity was the same for all harvesting systems. The chi-square test (Appendix E) indicated that neither the normal distribution nor the Weibull distribution could be rejected for this distribution, but the normal distribution had the lower value for the computed chi-square statistic. The histogram and normal density function are shown in Figure 55a.

Harvesting usually did not start on the day grain matured. A maximum grain moisture for starting harvest was specified for each harvesting system, and harvesting started either on the day the specified starting moisture was reached if field conditions were good, or on the first day after that with suitable field conditions. For example, a maximum starting grain moisture content of 28 percent was specified for all combine systems. Harvesting started on the day grain reached 28 percent moisture in 79 years out of 100 years simulated, and was delayed 1 day in 14 years, 2 days in 4 years, 3 days in 1 year, and 4 days in 2 years because of bad field conditions. The distribution of the climatic day harvesting started was positively skewed because of these delays. Therefore, the Weibull distribution of the starting day had a lower value of the computed chi-square statistic than the normal distribution of the starting day, although the chi-square test (Appendix E) indicated that neither distribution could be rejected at the 95 percent level of confidence.

The histogram and the Weibull density function for the climatic day harvesting started is shown in Figure 55b for a maximum starting grain moisture content of 28 percent. Maximum starting grain moisture contents of 32 or 35 percent were specified for harvesting corn refuse, and the distribtuions were skewed even more than the one in Figure 55b. The parameters of the distribution of maturity day and of the distributions of starting days for the three starting moisture contents are listed in Table 58.

Climatic week 8, ending April 25, was specified as the week of planting because it has been reported to be near the optimum planting date for a full season variety of corn in central Iowa (Frisby, 1965; Marley and Ayres, 1972). But grain matured before frost in only 90 of the 100 simulated years, indicating that a variety with a maturity requirement greater than 2700 growing degrees should not be used in central Iowa unless it was going to be harvested for silage. The maximum potential grain yield was reduced in the 10 years when frost occurred before maturity, and the average potential yield was 139.1



(a) (b)

Figure 55. Simulated results of the interactions between crop and weather variables; (a) Distribution of the climatic day grain matured, 21 classes; (b) Distribution of the climatic day harvesting started for a maximum grain moisture content of 28 percent, 21 classes

Table 58. Parameters of the distributions of the climatic day grain matured and the climatic day harvesting started

Variable	$\bar{x}$	$\hat{\sigma}$	XO	Θ	B	χ^2
Climatic day grain matured	206.26	10.92	-	-	-	13.643[1]
Climatic day harvesting started						
Starting moisture = 28 percent	212.71	13.02	184.508	31.834	2.297	17.612[2]
Starting moisture = 32 percent	205.58	13.06	180.623	28.160	1.998	13.255[2]
Starting moisture = 35 percent	201.53	12.73	180.869	23.124	1.668	16.745[2]

[1] The tabulated chi-square value for 18 degrees of freedom (21 classes), is 28.9 at the 0.95 level of confidence.

[2] The tabulated chi-square value for 17 degrees of freedom (21 classes), is 27.6 at the 0.95 level of confidence.

bushels per acre for the 100 simulated years.

Husklage

The performance of a combine with an attachment for collecting husklage was simulated for four values of man-machine capacity. The activity times for two of the man-machine combinations are listed in Table 59. The measured times were taken from Tables 24, 26, and 27 for dumping on a headland.

The measured activity times were observed during 1970 in a field heavily infested with giant foxtail. The combine was operated at an average forward speed of only 1.98 miles per hour (Table 25) to reduce the frequency of machine plugging. The field was wet and grain trucks could not be properly positioned, causing extra combine travel to unload grain which was recorded as an idle travel activity. The dumps were placed close to the fence at one end of the field, causing the combine operator to reduce turning speed to avoid hitting the fence. The extra turning time was recorded as a forage unloading activity.

The measured activity times reflect the adverse conditions often encountered by Corn Belt farmers, but the slow forward speed and the idle travel and forage unloading activities were not typical of a good man-machine combination with good field conditions. Therefore, they were adjusted as shown in the last column of Table 59.

The measured harvest activity time of 11.91 minutes was observed for an average forward speed of 1.98 miles per hour (Table 25). By

Table 59. Activity times and activity ratios for harvesting one load of husklage with a 4-row combine

Activity	Measured time(min.)	Activity ratio	Best time(min.)	Activity ratio
Harvest (primary activity)	11.91	1.000	9.43	1.000
Turn (i = 1)	2.71	0.228	2.25	0.239
Unload grain (i = 2)	1.03	0.086	1.03	0.109
Unload forage (i = 3)	0.90	0.076		
Machine plugging (i = 4)	0.41	0.034	0.41	0.043
Idle travel (i = 5)	0.69	0.058		
Other delay (i = 6)	0.07	0.006	0.07	0.007
Composite activity ratio, R(4)		1.488		1.398

increasing ground speed to 2.5 miles per hour, harvest time would be reduced to 9.43 minutes for the same quantity of forage. An average turn time of 2.25 minutes was observed when dumping husklage at random so that normal turns could be made (Table 26). Forage unloading and idle travel activites were not included for the best 4-row man-machine combinations.

Effective field capacities were calculated with equation 6 for the two 4-row man-machine combinations and for 6-row and 8-row machines. The calculation of the composite activity ratios for the 4-row machines are shown in Table 59. The composite activity ratios for the 6-row and 8-row machines were calculated from the activity ratios for the best 4-row man-machine combination.

The two delay activity times and the grain unloading time for one load of husklage with a 6-row combine were assumed to be the same as the values for the 4-row machine because the same field area would be harvested and the quantity of grain unloaded would be the same. Therefore, the activity ratios r_2, r_4, and r_6 would increase in direct proportion to combine size because the denominators (harvest time) would decrease. Activity ratio r_1 would remain the same if turn time was proportional to harvest time. But this activity ratio has been observed to increase as machine size increases (Barnes et al., 1959; Byg et al., 1970; Holtman et al., 1973). A 10 percent increase in r_1 was assumed for the 6-row combine. Therefore, the composite activity ratio for the 6-row combine was

$$R(6) = 1.000 + 1.1(0.239) + \frac{6}{4}(0.109 + 0.043 + 0.007)$$
$$= 1.502$$

The 8-row combine was assumed to have a grain unloading rate 50 percent greater than the 4-row and 6-row combines. The turn activity ratio was assumed to be 20 percent greater than the ratio for the 4-row combine. The composite activity ratio was

$$R(8) = 1.000 + 1.2(0.239) + \frac{8}{4}[\frac{1.0}{1.5}(0.103) + 0.043 + 0.007]$$
$$= 1.524$$

The effective field capacities calculated for the four man-machine combinations are listed in Table 60.

The performance of each of the man-machine combinations in Table 60 was simulated for three harvesting season lengths, and the results are listed in Table 61. A potential operating time of 8 hours per day

Table 60. Man-machine capacities for harvesting grain and husklage

Man-machine combination	Harvesting width (ft.)	Average speed (m.p.h.)	Composite activity ratio	Effective capacity (A./hr.)
Measured 4-row combine	10	1.98	1.488	1.61
Best 4-row combine	10	2.50	1.398	2.17
Best 6-row combine	15	2.50	1.502	3.03
Best 8-row combine	20	2.50	1.524	3.98

was assumed for all machines, and harvesting began as soon as field conditions permitted after grain reached a moisture content of 28 percent. A harvest loss modifier of 1.0 was used.

A harvesting season extending through December 26 represented the maximum number of harvesting days without leaving unharvested corn in the field over winter. The two shorter harvesting seasons represented more practical harvesting periods for the selection of harvesting system capacity.

The figures in Table 61 are mean values of harvesting performance expected over a period of many years. They are not very useful for selecting the capacity of a harvesting system because actual harvesting performances will be lower in many years, depending on the distributions of the values.

Mathematical distributions were fitted to the histograms of harvesting days for each length of harvesting season by the procedure described in the preceding chapter of this dissertation. The normal

Table 61. Mean values of simulated harvesting performance for grain and husklage[1]

Harvesting season man-machine combination	Harvest days	Acres harvested	Grain harvested (bu.)	Harvest losses (bu.)	Forage harvested (tons)[2]	Average moisture content(%) Grain	Average moisture content(%) Forage
Harvest completed on Dec. 26							
Measured 4-row	70	902	113,184	3,605	888	19.1	24.0
Best 4-row	70	1,215	152,549	4,859	1,197	19.1	24.0
Best 6-row	70	1,697	213,113	6,788	1,672	19.1	24.0
Best 8-row	70	2,229	279,898	8,916	2,196	19.1	24.0
Harvest completed on Nov. 30							
Measured 4-row	53	683	86,244	2,734	675	19.7	25.1
Best 4-row	53	920	116,162	3,682	909	19.7	25.1
Best 6-row	53	1,285	162,257	5,143	1,270	19.7	25.1
Best 8-row	53	1,688	213,140	6,756	1,668	19.7	25.1
Harvest completed on Nov. 15							
Measured 4-row	41	528	67,097	2,108	523	20.4	26.5
Best 4-row	41	712	90,477	2,843	706	20.4	26.5
Best 6-row	41	994	126,313	3,969	985	20.4	26.5
Best 8-row	41	1,305	165,838	5,211	1,293	20.4	26.5

[1] Harvesting began as soon as field conditions permitted after grain reached 28 percent moisture.

[2] Tons of dry matter.

Table 62. Parameters of the normal distributions of harvesting days for grain and husklage

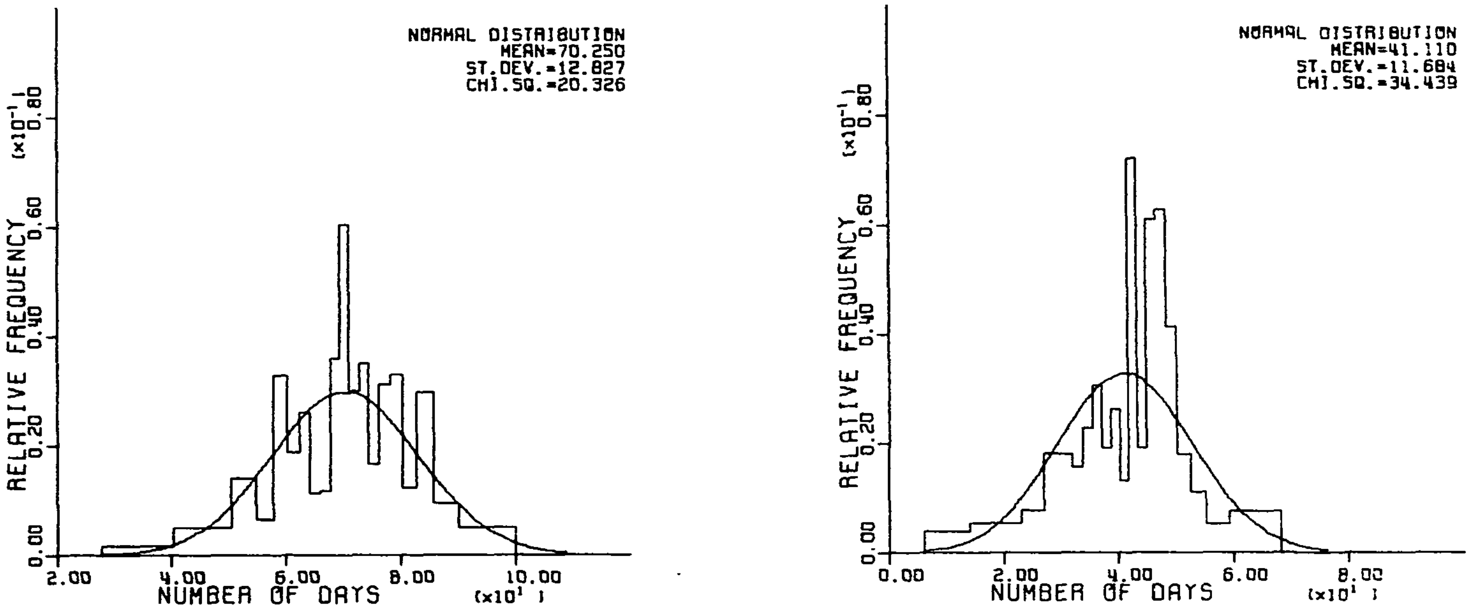
Harvesting season	$\bar{x}$	$\hat{\sigma}$	χ^2
Harvest completed on Dec. 26	70.250	12.827	20.326[1]
Harvest completed on Nov. 30	53.170	11.559	28.622[1]
Harvest completed on Nov. 15	41.110	11.684	34.439[1]

[1] The tabulated chi-square value for 18 degrees of freedom (21 classes) is 28.9 at the 0.95 level of confidence.

distribution had the lowest value of the computed chi-square statistic for all three histograms. The parameters of the three distributions are listed in Table 62, and the histograms and density functions for two harvesting season lengths are shown in Figure 56.

The chi-square test indicated that the normal distribution could be rejected at the 0.95 level of confidence for the number of harvesting days when harvesting was completed on November 15, but it could not be rejected at the 0.99 level of confidence. The Kolmogorov-Smirnov test indicated that the normal distribution could be rejected at both levels of confidence. The median number of harvesting days was 43, suggesting that the distribution of harvesting days for shorter harvesting season lengths might be negatively skewed.

The numbers of harvesting days at selected probability levels were calculated from each of the distributions, and the numbers of acres that could be harvested at each probability level were



(a) (b)

Figure 56. Distributions of harvesting days for grain and husklage; (a) Harvest completed on December 26, 21 classes; (b) Harvest completed on November 15, 21 classes

calculated for the three best man-machine capacities. The results are listed in Table 63. After the desired completion probability is known, Table 63 can be used to select the minimum machine size for a given acreage. For example, if 700 acres were to be harvested by November 15 with a completion probability of 0.80 or greater, a 6-row or larger combine should be selected. However, if harvesting can be performed for only 5-6 hours per day, or a completion probability of 0.90 or greater is desired, an 8-row combine should be selected.

Harvesting costs, excluding labor, for each of the three combine sizes were calculated for the assumed values of the economic parameters in Tables 57 and 64. The harvesting costs for several levels of annual use are listed in Table 65. Combine costs were calculated for two crop production systems. The first was all corn, and all combine costs were charged to corn harvesting. The second was a corn-corn-soybeans rotation, and only two-thirds of the combine base unit costs were charged to corn harvesting. All costs for the cornheads and husklage attachment were charged to corn harvesting for both crop production systems.

Costs were calculated for a self-contained husklage attachment similar to the model 6800 Foster Harvest Master. The model 6800 Harvest Master is similar to the model 5400 Harvest Master shown in Figure 7 and 8, except that the collecting auger and blower are mounted on the front of the dump trailer and driven by an air-cooled gasoline engine.

Table 63. Number of harvesting days for grain and husklage and number of acres harvested with three combine capacities at selected probabilities of completion[1]

Harvesting season man-machine capacity	Probability level						
	0.98	0.95	0.90	0.85	0.80	0.75	0.50
Harvest completed on Dec. 26							
Harvesting days	43	49	53	56	59	61	70
Acres harvested, 4-row	746	851	920	972	1024	1059	1215
6-row	1042	1188	1285	1357	1430	1479	1697
8-row	1369	1560	1688	1783	1879	1942	2229
Harvest completed on Nov. 30							
Harvesting days	29	34	38	41	43	45	53
Acres harvested, 4-row	503	590	660	712	746	781	920
6-row	703	824	921	994	1042	1091	1285
8-row	923	1083	1210	1305	1369	1433	1688
Harvest completed on Nov. 15							
Harvesting days	17	21	26	28	31	33	41
Acres harvested, 4-row	295	365	451	486	538	573	712
6-row	412	509	630	679	751	800	994
8-row	541	669	828	892	987	1051	1305

[1] Harvesting began as soon as field conditions permitted after grain reached 28 percent moisture. Potential operating time of 8 hours per day assumed.

Table 64. Economic parameters assumed for harvesting grain and husklage

Parameter	Value
4-row combine	
Base unit cost	$16,000
Cornhead cost	$ 4,880
Engine horsepower	90
6-row combine	
Base unit cost	$20,000
Cornhead cost	$ 6,190
Engine horspower	110
8-row combine	
Base unit cost	$23,400
Cornhead cost	$ 8,200
Engine horsepower	130
Husklage attachment	
Cost	$ 2,800
Engine horsepower	18

To determine total harvesting costs, labor must be added to the grain harvesting costs in Table 65. Labor cost for harvesting husklage was assumed to be zero because the husklage was dumped without stopping the combine and stored in the field. The cost of constructing an electric fence and moving it approximately twice per week during feeding would have to be included to determine total harvesting and feeding costs of husklage.

Table 65. Harvesting costs (dollars), excluding labor, for grain and husklage[1]

	Annual use, acres							
	200	400	600	800	1000	1200	1400	1600
Grain, all corn								
4-row combine	19.94	11.61	9.14	8.09	7.59			
6-row combine		13.05	9.68	8.14	7.31	6.83	6.55	
8-row combine			10.84	8.84	7.72	7.04	6.59	6.30
Grain, corn-corn-soybeans								
4-row combine	15.67	9.73	8.12	7.54	7.35			
6-row combine		10.50	8.15	7.15	6.66	6.43	6.34	
8-row combine			8.91	7.52	6.78	6.35	6.11	5.98
Husklage								
4-row combine	2.75	1.62	1.28	1.14	1.07			
6-row combine		1.47	1.11	0.94	0.85	0.80	0.77	
8-row combine		1.02	0.84	0.74	0.68	0.64	0.61	0.60

[1] Cost of labor must be added to figures for grain to find total grain harvesting costs. To find labor cost per acre, divide cost of labor per hour by 2.17 acres/hour for a 4-row combine, 3.03 acres/hour for a 6-row combine, and 3.98 acres/hour for an 8-row combine. There are no labor costs for harvesting husklage.

Corn Refuse

The performance of a machine similar to the Beefmaker for harvesting corn refuse and grain was simulated for seven man-machine combinations. The measured activity times for the Beefmaker are listed in Table 66. They are listed for field 1 in Tables 24, 26, and 27.

The delay activity times observed for the Beefmaker were too high for the machine to be commercially successful. They were reduced to the values for the best man-combine combination in Table 59 to simulate the performance of a more reliable machine that might be manufactured in the future. The measured activity times were also observed with the Beefmaker operating at 1.97 miles per hour (Table 25) to reduce the frequency of plugging in the snapping attachment. With the improved machine, an average field speed of 2.5 miles per hour should be possible. The harvest and turn activity times would decrease in direct proportion to the increase in field speed, but the other activity times would not be affected. The activity times for the improved machine are also listed in Table 66.

Effective field capacities for all man-machine combinations were calculated with equation 6. The composite activity ratios for two man-machine combinations are listed in Table 66. The composite activity ratios for the other man-machine combinations were calculated from the activity ratios in Table 66 for the improved machine.

The addition of a grain tank and grain unloading equipment to

Table 66. Activity times and activity ratios for harvesting one load of refuse with a 2-row pull-type harvester

Activity	Measured time (min.)	Activity ratio	Improved time (min.)	Activity ratio
Harvest (primary activity)	24.06	1.000	18.96	1.000
Turn (i = 1)	2.73	0.113	2.15	0.113
Change wagons (i = 2)	0.54	0.022	0.54	0.028
Machine plugging (i = 3)	6.12	0.254	0.41	0.022
Mechanical failure (i = 4)	1.43	0.059		
Other delay (i = 5)	1.41	0.059	0.07	0.004
Composite activity ratio, R(2)		1.507		1.167

the Beefmaker was proposed several times during the harvesting studies. The grain wagon would not be required in the field, so the forage wagon could be pulled by the machine, eliminating the extra tractor and driver. Grain would be unloaded into trucks or wagons positioned at the ends of the field.

The addition of a grain tank to the Beefmaker would have two effects on the activity times for a load of refuse. Without a grain tank, the grain wagon pulled by the machine was changed after two loads of refuse had been harvested. With a grain tank, the forage wagon pulled by the machine would be changed after every load of refuse was harvested, so the wagon changing activity time would be doubled and activity ratio r_2 would be

$$r_2 = \frac{1.08}{18.96} = 0.057$$

A grain unloading activity would also have to be added to the activities for one harvesting cycle. The 4-row combine had a grain unloading activity time of 1.03 minutes per load of husklage (Table 59), and two loads of husklage were harvested per acre. The total refuse yields in Table 5, and the average loads in the forage wagons listed in Table 32, indicate that approximately two loads of refuse were also harvested per acre. Therefore, the quantity of grain harvested per load of refuse was approximately equal to the quantity of grain harvested per load of husklage. If the grain unloading equipment added to the Beefmaker had the same unloading rate as the combine, the grain unloading activity time would be approximately 1.03 minutes per load of refuse. The grain unloading activity ratio would be

$$r_6(\text{grain unloading}) = \frac{1.03}{18.96} = 0.054$$

and the composite activity ratio would be

$$R(2/\text{grain tank}) = 1.000 + 0.113 + 0.057 + 0.022 + 0.004 + 0.054$$
$$= 1.250$$

Buchele (1972) proposed a system of crop production for the future that would utilize large self-propelled traction units. Attachments would be available for soil preparation, planting, other cultural practices, and harvesting so a single traction unit could be used for all field operations. The whole corn plant would be harvested and separated into grain and forage products similar to those produced by the Beefmaker. To simulate the performance of this harvesting system, man-machine capacities for 4-, 6-, and 8-row self-propelled machines were calculated from the activity ratios for the improved 2-row Beefmaker with a grain tank and grain unloading equipment.

Buchele (1972) proposed that forage and grain compartments be included on the self-propelled traction unit. After filling the two compartments, the harvesting attachment would be uncoupled and the traction unit would transport the harvested products to storage. Harvesting would be stopped until the traction unit returned to the field. This operating policy would permit one man to harvest and store the corn crop, but it would not result in the maximum daily harvesting capacity because of the interruptions to transport the harvested products to storage. Because the performance of each self-propelled harvesting machine was simulated to determine its maximum seasonal harvesting capacity, the harvesting system was assumed to include a separate transport unit for the harvested products. The grain and forage could be dumped into the transport unit at the end of the field, or the transport unit could be coupled to the harvesting machine and filled as the crop was being harvested. The activity time for positioning the harvesting machine and either dumping the harvested products or changing transport units was assumed to be 75 percent of the time to change wagons with the pull-type machine.

The turning activity ratio was assumed to be the same for the 4-row self-propelled machine and the pull-type machine. All other activity ratios would increase in direct proportion to machine size because of the reduced harvesting time. The composite activity ratio for the 4-row self-propelled machine was

$$R(4) = 1.000 + 0.113 + \frac{4}{2}[0.75(0.057) + 0.022 + 0.004 + 0.054]$$
$$= 1.359$$

The turning activity ratio for the 6-row self-propelled machine was assumed to be 10 percent greater than the ratio for the 4-row machine because of the larger machine size. The composite activity ratio for the 6-row machine was

$$R(6) = 1.000 + 1.1(0.113) + \frac{6}{2}[0.75(0.057) + 0.022 + 0.004 + 0.054]$$
$$= 1.493$$

The turning activity ratio for the 8-row self-propelled machine was assumed to be 20 percent greater than the ratio for the 4-row machine. The grain unloading rate for the 8-row machine was assumed to be 50 percent greater than the unloading rate for the 4-and 6-row machines, as it was for the combines. The composite activity ratio for the 8-row machine was

$$R(8) = 1.000 + 1.2(0.113) + \frac{8}{2}[0.75(0.057) + 0.022 + 0.004 + \frac{1.0}{1.5}(0.054)]$$
$$= 1.555$$

The effective field capacities computed with equation 6 for the six man-machine combinations are listed in Table 67. The effective capacity of the improved 2-row machine was 64 percent greater than the measured capacity of the Beefmaker because of the reduced delay from machine plugging and the higher average field speed. The capacity of 1.30 acres per hour represents the maximum capacity that would be expected with a 2-row machine like the Beefmaker unless the design of

Table 67. Man-machine capacities for harvesting grain and refuse

Man-machine combination	Harvesting width (ft.)	Field speed (m.p.h.)	Composite activity ratio	Effective capacity (A./hr.)
2-row pull-type machines				
Measured	5	1.97	1.507	0.79
Improved	5	2.50	1.167	1.30
Grain tank added	5	2.50	1.250	1.21
Self-propelled machines				
4-row	10	2.50	1.359	2.23
6-row	15	2.50	1.493	3.04
8-row	20	2.50	1.555	3.90

the snapping unit was changed to allow a higher field speed. Adding a grain tank and unloading system reduced the effective capacity of the machine to 1.21 acres per hour, but the elimination of the extra tractor and driver should reduce harvesting costs. The effective capacities of the three self-propelled machines were nearly the same as the capacities for the combines in Table 60. Since the values in the two tables were calculated from measured values for two different machines in two different fields, the close agreement illustrates the usefulness of activity ratios for estimating man-machine capacities when measured values are not available.

The performance of the 2-row machine with a grain handling system and of each of the self-propelled machines was simulated for two maximum grain moisture contents and three minimum forage moisture contents. Harvesting started as soon as possible after grain reached either 32 or 35 percent moisture. For each value of grain moisture, harvesting ended when the refuse moisture content reached 40, 45, or 50 percent. A potential operating time of 8 hours per day was used for all machines, and a grain loss modifier of 1.0 was used to represent average harvesting losses for all machines.

The mean values of harvesting performance are listed in Tables 68 and 69. Harvesting began when grain reached a moisture content of 32 percent during the research reported in this dissertation because of the usual recommendation that high-moisture corn should be between 25 and 30 percent moisture for satisfactory storage (Stoneberg et al., 1972). Comparing the mean number of harvesting days in Table 69 with those in Table 68 shows that an average of 3-4 additional harvesting days could be obtained by starting earlier, at a grain moisture content of 35 percent. Because of the asymptotic shape of the grain yield vs. moisture curve for the variety used in the simulation program, very little difference in average yield occurred between the two starting grain moisture contents. For example, with a starting grain moisture content of 32 percent and a minimum refuse moisture content of 45 percent, the 2-row machine harvested 27,338 bushels of grain and 574 tons of refuse dry matter from 206 acres, for average yields of 132.71 bushels of grain and 2.786 tons of refuse dry matter per acre. When harvesting started after grain reached 35 percent moisture, 31,730 bushels of grain and 667 tons of refuse dry matter were harvested from 240 acres, for average yields of 132.21 bushels of grain and 2.779 tons of refuse dry matter per acre. However, harvesting

Table 68. Mean values of simulated harvesting performance for grain and refuse with harvest starting after grain reaches 32 percent moisture[1]

Man-machine combination	Harvest days	Acres harvested	Grain harvested (bu.)	Harvest losses (bu.)	Forage harvested (tons)[2]	Average moisture content(%) Grain	Average moisture content(%) Forage
Minimum forage moisture = 40%							
2-row with grain tank	35	339	44,009	1,382	935	23.2	49.3
4-row SP	35	624	81,008	2,544	1,721	23.2	49.3
6-row SP	35	851	110,477	3,470	2,346	23.2	49.3
8-row SP	35	1,092	141,763	4,452	3,011	23.2	49.3
Minimum forage moisture = 45%							
2-row with grain tank	21	206	27,338	870	574	25.6	53.4
4-row SP	21	376	49,932	1,589	1,049	25.6	53.4
6-row SP	21	519	68,910	2,193	1,448	25.6	53.4
8-row SP	21	661	87,663	2,789	1,842	25.6	53.4
Minimum forage moisture = 50%							
2-row with grain tank	14	135	18,092	612	378	27.3	56.3
4-row SP	14	250	33,504	1,134	701	27.3	56.3
6-row SP	14	339	45,430	1,537	951	27.3	56.3
8-row SP	14	435	58,296	1,973	1,220	27.3	56.3

[1] Potential operating time of 8 hours/day and average harvest losses assumed for all machines.

[2] Tons of dry matter.

Table 69. Mean values of simulated harvesting performance for grain and refuse with harvest starting after grain reaches 35 percent moisture[1]

Man-machine combination	Harvest days	Acres harvested	Grain harvested (bu.)	Harvest losses (bu.)	Forage harvested (tons)[2]	Average moisture content (%) Grain	Forage
Minimum forage moisture = 40%							
2-row with grain tank	39	378	49,053	1,630	1,041	24.1	50.8
4-row SP	39	696	90,320	3,000	1,918	24.1	50.8
6-row SP	39	948	123,022	4,087	2,612	24.1	50.8
8-row SP	39	1,217	157,930	5,247	3,553	24.1	50.8
Minimum forage moisture = 45%							
2-row with grain tank	25	240	31,730	1,105	667	26.8	55.4
4-row SP	25	440	58,172	2,026	1,223	26.8	55.4
6-row SP	25	600	79,326	2,762	1,668	26.8	55.4
8-row SP	25	771	101,934	3,550	2,144	26.8	55.4
Minimum forage moisture = 50%							
2-row with grain tank	17	169	22,461	846	471	28.5	58.5
4-row SP	17	311	41,334	1,557	867	28.5	58.5
6-row SP	17	424	56,352	2,122	1,182	28.5	58.5
8-row SP	17	544	72,300	2,723	1,517	28.5	58.5

[1] Potential operating time of 8 hours/day and average harvest losses assumed for all machines.

[2] Tons of dry matter.

earlier than 35 percent grain moisture would result in greater yield reductions because of the increasing slope of the yield curve at higher moisture contents.

The minimum refuse moisture content for safe storage may depend on the type and quality of the storage structure. Refuse at 45 percent moisture content was successfully stored in both upright and horizontal structures during this research. Storage at lower moisture contents was not investigated, but a minimum of 40 percent moisture should be acceptable if the refuse is finely chopped and packed well in storage. The average forage moisture contents of 49.3 and 50.8 percent in Tables 68 and 69 indicate that the majority of the refuse would be above 45 percent moisture if harvesting continued until the refuse reached 40 percent moisture. The additional 14 harvesting days obtained by extending the harvesting season would allow a smaller harvesting machine to be used for a given acreage, decreasing harvesting costs. Further research is needed to determine the minimum refuse moisture content for acceptable storage quality and to investigate methods of preserving the top layer of low-moisture forage.

Mathematical distributions were fitted to the histograms of the number of harvesting days for each combination of limiting moisture content values. The data for the limiting forage moisture contents of 40 and 45 percent were divided into 21 classes for the chi-square test, as described in Appendix E. Because of the discreet nature of the simulated number of harvesting days, fewer classes had to be used for a limiting forage moisture content of 50 percent. The simulation program returned only whole numbers, and because of the narrower range of days for the higher forage moisture content, only 15 classes were used to insure that two class boundaries did not fall between two numbers.

The Weibull distribution had the lowest value of the computed chi-square statistic for all histograms except the one for a maximum grain moisture content of 35 percent and a minimum forage moisture content of 50 percent. For that histogram, the values of the computed chi-square statistic were equal for both the normal and Weibull distributions. The parameters of the six Weibull distributions are listed in Table 70, and the histograms and Weibull density functions for two of the moisture content combinations are shown in Figure 57.

The expected numbers of harvesting days at selected probability levels were calculated from each of the distributions. The number of acres that could be harvested at each probability level was then calculated for each man-machine capacity. The results are listed in Tables 71 and 72. These tables may be used to select the minimum machine size for a given acreage after the desired completion probability has been chosen.

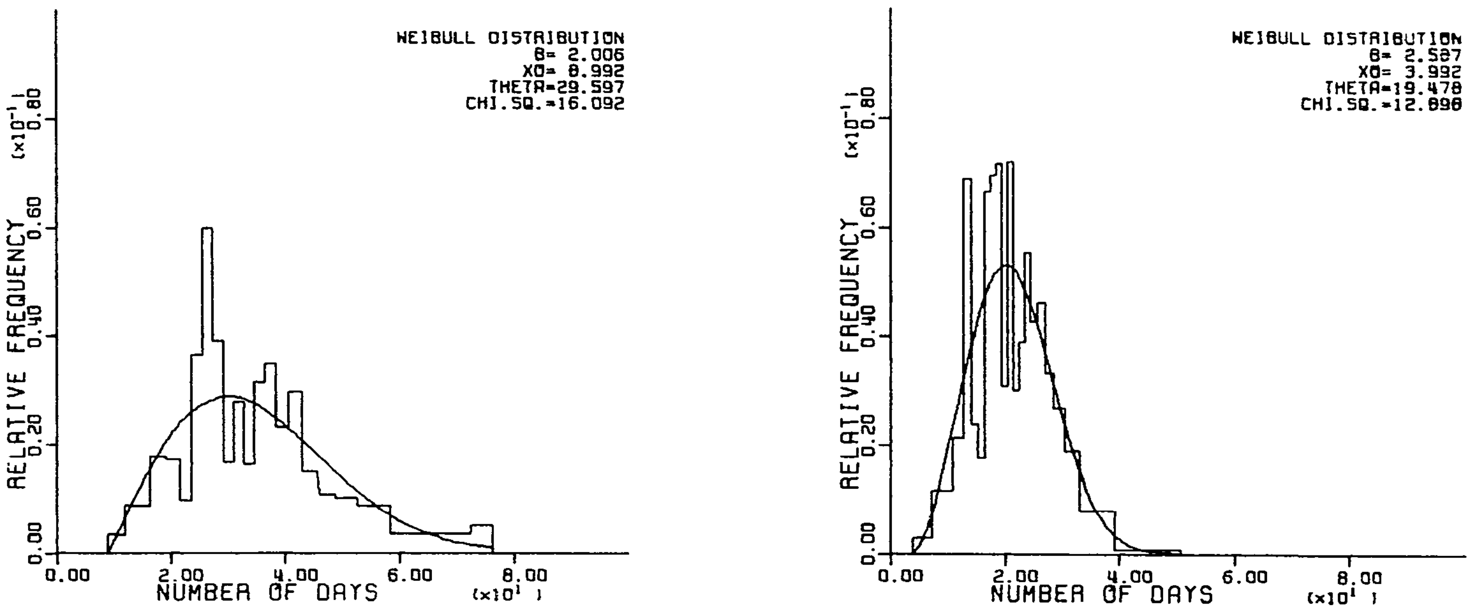
The small number of harvesting days at the higher probability levels illustrates the importance of selecting the proper hybrids if refuse and grain are to be harvested from a large acreage. The potential harvesting season length is determined by the relationship between grain and forage moisture contents. The values in Table 71 and 72 were obtained for the pooled regression of forage moisture

Table 70. Parameters of the Weibull distributions of harvesting days for grain and refuse

Limiting moisture contents	$\bar{x}$	$\hat{\sigma}$	XO	Θ	B	χ^2
32% grain, 40% forage	35.220	13.676	8.992	29.597	2.006	16.092*
32% grain, 45% forage	21.290	7.178	3.992	19.478	2.587	12.898*
32% grain, 50% forage	13.880	5.042	1.480	13.953	2.647	11.765**
35% grain, 40% forage	39.250	15.035	12.377	30.258	1.855	22.204*
35% grain, 45% forage	24.670	7.943	7.992	18.831	2.218	24.235*
35% grain, 50% forage	17.410	4.959	5.082	13.866	2.679	13.041**

*The tabulated value of chi-square for 17 degrees of freedom (21 classes) is 27.6 at the 0.95 level of confidence.

**The tabulated value of chi-square for 11 degrees of freedom (15 classes) is 19.7 at the 0.95 level of confidence.



(a) (b)

Figure 57. Distributions of harvesting days for grain and refuse; (a) Maximum grain moisture = 32%, minimum forage moisture = 40%, 21 classes; (b) Maximum grain moisture = 32%, minimum forage moisture = 45%, 21 classes

Table 71. Numbers of harvesting days for grain and refuse and acres harvested after grain reaches 32 percent moisture at selected probabilities of completion[1]

Man-machine combination	Probability level 0.98	0.95	0.90	0.85	0.80	0.75	0.50
Minimum forage moisture = 40%							
Harvesting days	13	15	18	20	23	24	33
Acres harvested, 2-row	125	145	174	193	222	232	319
4-row	231	267	321	356	410	428	588
6-row	316	364	437	486	559	583	802
8-row	405	468	561	624	717	748	1029
Minimum forage moisture = 45%							
Harvesting days	8	10	12	13	14	16	20
Acres harvested, 2-row	77	96	116	125	135	154	193
4-row	142	178	214	231	249	285	356
6-row	194	243	291	316	340	389	486
8-row	249	312	374	405	436	499	624
Minimum forage moisture = 50%							
Harvesting days	4	6	7	8	9	10	13
Acres harvested, 2-row	39	58	68	77	87	96	125
4-row	71	107	125	142	161	178	231
6-row	97	146	170	194	219	243	316
8-row	125	187	218	249	281	312	405

[1] Potential operating time of 8 hours/day assumed for all machines.

Table 72. Numbers of harvesting days for grain and refuse and acres harvested after grain reaches 35 percent moisture at selected probabilities of completion[1]

Man-machine combination	Probability level 0.98	0.95	0.90	0.85	0.80	0.75	0.50
Minimum forage moisture = 40%							
Harvesting days	16	18	21	23	25	27	37
Acres harvested, 2-row	154	174	203	222	242	261	358
4-row	285	321	374	410	446	481	660
6-row	389	437	510	559	608	656	899
8-row	499	561	655	717	780	842	1154
Minimum forage moisture = 45%							
Harvesting days	11	12	14	16	17	18	23
Acres harvested, 2-row	106	116	135	154	164	174	222
4-row	196	214	249	285	303	321	410
6-row	267	291	340	389	413	437	559
8-row	343	374	436	499	530	561	717
Minimum forage moisture = 50%							
Harvesting days	8	9	11	12	13	13	17
Acres harvested, 2-row	77	87	106	116	125	125	164
4-row	142	161	196	214	231	231	303
6-row	194	219	267	291	316	316	413
8-row	249	281	343	374	405	405	503

[1] Potential operating time of 8 hours/day assumed for all machines.

content on grain moisture content shown in Figure 20. Hybrids are available with lower forage drying rates (Hitzhusen, 1969), and they should result in a longer harvesting season than the values listed in Tables 71 and 72. If refuse and grain harvesting is to become an accepted practice in the Corn Belt, development of hybrids with high forage moisture contents and low grain moisture contents should be encouraged.

Harvesting costs, excluding labor, were calculated for each man-machine capacity from the assumed values of the economic parameters in Tables 57 and 73. Since the harvesting machines were assumed to be conventional forage harvesters with attachments for snapping and shelling grain, they could also be used to harvest other types of forage. Therefore, harvesting costs were calculated for both 50 percent and 100 percent of base unit annual use harvesting refuse. All costs of the gathering and shelling attachments were charged to the refuse and grain for both levels of base unit annual use. The costs of hauling the refuse in self-unloading forage wagons were calculated for an assumed load size of 3,000 pounds of dry matter (Tables 32) and a total transport and unloading time of 30 minutes per load.

The initial costs of the harvesting machines listed in Table 73 are only estimated costs to permit a preliminary estimate of harvesting costs. Since the harvesting machines have not been manufactured, actual costs were not available, and the estimates in Table 73 may be too high or too low. The base unit for the 2-row

Table 73. Initial costs assumed for refuse harvesting machines

2-row harvesting machine (requires 100 hp. tractor)	
Pull-type forage harvester base unit	$ 3,500
2-row gathering unit with snapping rolls	4,180
Shelling and grain handling attachment	2,000
4-row harvesting machine	
Self-propelled forage harvester base unit (225 hp.)	$24,000
4-row gathering unit with snapping rolls	5,680
Shelling and grain handling attachment	4,200
6-row harvesting machine	
Self-propelled forage harvester base unit (275 hp.)	$27,000
6-row gathering unit with snapping rolls	7,390
Shelling and grain handling equipment	6,600
8-row harvesting machine	
Self-propelled forage harvester base unit (320 hp.)	$31,400
8-row gathering unit with snapping rolls	9,800
Shelling and grain handling attachment	8,600
Self-unloading forage wagon, heavy duty (65 hp. tractor)	$ 2,500
100 horsepower diesel tractor with ROPS cab	$13,000
65 horsepower gasoline tractor with ROPS	$ 7,300

harvester was assumed to be a conventional forage harvester with a recutting screen. The costs of the gathering unit and shelling attachment were estimated from costs of available components that could be purchased and assembled like the Beefmaker. The base unit for the 4-row machine was assumed to be a heavy-duty self-propelled forage harvester. The same base unit was used for the 6- and 8-row machines, with allowances for larger engines and heavier drive trains.

Harvesting and hauling costs for several levels of annual use are listed in Table 74. The figures for the self-propelled machines are high compared to the 2-row machine, indicating that the estimated initial costs in Table 73 may be high.

The harvesting costs in Table 74 include harvesting both grain and forage. Therefore, the cost of harvesting only grain with a combine or corn picker should be subtracted to determine the harvesting costs of the refuse. The costs of labor and storage must also be added to the figures in Table 74 to find the total cost of the refuse.

To illustrate the calculation of the total harvesting, hauling, and storage costs of refuse, the costs for refuse harvested from 200 acres per year are shown in Table 75. A 2-row harvesting machine was selected, requiring 21 harvesting days. A 10-hour working day was assumed to allow 8 hours of potential harvesting time and additional time for servicing equipment, travel to and from the field, and packing refuse in the silo. Labor costs were calculated for three men, one operating the harvesting machine and two hauling and packing refuse, and a labor cost of $3.00 per hour was used. Three forage wagons were used to haul refuse, and storage costs were taken from Stoneberg et al. (1972).

The cost of $11.68 per ton of dry matter represents the total feed cost to the animal except for the labor and equipment costs for removing the refuse from storage and hauling it to a feed bunk. In the chapter on animal performance, a daily requirement of 18.6 pounds of refuse dry matter per cow was calculated from the consumption of

Table 74. Harvesting costs per acre and handling cost per ton (dollars), excluding labor, for grain and refuse

	Annual use, acres								
	100	200	300	400	500	600	700	800	1000
Harvesting unit, 100% refuse									
2-row machine	24.63	16.99	14.71	13.73					
4-row machine		34.53	25.22	20.71	18.10	16.42			
6-row machine		39.78	28.32	22.70	19.40	17.26	15.77	14.68	
8-row machine			32.93	26.00	21.91	19.23	17.35	15.97	14.09
Harvesting unit, 50% refuse									
2-row machine	21.87	15.81	14.08	13.38					
4-row machine		24.74	18.99	16.28	14.76	13.82			
6-row machine		29.78	21.84	18.00	15.78	14.36	13.39	12.70	
8-row machine			26.33	21.16	18.14	16.18	14.81	13.82	12.50
	Annual use, tons[1]								
	100	150	200	250	300	350	400	450	500
Forage wagon and tractor	5.08	3.66	2.96	2.55	2.27	2.08	1.95	1.84	1.76

[1] Dry matter.

Table 75. Calculation of harvesting, handling, and storage costs for corn refuse harvested from 200 acres per year

	As harvested	Dry matter
Harvesting cost per acre (Table 74)	$16.99	$16.99
Assumed cost of custom harvesting	8.00	8.00
Additional cost of harvesting refuse per acre	$ 8.99	$ 8.99
Average refuse yield (Table 68), tons per acre	5.99	2.79
Harvesting cost per ton	$ 1.50	$ 3.22
Total yield = 2.79 tons of dry matter/acre x 200 acres		
= 558 tons of dry matter		
558 tons/3 wagons = 186 tons of dry matter/wagon		
Hauling cost per ton (Table 74)	$ 1.47	$ 3.16
Total labor = 3 men x 10 hours/day x 21 days		
= 630 hours		
630 hours x $3.00/hour = $1890		
Labor cost per ton	$ 1.58	$ 3.39
Equivalent volume[1] of corn silage at 60% moisture		
= 558 tons of dry matter/0.4 = 1395 tons of corn silage		
From Stoneberg et al. (1972), annual storage cost		
= $0.71/ton for a 1500-ton bunker silo		
$0.71/ton x 1500 tons = $1065 annual storage cost		
Storage cost per ton	$ 0.89	$ 1.91
Total harvesting, handling, and storage cost/ton	$ 5.44	$11.68

[1] From Table 33, dry matter densities of corn silage and refuse are nearly equal in storage.

14.9 pounds per day listed in Table 41 and an assumed storage and feeding loss of 20 percent. Therefore, daily feed cost would be approximately $0.11 per cow for refuse, plus the cost of equipment and labor for feeding.

Stalklage

The observed activity times, shown in Tables 24, 26, and 27, for the forage harvester with the 2-row flail pickup operating behind a combine and a corn picker are listed in Table 76. The primary activity time of 24.25 minutes per load was used for the harvesting simulation, but two changes were made in the other activity times. The observed activity times for the flail harvester operating behind a combine were measured in a field with relatively short rows, and the activity ratio for turning was high. Therefore, the turning activity ratio measured in the field with the corn picker was used to represent more normal harvesting conditions, resulting in an adjusted turning time of 1.90 minutes per load. The second change was to include the 0.20 minute delay activity observed in the field with the corn picker to account for minor field interruptions. The adjusted activity times used for the harvesting simulation are also listed in Table 76.

Effective field capacities were calculated with equation 6, and the adjusted composite activity ratio for the 2-row machine is shown in the last column of Table 76. The activity ratios for a 4-row self-propelled flail harvester were calculated from the adjusted activity ratios for the 2-row harvester. The 2-row harvester had an

Table 76. Activity times and activity ratios for harvesting one load of stalklage with a 2-row flail harvester

Activity	Behind combine time (min.)	Behind combine ratio	Behind picker time (min.)	Behind picker ratio	Adjusted time (min.)	Adjusted ratio
Harvest (primary activity)	24.25	1.000	17.98	1.000	24.25	1.000
Turn (i = 1)	3.60	0.148	1.41	0.078	1.90	0.078
Change wagons (i = 2)	1.08	0.045	1.08	0.060	1.08	0.045
Delay (i = 3)	--	--	0.20	0.011	0.20	0.008
Composite activity ratio		1.193		1.149		1.131

observed average field speed of 2.72 miles per hour, and the 4-row machine was assumed to have an average field speed of 3 miles per hour. The harvest and turning times would both decrease in proportion to the increased field speed, so the turning activity ratio would not change. But the other activity ratios would increase in proportion to the increased field speed because the denominators (harvest time) would decrease. They would also increase in direct proportion to the increase in machine size because of the smaller harvest time. Finally, wagon changing time was assumed to be 75 percent of the time for the 2-row machine because of the better maneuverability of the self-propelled machine, the same as for the refuse harvesting machines. The resulting activity ratio for the self-propelled machine was

$$R(4) = 1.000 + 0.078 + \left(\frac{4}{2}\right)\left(\frac{3.00}{2.72}\right)[0.75(0.045) + 0.008]$$

$$= 1.170$$

Activity times were not measured for the Hesston Stakhand, but the operators consistently reported that two stacks could be completed in an hour with an average field speed of 2.5 miles per hour when the two center rows were being harvested behind a 6-row combine. From the average stack weight of 3437 pounds of dry matter (Table 13) and the average yield of 1900 pounds of dry matter per acre (Table 12), an average harvest time of 23.88 minutes per stack was calculated. The turning activity ratio of 0.078 for the 2-row flail harvester (Table 76) was also assumed for the Stakhand, resulting in an average turning time of 1.86 minutes per stack. Each stalklage stack was compressed four times as it was being harvested, and total compressing activity time of 2.0 minutes per stack was assumed. The 0.20 minute delay activity time for the flail harvester (Table 76) was used, and the remaining time was assigned to positioning a stack and unloading. The activity times and activity ratios are listed in Table 77.

The activity ratios for other harvesting patterns with the Stakhand were calculated from the activity ratios in Table 77 and the dry matter recovery values in the last line of Table 49. A uniform stack weight of 3437 pounds of dry matter, and an average field speed of 2.5 miles per hour, were assumed for all harvesting patterns. Therefore, harvest activity time was proportional to the dry matter recovery from the field area harvested.

The estimated harvest activity times for four harvesting patterns with the Stakhand are listed in Table 78. By harvesting the center two rows behind a 6-row combine, 1900 pounds of stalklage dry matter were recovered per acre (Table 12). Since only one-third of each acre was actually harvested, the dry matter recovery per harvested acre was 5700 pounds. Therefore, 23.88 minutes of harvesting time would be required to harvest a stack at 2.5 miles per hour, as listed in Table 77. A similar calculation was made for the other harvesting patterns.

If turning time was assumed to be proportional to harvesting time, the turning activity ratio would be 0.078 for all four harvesting patterns. The times for the other three activities (compressing,

Table 77. Estimated activity times and activity ratios for harvesting stalklage from the two center rows behind a 6-row combine with the Hesston Stakhand 30[1]

Activity	Estimated time (min.)	Activity ratio
Harvest (primary activity)	23.88	1.000
Turn (i = 1)	1.86	0.078
Compress four times (i = 2)	2.00	0.084
Unload (i = 3)	2.06	0.086
Delay	0.20	0.008
Composite activity ratio, R(2/6)		1.256

[1] Calculated for an average field speed of 2.5 miles per hour.

Table 78. Estimated harvest times per stack[1] for several harvesting patterns with the Hesston Stakhand 30

Harvesting pattern	Dry matter recovery (%)[2]	Dry matter recovery (lb.)		Harvest time per stack(min.)
		Per field acre	Per acre actually harvested	
2 of 6 rows	36.7	1900[3]	5700	23.88[4]
2 of 4 rows	43.3	2242	4484	30.36
2 of 8 rows	33.4	1729	6916	19.68
All rows	52.6	2723	2723	49.99

[1] All stacks assumed to contain 3437 pounds of dry matter.
[2] From Table 49.
[3] Average yield from the four fields listed in Table 12.
[4] From Table 77.

unloading, delay) were assumed to have the values listed in Table 77 for all harvesting patterns. Therefore, the activity ratios would either increase or decrease inversely with changes in the harvest activity time. The resulting composite activity ratios for harvesting two rows out of four, two rows out of eight, and all rows were

$$R(2/4) = 1.000 + 0.078 + \frac{23.88}{30.36}[0.084 + 0.086 + 0.008]$$
$$= 1.218$$
$$R(2/8) = 1.000 + 0.078 + \frac{23.88}{19.68}[0.084 + 0.086 + 0.008]$$
$$= 1.294$$
$$R(all) = 1.000 + 0.078 + \frac{23.88}{49.99}[0.084 + 0.086 + 0.008]$$
$$= 1.163$$

The effective field capacities calculated for all stalklage harvesting machines and harvesting patterns are listed in Table 79.

Harvesting stalklage could not begin until after combining had started, so a starting grain moisture content of 28 percent was used to simulate harvesting performance, as it was with husklage. Stalklage harvested with a flail-type forage harvester would be ensiled, so harvesting would be done immediately after combining while the forage moisture content was still high. The performance of the two flail harvesters was simulated for minimum stalklage moisture contents of 40, 45, and 50 percent, and the mean values of simulated performance are listed in Table 80.

The large number of harvesting days with a minimum forage moisture content of 40 percent resulted from the relationship between grain and

Table 79. Man-machine capacities for harvesting stalklage

Man-machine combination	Harvesting width (ft.)	Average speed (m.p.h.)	Composite activity ratio	Effective capacity (A./hr.)
2-row flail harvester	5	2.72	1.131	1.46
4-row flail harvester	10	3.00	1.170	3.11
Stakhand, all rows	5	2.50	1.163	1.30
Stakhand, 2 of 4 rows	10	2.50	1.218	2.49
Stakhand, 2 of 6 rows	15	2.50	1.256	3.62
Stakhand, 2 of 8 rows	20	2.50	1.294	4.68

forage moisture contents used in the model. Equation 28 was used with the values of C_1 and C_2 listed in the top line of Table 50, and a forage moisture content of 40 percent occurred when grain reached 15.76 percent moisture. Since the grain did not reach a moisture content that low during many years, simulated harvesting was performed until December 26 during those years. Data were not obtained during this study to confirm that stalklage moisture would remain above 40 percent during years when grain dried slowly, so the results from the simulation with a minimum forage moisture content of 40 percent should be used with caution.

Mathematical distributions were fitted to the histograms of the number of harvesting days for each limiting forage moisture content. The data for forage moisture contents of 40 and 45 percent were divided into 21 classes for the chi-square test, as described in Appendix E. Because the simulation program returned only whole numbers, and because of the narrow range of data for a limiting forage moisture content

Table 80. Mean values of simulated harvesting performance for ensiled stalklage[1]

Man-machine combination	Harvest days	Acres harvested	Forage harvested (tons)[2]	Average forage moisture(%)
Minimum forage moisture = 40%				
2-row	61	706	1008	45.2
4-row	61	1525	2176	45.2
Minimum forage moisture = 45%				
2-row	19	220	321	50.6
4-row	19	484	706	50.6
Minimum forage moisture = 50%				
2-row	10	116	171	53.3
4-row	10	251	370	53.3

[1] Grain harvest began as soon as field conditions permitted after grain reached a moisture content of 28 percent. Stalklage harvest followed immediately behind the combine. A potential operating time of 8 hours/day was assumed.

of 50 percent, only 10 classes were used to insure that two class boundaries did not fall between two numbers.

The chi-square test indicated that the normal and Weibull distributions could both be rejected for a minimum forage moisture content of 40 percent. The normal distribution had the lower value of the computed chi-square statistic. The Weibull distribution had the lower value of the computed chi-square for a minimum forage moisture of 45 percent, and the normal distributuion had the lower value for a minimum forage moisture of 50 percent. The parameters of the three distributions are listed in Table 81. The histograms and density functions for the number of harvesting days with minimum forage moisture contents of 40 and 45 percent are shown in Figure 58.

The expected numbers of harvesting days at selected probability levels were calculated from each of the distributions, and the number of acres that could be harvested at each probability level was calculated for each man-machine capacity. The results are listed in Table 82. The small number of harvesting days at the high forage moisture levels illustrates the importance of selecting the proper hybrid. As with corn refuse, a hybrid with a high forage moisture content at low grain moisture contents should be selected to allow a maximum harvest season length.

Harvesting of stalklage to be stacked and stored as dry feed should not begin until 2-3 days after combining to allow time for the forage to dry to 40 percent moisture. But stalklage harvesting could continue for 2-3 days after combining was finished, so the harvesting season for stacking stalklage would be the same as the harvesting season for a combine. Therefore, the numbers of harvesting days for the Hesston Stakhand at selected completion probabilities were the same as the numbers of harvesting days listed in Table 63 for the combines. The numbers of harvesting days, and the numbers of acres that could be harvested with each harvesting pattern, are listed in Table 83.

The man-machine capacity of the Stakhand harvesting all the rows was less than the man-machine capacity of any of the combines, so the

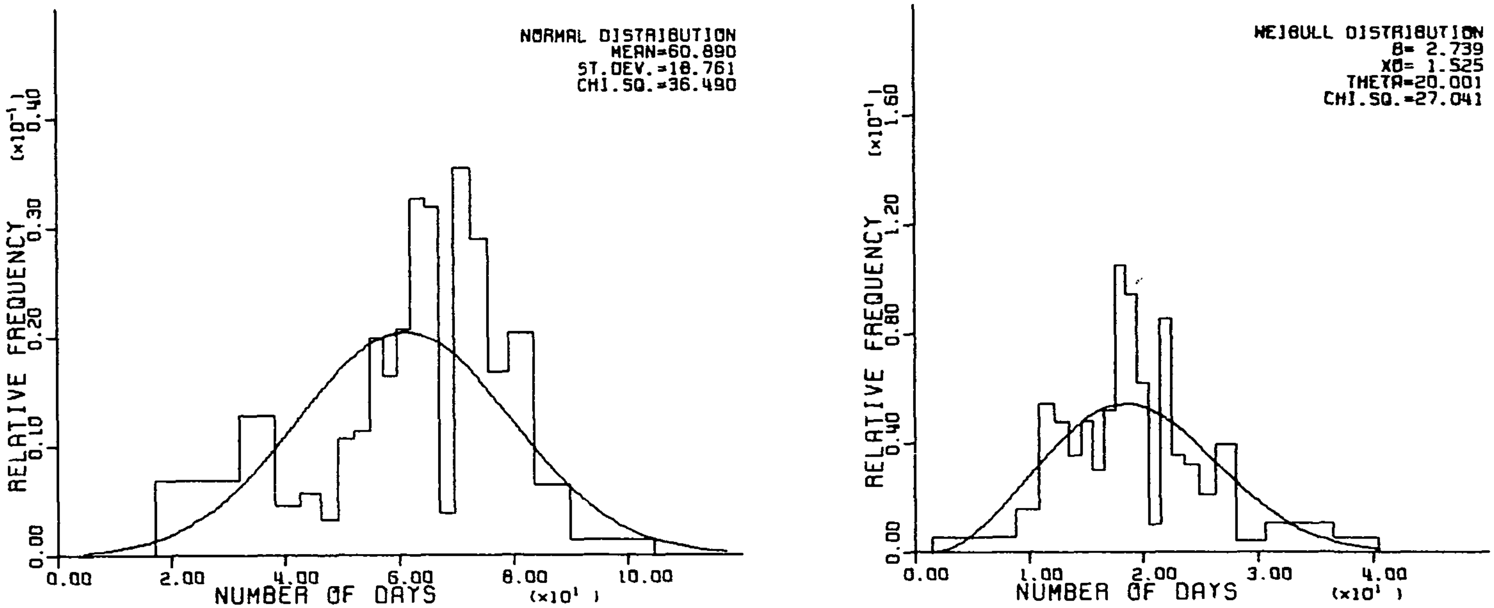
Table 81. Parameters of the distributions of harvesting days for ensiled stalklage

Minimum forage moisture (%)	$\overline{x}$	$\hat{\sigma}$	XO	θ	B	χ^2
40	60.890	18.761	--	--	--	36.490*
45	19.320	7.016	1.525	20.001	2.739	27.041**
50	10.040	4.007	--	--	--	13.224***

*The tabulated value of the chi-square statistic for 18 degrees of freedom (21 classes), is 28.9 at the 0.95 level of confidence and 34.8 at the 0.99 level of confidence.

**The tabulated value of the chi-square statistic for 17 degrees of freedom (21 classes), is 27.6 at the 0.95 level of confidence.

***The tabulated value of the chi-square statistic for 7 degrees of freedom is (10 classes), is 14.1 at the 0.95 level of confidence.



(a) (b)

Figure 58. Distributions of harvesting days for ensiled stalklage; (a) Minimum forage moisture = 40%, 21 classes; (b) Minimum forage moisture = 45%, 21 classes

Table 82. Numbers of harvesting days for ensiled stalklage and acres harvested at selected probabilities of completion[1]

Man-machine combination	Probability level 0.98	0.95	0.90	0.85	0.80	0.75	0.50
Minimum forage moisture = 40%							
Harvesting days	22	30	36	41	45	48	60
Acres harvested, 2-row	257	350	420	479	526	561	701
4-row	547	746	896	1020	1120	1194	1493
Minimum forage moisture = 45%							
Harvesting days	6	8	10	11	13	14	19
Acres harvested, 2-row	70	93	117	128	152	164	222
4-row	149	199	249	274	323	348	473
Minimum forage moisture = 50%							
Harvesting days	1	3	4	5	6	7	10
Acres harvested, 2-row	12	35	47	58	70	82	117
4-row	25	75	100	124	149	174	249

[1] Potential operating time of 8 hours/day assumed for both machines. Grain harvest started as soon as field conditions permitted after grain reached 28 percent moisture.

Table 83. Numbers of harvesting days for stacking stalklage and acres harvested at selected probabilities of completion[1]

Harvesting season and pattern	Probability level						
	0.98	0.95	0.90	0.85	0.80	0.75	0.50
Combining completed on Dec. 26							
Harvesting days	43	49	53	56	59	61	70
Acres harvested, all rows	447	510	551	582	614	634	728
2 of 4 rows	857	976	1056	1116	1175	1215	1394
2 of 6 rows	1245	1419	1535	1622	1709	1767	2027
2 of 8 rows	1610	1835	1984	2097	2209	2284	2621
Combining completed on Nov. 30							
Harvesting days	29	34	38	41	43	45	53
Acres harvested, all rows	302	354	395	426	447	468	551
2 of 4 rows	578	677	757	817	857	896	1056
2 of 6 rows	840	985	1100	1187	1245	1303	1535
2 of 8 rows	1086	1273	1423	1535	1610	1685	1984
Combining completed on Nov. 15							
Harvesting days	17	21	26	28	31	33	41
Acres harvested, all rows	177	218	270	291	322	343	426
2 of 4 rows	339	418	518	558	618	657	817
2 of 6 rows	492	608	753	811	898	956	1187
2 of 8 rows	636	786	973	1048	1161	1236	1535

[1] Combining began as soon as field conditions permitted after grain reached 28 percent moisture. Potential operating time of 8 hours/day assumed.

values in Table 83 for that harvesting pattern are the actual seasonal capacities of the Stakhand. But the man-machine capacities for the other three harvesting patterns were greater than the man-machine capacities of the combines, so the values in Table 83 are higher than the actual number of acres that could be harvested unless more than one combine was used or the combine was operated more than 8 hours per day. If only one combine was operated, the capacities of the Stakhand would be limited to the numbers of acres listed in Table 63 for the combine. For example, a 6-row combine could harvest 751 acres of corn by November 15 with a completion probability of 80 percent (Table 63). Therefore, if only the center two rows were harvested with a Stakhand, the seasonal capacity of the Stakhand would also be 751 acres. However, if custom harvesting were done so that several fields might be ready at any time, the Stakhand could harvest 898 acres with a completion probability of 80 percent (Table 83).

Harvesting costs, excluding labor, were calculated for the assumed values of the economic parameters in Tables 57 and 84. Harvesting and hauling costs are listed in Table 85 for several levels of annual use. Since the flail harvesters and the Stakhand could both be used to harvest other types of forage, harvesting costs were calculated for both 50 percent and 100 percent of annual use harvesting stalklage. The costs of hauling stalklage in self-unloading forage wagons were calculated for an assumed load size of 2000 pounds of dry matter (Table 32) and a total transport and unloading time of 30 minutes

Table 84. Initial costs and power requirements assumed for stalklage harvesting machines

2-row pull-type forage harvester	
Base unit cost	$3,500
Flail pickup cost	$1,675
Tractor PTO horsepower required	100
4-row self-propelled forage harvester	
Base unit cost	$18,500
Flail pickup cost	$ 3,350
Engine horsepower	160
3-ton stacker	
Cost	$ 8,000
Tractor PTO horsepower required	80
Self-unloading forage wagon, heavy duty (65 hp. tractor)	$ 2,500
100 horsepower diesel tractor with ROPS cab	$13,000
80 horsepower diesel tractor with ROPS cab	$11,000
65 horsepower gasoline tractor with ROPS cab	$ 7,300

per load.

The cost of labor must be added to the harvesting costs in Table 85, and storage costs have to be added for stalklage harvested with a forage harvester. The calculations of total harvesting, handling, and storage costs of 558 tons of stalklage dry matter are shown in Tables 86 and 87 to permit a comparison with similar costs for refuse

Table 85. Harvesting costs per acre and handling costs per ton (dollars), excluding labor, for stalklage

	Annual use, acres							
	200	400	600	800	1000	1200	1400	1600
Harvesting, 100% stalklage								
2-row forage harvester	9.99	8.14	7.67	7.51				
4-row forage harvester	21.22	12.11	9.20	7.82	7.04	6.56	6.23	
Stacker, all rows	11.42	8.52	7.81	7.63				
2 of 4 rows	9.09	5.84	4.85	4.41	4.19	4.07	4.02	
2 of 6 rows	8.35	5.00	3.94	3.44	3.16	2.99	2.89	2.82
2 of 8 rows	7.88	4.49	3.39	2.86	2.55	2.35	2.22	2.13
Harvesting, 50% stalklage								
2-row forage harvester	8.74	7.72	7.54	7.54				
4-row forage harvester	13.51	8.48	6.96	6.29	5.95	5.76	5.65	
Stacker, all rows	8.52	7.63	7.73	8.03				
2 of 4 rows	5.84	4.41	4.07	3.99	4.01	4.07	4.15	
2 of 6 rows	5.00	3.44	2.99	2.82	2.75	2.73	2.74	2.76
2 of 8 rows	4.49	2.86	2.35	2.13	2.02	1.95	1.92	1.91
	Annual use, tons[1]							
	100	150	200	250	300	350	400	450
Forage wagon and tractor	5.49	4.09	3.41	3.02	2.76	2.59	2.47	2.38

[1] Tons of dry matter.

Table 86. Calculation of harvesting, handling, and storage costs for 558 tons of ensiled stalklage dry matter

	As harvested	Dry matter
Average yield (Table 80), tons per acre	2.61	1.43
Acres harvested (558/1.43)	390	390
Harvesting cost per acre (Table 85)	\$8.60	\$8.60
Harvesting cost per ton	\$3.30	\$6.01
558 tons/3 wagons = 186 tons of dry matter/wagon		
Hauling cost/ton (Table 85), 50% of annual use	\$1.39	\$2.53
Total labor = 3 men x 10 hours/day x 16 days		
= 480 hours		
480 hours x \$3.00/hour = \$1440		
Labor cost per ton	\$1.41	\$2.58
Equivalent volume[1] of corn silage at 60% moisture		
= 558 tons of dry matter x 2/0.4 = 2790 tons of corn silage		
From Stoneberg et al. (1972) annual storage costs		
= \$0.66/ton for a 3000-ton bunker silo		
\$0.66 x 3000 tons = \$1980 annual storage cost		
Storage cost per ton	\$1.94	\$3.55
Total harvesting, handling, and storage cost per ton	\$8.04	\$14.67

[1] From Table 33, dry matter density of stalklage in storage will be approximately one-half of the dry matter density of corn silage or refuse in storage.

shown in Table 75.

Harvesting costs were calculated using the figures for 50 percent of total annual use harvesting stalklage because many farmers would

Table 87. Calculation of total harvesting costs for 558 tons of stalklage dry matter stacked in the field

	Harvesting pattern			
	All rows	2 of 4 rows	2 of 6 rows	2 of 8 rows
Average yield (Table 78), tons per acre	1.36	1.12	0.95	0.86
Acres harvested for 558 tons of dry matter	410	500	590	650
Harvesting cost per acre (Table 85)	$7.63	$4.24	$3.00	$2.30
Harvesting cost per ton	$5.61	$3.79	$3.16	$2.67
Number of harvesting days[1]	40	25	21	18
Total labor cost =				
1 man x 9 hours/day x $3.00/hour x days	$1080.00	$675.00	$567.00	$486.00
Labor cost per acre	$2.63	$1.35	$0.96	$0.75
Labor cost per ton	1.94	1.21	1.02	0.87
Total harvesting and labor cost per acre	$10.26	$5.59	$3.96	$3.05
Total harvesting and labor cost per ton	$ 7.55	$5.00	$4.18	$3.54

[1] Potential operating time of 8 hours/day assumed; man-machine capacities are listed in Table 79.

harvest grass-legume forage or corn silage with the same machines. A 4-row forage harvester was used for harvesting ensiled stalklage, requiring 16 days to complete the harvest. Labor costs were calculated for 3 men, one operating the harvester and two hauling and packing forage. A 10-hour working day was assumed to permit time for servicing equipment, travel to the field, and packing of forage in the silo. Three forage wagons were used, each hauling one-third of the stalklage. Since hauling stalklage was only 50 percent of the total annual use of the forage wagons, hauling costs were based on a total annual use of 372 tons of dry matter per wagon. Storage costs reported by Stoneberg et al. (1972) were used, assuming that storage volume of stalklage would be twice that of regular corn silage. Labor costs for stacking stalklage (Table 87) were calculated for one man operating the machine 8 hours per day, with an additional hour per day for servicing the machine and travel to and from the field.

The cost of $14.67 per ton of dry matter for ensiled stalklage represents the total feed cost per animal except for labor and equipment costs for feeding. In the chapter on animal performance, a daily requirement of 19.3 pounds of stalklage dry matter per cow was calculated. Therefore, daily feed cost would be approximately $0.14 per cow, plus the cost of labor and equipment for feeding. This is slightly higher than the daily cost for refuse because of a higher harvesting cost resulting from the lower yield per acre, and because of greater storage costs resulting from the low dry matter density of stalklage.

Harvesting costs for stacked stalklage were lower than for ensiled stalklage because of lower labor costs and no hauling or storage costs. However, the costs of some type of feeding panels and of labor to move the panels must be added to the costs in Table 87 to find total feed costs. In Table 45, 45 additional cow days per acre are listed for grazing with stalklage stacks than for grazing alone. This additional animal carrying capacity was obtained when two of every six rows were harvested. Therefore, dividing the harvesting and labor cost of $3.96 per acre (Table 87) by 45 cow-days per acre resulted in a daily feed cost of $0.09 per cow.

Comparing the number of harvesting days in Table 87 for the four harvesting patterns indicates that any of the three harvesting patterns in which only part of the rows are harvested are better management practices for efficient labor utilization than harvesting all rows. Harvesting time and harvesting costs were higher when all rows were harvested because of the lower forage recovery per area harvested (Table 78).

Summary

The seasonal capacities of four harvesting systems for corn plant forage were evaluated, and harvesting costs were estimated for several levels of annual use. The numbers of acres that could be harvested with several man-machine combinations were estimated for seven completion probabilities for each harvesting system.

A comparison of the four harvesting systems is shown in Table 88

Table 88. A comparison of alternative harvesting systems for 558 tons of corn plant forage dry matter

Harvesting system	Acres required	Harvesting days	Labor required[1]	Cost of stored forage[2] Per acre	Per ton	Per cow day[3]	Cow days of feed[3]
Husklage, 4-row combine	563	33	0	$1.34	$ 1.36	$0.05	16,890
Stalklage, 2 of 6 rows stacked	590	21	1	3.96	4.18	0.09	26,550
Refuse	200	21	3	--	11.68	0.11	60,000
Stalklage ensiled	390	16	3	--	14.67	0.14	57,824

[1] Labor charged to the forage. No additional labor was required to harvest husklage. A fourth man was required to haul and unload grain with the refuse harvesting system.

[2] Total costs of harvesting, hauling, and storage; no feeding costs included.

[3] Additional animal carrying capacities of 30 cow days per acre for husklage and 45 cow days per acre for stacked stalklage (Table 45). Daily requirements of 18.6 pounds of refuse dry matter and 19.3 pounds of ensiled stalklage iry matter assumed.

for an annual production of 558 tons of forage dry matter. The harvesting systems for husklage and stalklage stacked in the field required larger acreages of corn than the other two harvesting systems because of lower yields of dry matter. But the forage from these two harvesting systems was stored in the field, so no storage structures were required. Since forage did not have to be hauled to storage, labor requirements were low, and the husklage and stalklage stacking systems had lower daily feed costs per cow than the other two systems. However, careful management during feeding of field-stored forage was required to obtain the animal carrying capacities used in Table 88.

The animal carrying capacities for refuse and ensiled stalklage were nearly the same, but the stalklage system required almost twice as many acres of corn. The most intensive use of the corn plant forage was obtained with a refuse harvesting system, and daily feed costs for refuse were lower than for stalklage because of the fewer acres that had to be harvested and the greater refuse dry matter density during hauling and in storage.

The seasonal capacities for a completion probability of 80 percent are listed in Table 89 for each of the four harvesting systems. The limiting harvest season dates for husklage and stacked stalklage are the recommended values for system design, although harvesting could extend longer if desired. The minimum forage moisture content of 45 percent for ensiled stalklage and refuse will insure an acceptable product from storage.

Table 89. Seasonal capacities of alternative harvesting systems for corn plant forage with a completion probability of 80 percent

Harvesting system	Acres	Forage dry matter (tons)
Husklage, harvest completed by Nov. 15[1]		
4-row combine	538	533
6-row combine	751	743
8-row combine	987	977
Stalklage, stacked, harvest completed by Nov. 30[1]		
Harvesting all rows	447	608
Harvesting 2 of 4 rows	857[2]	960
Harvesting 2 of 6 rows	1245[2]	1182
Harvesting 2 of 8 rows	1610[2]	1392
Stalklage, ensiled, minimum forage moisture = 45%[1]		
2-row pull-type harvester	152	222
4-row self-propelled harvester	323	471
Refuse, ensiled, minimum forage moisture = 45%[3]		
2-row pull-type harvester	135	378
4-row self-propelled harvester	249	697
6-row self-propelled harvester	340	952
8-row self-propelled harvester	436	1220

[1] Grain harvest started as soon as field conditions permitted after grain reached 28 percent moisture.

[2] Maximum capacity if more than one combine available; otherwise, capacity limited to values shown above for the combines.

[3] Harvest started as soon as field conditions permitted after grain reached 32 percent moisture.

CONCLUSIONS

Corn plant forage was successfully harvested and stored with all four harvesting systems studied. The four types of harvested forage were satisfactory winter roughages for beef cows when they were properly supplemented with protein, energy, vitamins, and minerals. The Beefmaker produced the greatest quantity of harvested forage and the highest animal carrying capacity per acre of corn.

The following specific conclusions were drawn for the range of variable values studied.

Harvesting Studies

1. The yield of forage dry matter per acre increased linearly as the yield of grain per acre increased.
2. Corn refuse and husklage moisture contents decreased linearly as grain moisture content decreased. Stalklage moisture content decreased as grain moisture content decreased, but sufficient data were not obtained to enable a statistical relationship to be determined.
3. After grain reached maturity, total plant dry matter decreased as grain moisture content decreased. Grain dry matter decreased quadratically, and forage dry matter decreased linearly, as grain moisture content decreased. Within the forage fraction of the plant, stalk, leaf, and cob dry matter decreased linearly as the grain dried, with stalk and leaf dry matter decreasing

more rapidly than cob dry matter. Husk dry matter did not change significantly as the grain dried.

4. For corn plants harvested when average grain moisture content was 24 percent, the forage fraction contained 45.6 percent of the total dry matter, 32.8 percent of the *in vitro* digestible dry matter, and 25.7 percent of the total crude protein produced by the plant.
5. Within the forage fraction of the corn plant, the leaves had the highest crude protein content and the husks had the highest *in vitro* digestible dry matter content.
6. Corn refuse silage had the highest crude protein and *in vitro* digestible dry matter content of all the harvested forages.
7. Both types of stalklage (dry and ensiled) had higher average crude protein contents than husklage. Husklage had a higher average *in vitro* digestible dry matter content than either type of stalklage.
8. The Beefmaker performed satisfactorily as an experimental machine after several modifications were made to the original design. Field losses were reduced to 2.1 bushels of grain per acre, and an average corn refuse yield of 5587 pounds of forage dry matter per acre was harvested. But the low mechanical reliability of the Beefmaker and the large quantity of grain in the refuse were unacceptable for a commercial machine. The snapping unit on the Beefmaker should be redesigned to reduce the frequency of plugging and the quantity of grain in the refuse.

9. The quality of corn refuse silage from a horizontal silo, a concrete-stave silo, and a gastight silo was excellent when it was stored at a moisture content above 45 percent. Corn refuse silage with a moisture content lower than 45 percent was not harvested, and no conclusion about drier silage is intended.
10. The performance of the Foster Harvest Master was excellent except for an occasional failure of the trailer to properly dump. An average husklage yield of 1937 pounds of dry matter per acre was harvested.
11. The quality of husklage stored in field dumps and in a horizontal silo was satisfactory.
12. The performances of the Johnson Strawbuncher and the Hesston combine attachment for husklage were unsatisfactory under the harvesting conditions encountered during this research.
13. The performance of the Fox forage harvester was satisfactory except for cutterhead and feeder wear caused by soil in the stalklage. Forage recovery was higher behind a corn picker than behind a combine.
14. The performance of the Hesston Stakhand 30 was excellent. Soil picked up by the flails did not affect the operation of the machine.
15. An average yield of 1900 pounds of stalklage dry matter was harvested with the Hesston Stakhand by harvesting only the center two of every six rows, and the stalklage had a higher husk and cob content and a lower stalk content than stalklage harvested

from all rows.

16. The quality of ensiled stalklage harvested immediately after combining was satisfactory. The quality of stacked stalklage harvested at a moisture content below 40 percent was satisfactory. Mold formed in stacked stalklage harvested at higher moisture contents.

Animal Performance Studies

1. Grazing trials indicated that cornstalks can provide the forage needs of dry, pregnant beef cows in good fall condition with proper supplementation during stress periods.
2. Supplemental feeding of forage to grazing animals was required during five of the last eight winters in central Iowa.
3. An average carrying capacity of 45 cow days per acre of cornstalks was obtained with a stocking rate of 1.7-2.0 acres per cow during winter grazing.
4. A combination of cornstalk grazing and controlled feeding of field-stored forage was a satisfactory system for winter feeding of beef cows.
5. Controlled feeding with an electric fence resulted in a utilization of 35-45 percent of the husklage stored in field dumps. Cobs and large pieces of forage in the husklage were not eaten. An animal carrying capacity of 51-95 cow days per acre of cornstalks was obtained at a stocking rate of 0.67-1.67 acres per cow.

6. Controlled feeding of stalklage stacks by using movable feeding panels resulted in an animal carrying capacity of 93 cow days per acre at a stocking rate of 0.67 acres per cow.
7. All harvested forages could be fed ad libitum to beef cows in drylot. Additional protein and energy were required with all forages to prevent weight loss by the cows, but corn refuse silage required less supplemental energy than the other forages.
8. Bred heifers required a higher level of supplementation than mature cows to enable them to gain weight during the feeding period.
9. Cows fed on alternate days performed as well as cows fed daily.
10. Recutting stacked stalkage did not increase forage consumption or animal weight gain significantly. Recutting husklage stored in a horizontal silo resulted in increased forage consumption and a greater animal weight gain.
11. Harvesting and feeding corn plant forage to beef cows in drylot increased the animal carrying capacity per acre of corn compared to a combination of cornstalk grazing and controlled feeding of field-stored forage. Animal carrying capacities of 105 cow days per acre for husklage stored in a horizontal silo, 80-197 cow days per acre for ensiled stalklage, 357 cow days per acre for corn refuse silage, and 702-789 cow days per acre for whole-plant corn silage were calculated.

Simulated Harvesting Performance

1. The simulation model was an excellent computational tool for evaluating the seasonal harvesting capacity of each machinery system. It permitted an evaluation of the random effects of weather on the mobility of harvesting equipment and on the yields and moisture contents of grain and forage throughout the harvesting season. It also permitted the response of a harvesting system to alternative values of crop and machinery input parameters to be evaluated.
2. By simulating the performance of each harvesting machine for several harvesting seasons, mathematical distributions could be used to estimate the seasonal harvesting capacities of each machine at any desired completion probability. The tables of seasonal capacity at selected completion probabilities provide practical information for the selection of the proper machine size for a given acreage of corn.
3. For the values of the crop parameters used in the simulation experiments, the climatic day on which grain reached maturity was approximately normally distributed. The climatic day on which harvesting began was positively skewed because of delays caused by unsuitable field conditions.
4. A corn variety with a maturity requirement of 2700 growing degrees matured before frost in only 90 of 100 simulated years when it was planted during the climatic week ending April 25.

5. The number of harvesting days for grain and husklage was approximately normally distributed for the three harvest completion dates studied.
6. The Weibull distribution had the better fit for the distributions of the number of harvesting days for grain and refuse. By starting harvest when grain reached a moisture content of 35 percent, an average of 3-4 more harvesting days was available than when harvest was delayed until grain reached a moisture content of 32 percent. By continuing to harvest until refuse moisture content reached 40 percent, an average of 14 more harvesting days was available than when harvesting was terminated at a refuse moisture content of 45 percent.
7. For a minimum stalklage moisture content of 50 percent, the number of harvesting days was approximately normally distributed. For a minimum stalklage moisture content of 45 percent, the Weibull distribution had the better fit for the distribution of the number of harvesting days. By continuing to harvest stalklage until the moisture content reached 45 percent, an average of 9 more harvesting days was available than when harvesting was terminated at a stalklage moisture content of 50 percent.
8. When stalklage was stacked, the seasonal harvesting capacity was determined by the number of days available for grain harvest.
9. For a harvest completion probability of 80 percent, harvesting systems for stacked stalklage and corn refuse silage produced the

greatest quantities of stored forage, and corn refuse silage produced a greater animal carrying capacity per acre of corn.

10. For an annual requirement of 558 tons of forage dry matter, all four harvesting systems produced stored forage for a cost of $0.14 per cow day or less. Field-stored husklage was the least cost forage and ensiled stalklage was the most expensive forage.

RECOMMENDATIONS FOR FUTURE RESEARCH

1. More knowledge about the nutritional characteristics of corn plant forages must be obtained if they are to become a major feed supply for beef cows. Detailed animal performance studies and laboratory analyses should be conducted to determine mineral composition and protein and mineral availability as they are affected by stage of maturity at harvest and method of storage.
2. The range of forage moisture for ensiling and stacking without undesirable levels of mold, or bacterial or fungal activity should be determined.
3. Stalklage moisture content vs. time after combining should be investigated to determine how closely a flail-type forage harvester should follow a combine, and how many drying days are required before stalklage can be stacked.
4. The use of organic acids and other preservatives should be investigated for low-moisture corn plant forage stored in horizontal structures or stacks to determine the quantities of preservative required for storage periods of different lengths, methods and times of application, and the economics of their use.
5. Methods of adding supplemental protein, vitamins, and minerals to corn plant forage as it is being harvested and stored should be investigated so that a complete ration can be fed ad libitum with a minimum of labor and equipment.
6. Vehicle mobility models should be developed and verified for all

field operations, and input data should be developed for soybeans, so that a complete crop production machinery system can be simulated. The simulation model should be expanded to include simultaneous and competing field operations.

7. Data should be obtained to allow machine reliability and stochastic man-machine performance to be included in the simulation model.

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ACKNOWLEDGEMENTS

The author wishes to thank the following people who contributed in many ways during the research and preparation of this dissertation:

Dr. Wesley F. Buchele, major professor, for his suggestions and encouragement throughout the course of this study.

Dr. Charles R. Mischke, for serving on my graduate committee and for an inspirational and exciting educational experience in engineering design.

Dr. C. W. Bockhop, Dr. T. E. Hazen, Dr. S. J. Marley, and Dr. R. R. Beneke, for serving on my graduate committee and for their suggestions during the preparation of this dissertation.

Mr. Robert A. Norton, for his critical review of this dissertation and for his countless hours of counseling and friendship during my years at Iowa State University.

Dr. Richard L. Vetter, for conducting the animal performance studies and for his enthusiasm during this research.

Mr. Robert Fish, Mr. Orvil Rutzen, Mr. Rex Whitcanack, Mr. R. P. Nicholson, and Mr. F. H. McGuire for their assistance and support during the harvesting studies.

Mr. Dale Weber, Mr. Michael Danley, and other graduate students in Animal Science for their assistance with sample collections and analyses and with the animal performance studies.

Appreciation is also expressed to the following companies for their support of this research:

Deere and Company, Moline, Illinois and Hesston Corporation, Hesston, Kansas for providing equipment and financial assistance.

Foster Manufacturing Company, Madras, Oregon and Koehring Farm Division, Appleton, Wisconsin for providing equipment.

Finally, a very special thank-you to my wife, Pat, for her love and understanding throughout my graduate program, and for her willing sacrifices during the many hours spent typing and retyping this dissertation; and to my children, who accepted a part-time father for too many years.

APPENDIX A: SUMMARY OF HARVESTED PRODUCTS

The total quantities and average moisture and grain contents of the forages stored for feeding trials are listed in the following four tables. All loads of harvested material were weighed, and samples of each product were obtained from random loads to estimate moisture and grain content. Moisture contents were estimated for all loads not sampled by interpolating between the sample moisture contents. A dry matter weight was calculated for each load from the as harvested weight and the estimated moisture content. The average moisture and grain content values listed in the tables were calculated from the total as harvested and dry matter weights for each material.

Table A1. Summary of products harvested during 1969

Product and field location	Storage location	As harvested (lb.)	Dry matter (lb.)	Average moisture content (%)	Average grain content (% of D.M.)
Corn silage Field 7	East Harvestore	285,500	115,704	59.5	25.0
Corn refuse Field 1	Concrete stave silo	235,940	114,928	51.3	19.4
Corn refuse Field 4	West Stack	106,340	47,989	54.9	11.1
Corn husklage Field 3	Field dumps	54,470	37,540	32.5	3.3
Corn husklage Field 6	East stack	77,271	51,602	33.2	1.0
Corn stalklage Field 6,9	West Harvestore	108,126	57,830	46.5	1.3
Shelled corn Fields 1,3,4	Old Harvestore	411,130	303,730	26.1	100.0

Table A2. Summary of products harvested in 1970

Product and field location	Storage location	As harvested (lb.)	Dry matter (lb.)	Average moisture content (%)	Average grain content (% of D.M.)
Corn silage Field 4	Concrete stave silo	256,300	121,486	52.6	38.8
Corn refuse Field 10	West trench	139,310	63,804	54.2	18.2
Corn refuse Field 10	East Harvestore	175,210	86,904	50.4	17.0
Corn husklage Field 11	East trench	64,490	46,562	27.8	0.4
Corn husklage Field 11	West Harvestore	47,260	32,562	31.1	0.3
Corn husklage Field 2	Field dumps	92,820	67,490	27.3	1.6
Corn husklage Field 3	Field dumps	33,080	25,504	22.9	0.7
Shelled Corn Field 10	Old Harvestore	251,262	187,211	25.5	100.0

Table A3. Summary of products harvested in 1971

Product and field location	Storage location	As harvested (lb.)	Dry matter (lb.)	Average moisture content (%)
Corn silage Field 4	Concrete stave silo	294,400	117,760	60.0
Corn husklage Field 6	West Harvestore	59,050	46,460	21.3
Corn husklage Field 6	Center trench	59,920	49,550	17.3
Corn husklage Field 1	Field dumps	57,125	44,550	22.0
Sorghum stalklage Field 5	East trench	81,040	35,155	56.6
Corn stalklage Field 6	West trench	44,560	33,157	25.6

Table A4. Summary of products harvested in 1972

Product and field location	Storage location	As harvested (lb.)	Dry matter (lb.)	Average moisture content (%)
Corn husklage Field 1	Field dumps	40,520	25,770	36.4
Corn stalklage Field 1	Field stacks	35,920	22,270	38.0
Corn stalklage Field 3	Field stacks	34,160	19,762	42.1

APPENDIX B: ACTIVITY TIMES FOR HARVESTING AND PROCESSING EQUIPMENT

Observations of several harvesting and processing cycles were made in 1969 and 1970 to provide estimates of activity times and materials handling rates. A harvesting cycle was defined as the field activities required to harvest one load of forage. A processing cycle was defined as the activities required to unload and process one load of forage or grain. The number of observations was limited by the labor available, and observations were not made of travel and service activities of field machines. Forage blowers were located alongside a driveway so that wagons had only to be stopped with their discharge openings over the blower hopper, making a measurement of initial positioning time impossible. Initial positioning times were measured for backing the barge wagon up to the blower and for positioning the discharge auger of the gravity-flow wagon. Travel time from and to the field was not measured.

The following tables list the activity times for the machines observed. Where blanks appear, the particular activity did not occur during the observation. Where dashes are shown, the activity did occur during the observation but was not recorded by the observer. Consequently, the total time of all activities should be adjusted to account for the missing values.

Table B1. Activity times and forage harvested, forage harvester with 3-row rowcrop attachment harvesting corn silage, 1970[1]

Obser-vation	Activity times (min.)					Forage (lb.)	
	Harvest	Turn	Change wagons	Machine plug	Total	Wet	Dry
1	11.86	3.73	1.43		17.02	8480	4087
2	11.68	3.64	1.20		16.52	9010	4271
3	12.17	3.41	0.89		16.47	9130	4238
4	12.05	3.07	1.18		16.30	9180	4351
5	12.19	3.01	1.01		16.21	8880	4191
6	12.20	2.55	0.90		15.65	9220	4352
7	12.17	2.30	0.90		15.37	9360	4605
8	12.30	2.36	1.15	1.90	17.71	9060	4458

[1] 131 PTO horsepower tractor.

Table B2. Activity times and forage harvested, Beefmaker II with 2-row rowcrop attachment harvesting corn refuse and grain, 1969[1]

Observation	Activity times (min.) Harvest	Turn	Machine plug	Mech. failure	Other	Total	Forage (lb.) Wet	Dry
				Field 1				
1	23.75	2.56	1.89		2.94[2]	31.14	6330	3152
2	22.20	2.30	7.25		2.30[2]	34.05	6410	3100
3	28.59	4.08	15.57			48.24	8140	3983
4	24.31	2.68	10.40			37.39	6550	3070
5	22.99	2.43	2.21	10.00[3]	4.40[2]	42.03	6610	3098
6	24.07	2.20	0.80			27.07	6710	3276
7	22.53	2.83	4.70		0.24[4]	30.30	5350	2772
				Field 4				
10	31.24	6.48	26.64	35.95[5]	-	100.31	6750	2786
11	33.80	5.13	16.05	-	-	54.98	5710	2579
12	31.18	5.60	23.13	-	-	59.91	5850	2699

[1] 75 PTO horsepower tractor.

[2] Manually distributed shelled corn in grain wagon.

[3] Sheared bolts in snapping roll drive.

[4] Management stop.

[5] Shaft through upper snapping roll failed.

Table B3. Activity times and forage harvested, 4-row combine and Foster Harvest Master stacking[1] husklage dumps at one end of field, 1969

Observation	Activity times (min.)							
	Harvest	Turn	Unload grain	Unload forage	Machine plug	Mech. failure	Other	Total
15	8.62	2.10	1.79	3.70				16.21
16	10.07	2.06	-	-				12.13
17	10.07	1.60	-	-				11.67
18	10.62	2.27	1.10	2.90		12.05[2]	0.21	29.15
19	8.43	3.26	2.30	-				13.99
21	10.26	2.56	1.80	2.90		1.29[3]	2.10[4]	20.91
22	9.71	2.20	1.60	1.90				15.41
23	9.10	2.20	1.45	1.72				14.47
24	8.30	1.95	1.55	1.28				13.08
25	9.27	1.77	2.60	-			0.38[4]	13.64
26	8.58	1.90	1.80	4.21				16.49
27	8.70	1.31	2.20	3.00	15.75			30.96

Average weight of husklage dump, wet = 1757 lb.

, dry = 1186 lb.

[1] Husklage dumps were placed close together in one corner of the field by backing the combine.
[2] Gathering chain on combine head came off.
[3] Idler sprocket for gathering chain on combine jammed.
[4] Management stop to adjust machinery.

Table B4. Activity times and forage harvested, 4-row combine with Foster Harvest Master dumping husklage on headland during turn, 1970

Obser-vation	Operator	Activity times (min.)							
		Harvest	Turn	Unload grain	Unload forage	Machine plug	Travel[1]	Other	Total
1	C	15.00	2.46	1.10	1.45	0.53	0.08		20.54
2	C	14.78	2.64	1.03	1.30		1.17		19.83
3	C	13.76	2.85	0.56	1.14				19.48
4	A	10.48	3.10	1.06	1.00	3.98		0.23	19.85
5	A	10.69	2.92	1.10	0.49				15.20
6	A	10.77	2.75	1.07	1.08		1.95		17.62
7	A	10.69	2.31	1.15	0.90	0.25	1.72		17.02
8	A	9.90	2.21	1.14	0.35	0.21	1.73		15.54
9	A	9.92	2.10	1.10	0.57		1.63		15.32
10	C	11.73	3.29	0.90	0.59			0.58[2]	17.09
11	C	11.86	3.15	0.98	0.82				16.81
12	C	13.33	2.73	1.17	1.14				18.37

Average weight of husklage dump, wet = 1136 lb.
, dry = 816 lb.

[1] Travel to grain truck in poor position due to muddy conditions.
[2] Operator stopped to clean combine windshield.

Table B5. Activity times and forage harvested, 4-row combine with Foster Harvest Master dumping husklage randomly, 1970

Obser- vation	Activity times (min.)						
	Harvest	Turn	Unload grain	Unload forage	Machine plug	Travel[1]	Total
13	11.06	1.80	1.10	0.75			15.25
14	10.85	3.03	1.63	0.54	0.49		16.54
15	11.47	1.97	0.90	0.53			14.87
16	14.69	2.23	1.21	0.48		0.64	19.25
17	12.86	2.29	1.11	0.35			16.61
19	12.10	2.15	1.14	0.16		1.56	17.11
20	11.16	2.27	1.04	0.14			14.61
21	10.92	2.29	0.99	0.18	1.80		16.18
22	12.00	2.56	0.98	1.19		1.23	17.96
23	10.47	1.95	1.03	0.14	0.74		14.33

Average weight of husklage dump, wet = 1127 lb.

, dry = 845 lb.

[1] Travel to grain truck in poor position due to muddy conditions.

Table B6. Activity times and forage harvested, 4-row combine with Foster Harvest Master collecting husklage in forage wagons, 1969

Obser-vation	Activity times (min.) Harvest	Turn	Unload grain	Change wagons	Other	Total	Forage (lb.) Wet	Dry
31	11.50	1.82	1.30	-		14.62	3270	2060
32	15.10	2.29	2.10	-	2.21	21.70	3200	2016
34	13.31	2.15	1.50	5.85	3.60[1]	26.41	2130	1358
35	11.03	0.99	1.53	2.90		16.45	1940	1237
36	9.97	1.05	1.65	-		12.67	2020	1288
37	15.94	1.59	2.19	-	5.09[1]	24.81	2620	1901
38	11.41	1.04	1.58	2.84		16.87	2363	1714
39	13.00	1.04	1.65	-	0.71[2]	16.40	2373	1722
40	11.89	0.82	1.85	-		14.56	2353	1707

[1] Position grain truck for unloading.

[2] Management stop to adjust combine.

Table B7. Activity times and forage harvested, 4-row combine with Hesston flail shredder attachment and Foster trailer dumping on headland, 1970

Obser- vation	Activity times (min.)							
	Harvest	Turn	Unload grain	Unload forage	Machine plug	Mech. failure	Other	Total
1	14.24	1.70	0.96	2.34[1]			0.87[2]	20.11
2	13.77	1.57	1.11	1.08				17.53
3	11.32	1.77	0.97	1.59[1]				15.65
4	12.00	1.68	1.02	0.82[1]				15.52
5	12.05	1.79	0.98	0.56				15.38
6	11.17	1.36	1.08	-				13.61
7	11.68	1.61	0.97	0.51				14.77
8	11.28	1.29	0.93	0.21		3.99[3]		17.70
11	12.11	0.84	0.96	0.73	7.91		3.04	25.59

[1] Trailer failed to complete dumping cycle properly.

[2] Repaired trip rope on trailer.

[3] Gathering chain on combine cornhead came off.

Table B8. Activity times and forage harvested, Fox forage harvester with flail pickup attachment, 1969[1]

Observation	Activity times (min.) Harvest	Turn	Machine plug	Total	Forage (lb.) Wet	Dry
	Following combine, 4-inch recutting screen					
50	49.46	3.27		52.73	4650	2815
51	44.37	2.41		46.78	4170	2190
52	40.94	4.70	3.65	49.29	4880	2562
53	42.49	1.95		44.44	5410	3166
	Following combine, no recutting screen					
54	28.21	5.49		33.70	5280	2730
55	20.49	3.36		23.85	3480	1800
56	23.94	2.69		26.63	4560	2358
57	24.35	2.87		27.22	4630	2394
	Following picker, no recutting screen					
58	17.42	1.90		19.32	2450	1714
59	20.62	1.38		22.00	-	-
60	18.53	1.95		20.48	2990	2130
61	13.85	0.90	1.00	15.75	3100	2257
62	19.49	0.94		20.43	-	-

[1] 75 PTO horsepower tractor.

Table B9. Activity times and forage processed, blower with recutting attachment handling corn refuse and husklage, 1969[1]

Material	Obser-vation	Activity times (min.)					Forage (lb.)	
		Primary	Idle	Cleanup	Delay	Total	Wet	Dry
Refuse	1	12.33	2.18			14.51	5150	1924
Refuse	2	12.53	3.55			16.08	6960	3447
Refuse	3	11.70	1.75			13.45	6330	3152
Refuse	5	10.31	0.99			11.30	6570	3177
Refuse	7	14.84	3.12			17.96	8140	3983
Refuse	8	12.60	2.28			14.88	6550	3070
Refuse	9	8.92	1.40			10.32	6610	3098
Refuse	10	13.40	6.13	3.50		23.03	6710	3276
Refuse	12	11.15	2.08	0.68	9.45	23.36	5590	2710
Refuse	14	11.61	1.89			13.50	5420	2801
Husklage	42	21.18	1.00		2.92[2]	25.10	2620	1901

[1] 105 PTO horsepower tractor.

[2] Unloading apron on forage wagon plugged.

Table B10. Activity times and forage processed, blower handling corn silage, 1969[1]

Obser-vation	Activity times (min.)			Forage (lb.)	
	Primary	Idle	Total	Wet	Dry
21	8.09	4.05	12.14	7700	3189
22	4.37	1.51	5.88	8020	3171
23	8.38	1.06	9.44	9750	3855
24	8.40	2.85	11.25	8140	3204
25	5.66	0.89	6.55	7810	3072
26	9.64	2.14	11.78	9100	3704
27	5.56	1.23	6.79	7450	3148
29	7.52	2.90	10.42	9640	3965
30	6.60	1.48	8.08	9060	3413
31	5.58	2.05	7.63	8550	3613

[1] 95 PTO horsepower tractor.

Table B11. Activity times and forage processed, blower with recutting attachment handling corn silage, 1970[1]

Obser-vation	Operator	Activity times (min.) Primary	Idle	Delay	Total	Forage (lb.) Wet	Dry
1	C	7.71	1.42		9.13	8,300	3,793
2	W	7.50	1.17	4.95[2]	13.62	7,360	3,364
3	C	8.25	2.96		11.21	8,100	3,702
4	W	7.89	1.38		9.27	8,150	3,725
5	C	9.53	1.88		11.41	10,450	4,901
6	W	8.35	1.26		9.61	8,790	4,123
7	C	7.75	1.23	0.13[3]	9.11	8,020	3,761
8	W	8.54	1.18		9.72	9,500	4,456
9	W	8.81	1.75		10.56	7,270	3,504
10	X	9.65	2.43		12.08	9,730	4,690
11	W	9.04	1.11		10.15	8,480	4,087
12	X	9.15	3.10		12.25	9,010	4,271
13	W	8.89	1.24		10.13	9,130	4,328
14	X	9.41	1.81		11.22	9,180	4,351
15	W	8.50	1.15	2.47[4]	12.12	8,880	4,191
16	X	9.93	1.96		11.89	10,010	4,725
17	W	9.27	1.56	11.67[5]	22.50	9,220	4,352
18	X	10.16	5.29		15.45	9,360	4,605

[1] 95 PTO horsepower tractor.

[2] Operator installed door in silo discharge chute.

[3] Blower plugged.

[4] Shear bolt failed in blower PTO shaft.

[5] Operator repositioned blower discharge spout in silo.

Table B12. Activity times and grain processed, blower handling shelled corn, 1969[1]

Obser-vation	Activity times (min.)						Grain (lb.)	
	Initial positioning	Primary	Idle	Cleanup	Delay	Total	Wet	Dry
			Barge wagon, hydraulic hoist[2]					
4	1.43	26.98	0.90			29.31	10,230	7,280
6	2.20	15.51	1.40			19.11	5,440	3,916
11	2.65	14.85	0.87			18.37	7,860	5,680
13	2.47	17.39	1.07		3.37[3]	24.30	8,530	6,164
28	1.20	18.22	0.90			20.32	7,720	5,687
33	1.34	18.12	0.73			20.19	7,530	5,654
36	2.57	9.71	0.68			12.96	10,750	8,100
38	1.08	11.34	0.75	4.15	2.10[4]	19.42	12,120	9,254
39	2.80	9.98	0.65	0.90		14.33	11,480	8,781
40	2.40	11.02	1.10			14.52	10,630	8,131
41	3.20	8.45	0.77			12.42	8,980	6,869
			Gravity-flow wagon, hydraulic auger[5]					
32	0.49	14.82	0.25			15.56	8,470	6,359
37	2.90	15.69	1.92			20.51	8,500	6,449

[1] 50 PTO horsepower tractor.
[2] Processing rate limited by tractor power available.
[3] Operator repositioned wagon.
[4] Blower plugged.
[5] Processing rate limited by hydraulic auger capacity.

APPENDIX C: SUMMARY OF STATISTICAL TESTS

Table C1. Analysis of variance for the linear regression of total refuse dry matter yield per acre on grain yield per acre

Source	Sum of Squares $X\ 10^{-5}$	DF	Mean Square $X\ 10^{-5}$	F
Total	1,327.925	3	442.642	
Mean	1,323.085	1	1,323.085	546.73**
Residual	4.840	2	2.420	
Grain yield	4.823	1	4.823	283.77*
Residual	0.017	1	0.017	
Total reduction	1,327.909	2	663.954	39064.75**

*Calculated F-statistic exceeds the tabulated value at the 5 percent level of significance; also for Tables C2-C23.

**Calculated F-statistic exceeds the tabulated value at the 1 percent level of significance; also for Tables C2-C23.

Table C2. Analysis of variance for the linear regression of refuse forage dry matter yield per acre on grain yield per acre

Source	Sum of Squares $X\ 10^{-5}$	DF	Mean Square $X\ 10^{-5}$	F
Total	944.965	3	314.988	
Mean	936.548	1	936.548	222.53**
Residual	8.417	2	4.209	
Grain yield	7.647	1	7.647	9.93
Residual	0.770	1	0.770	
Total reduction	944.194	2	472.097	612.78**

Table C3. Analysis of variance for the linear regression of corn refuse forage dry matter yield per acre on grain yield per acre, with values from Schroeder (1968a) and Hitzhusen (1969) added

Source	Sum of Squares X 10^{-5}	DF	Mean Square X 10^{-5}	F
Total	1,507.933	5	301.587	
Mean	1,483.379	1	1,483.379	241.65**
Residual	24.554	4	6.139	
Grain yield	21.600	1	21.600	21.93*
Residual	2.954	3	0.985	
Total reduction	1,504.979	2	752.489	764.11**

Table C4. Analysis of variance for the linear regression of corn refuse forage moisture content on grain moisture content, field 1, 1969

Source	Sum of Squares	DF	Mean Square	F
Total	24,473.188	8	3,059.148	
Mean	24,288.051	1	24,288.051	918.33**
Residual	185.137	7	26.488	
Grain moisture	140.363	1	140.036	18.81**
Residual	44.773	6	7.462	
Total reduction	24,428.414	2	12,214.207	1636.82**

Table C5. Analysis of variance for the linear regression of corn refuse forage moisture content on grain moisture content, field 10, 1970

Source	Sum of Squares	DF	Mean Square	F
Total	27,144.004	9	3,016.000	
Mean	26,906.895	1	26,906.895	907.83**
Residual	237.109	8	29.639	
Grain moisture	94.776	1	94.776	4.66
Residual	142.334	7	20.333	
Total reduction	27,001.668	2	13,500.832	663.97**

Table C6. Analysis of variance for the pooled linear regression of corn refuse forage moisture content on grain moisture content

Source	Sum of squares	DF	Mean square	F
Total	51,617.188	17	3,036.305	
Mean	51,194.199	1	51,194.199	1,936.48**
Residual	422.988	16	26.437	
Grain moisture	132.135	1	132.135	6.815*
Residual	290.853	15	19.390	
Total reduction	51,326.335	2	25,663.167	1,323.526**

Table C7. Comparison of linear regressions of corn refuse forage moisture content on grain moisture content

$\hat{B}_{11} = b_{11} = 1.85^a$	$\hat{B}_{01} = b_{01} = 7.33$
$\hat{B}_{12} = b_{12} = 1.55^a$	$\hat{B}_{02} = b_{02} = 12.27$
Hypotheses:	Hypotheses:
Ho: $\hat{B}_{11} = \hat{B}_{12} = \hat{B}_1$	Ho: $\hat{B}_{01} = \hat{B}_{02} = \hat{B}_0$
H1: $\hat{B}_{11} \neq \hat{B}_{12}$	H1: $\hat{B}_{01} \neq \hat{B}_{02}$
$s_p^2 = 14.393$	$s_p^2 = 13.495$
$s_{b_{11}-b_{22}} = 0.846$	$s_{b_{01}-b_{02}} = 21.780$
calc. t = 0.356	calc. t = -0.227
$t_{.025}(13) = 2.160$	$t_{.025}(14) = 2.145$
Fail to reject Ho	Fail to reject Ho
$\hat{B}_1 = b_1 = 1.70$	$\hat{B}_0 = b_0 = 9.94$
New $b_{01} = 7.33^b$	
New $b_{02} = 12.27^b$	

[a]Values listed as b_1 coefficients in Table 11.

[b]New values for b_0 coefficients calculated using $b_1 = 1.70$.

Table C8. Analysis of variance for the linear regression of husklage dry matter yield per acre on grain yield per acre

Source	Sum of squares X 10^{-5}	DF	Mean square X 10^{-5}	F
Total	266.775	7	38.111	
Mean	262.637	1	262.637	380.85**
Residual	4.138	6	0.690	
Grain yield	3.438	1	3.438	24.59**
Residual	0.699	5	0.140	
Total reduction	266.076	2	133.038	951.32**

Table C9. Analysis of variance for the linear regression of husklage moisture content on grain moisture content

Source	Sum of squares	DF	Mean square	F
Total	9,535.086	10	953.509	
Mean	9,253.746	1	9,253.746	296.03**
Residual	281.340	9	31.260	
Grain moisture	212.068	1	212.068	24.49**
Residual	69.272	8	8.659	
Total reduction	9,465.813	2	4,732.906	546.59**

Table C10. Analysis of variance for the linear regression of percent of total corn plant dry matter in the grain fraction on grain moisture content

Source	Sum of squares	DF	Mean square	F
Total	23,044.380	11	2,094.944	
Mean	22,818.250	1	22,818.250	1,009.077**
Residual	226.130	10	22.613	
Grain moisture	204.567	1	204.567	85.379**
Residual	21.563	9	2.396	
Total reduction	23,022.817	2	11,511.408	4,804.427**

Table C11. Analysis of variance for the linear regression of percent of total corn plant dry matter in the cob fraction on grain moisture content

Source	Sum of squares	DF	Mean square	F
Total	1,404.338	11	127.667	
Mean	1,401.427	1	1,401.427	4,815.900**
Residual	2.911	10	0.291	
Grain moisture	0.411	1	0.411	1.478
Residual	2.500	9	0.278	
Total reduction	1,401.838	2	700.919	2,521.291**

Table C12. Analysis of variance for the linear regression of percent of total corn plant dry matter in the stalk on grain moisture content

Source	Sum of squares	DF	Mean square	F
Total	5,941.121	11	540.102	
Mean	5,844.319	1	5,844.319	603.752**
Residual	96.802	10	9.680	
Grain moisture	86.171	1	86.171	72.964**
Residual	10.631	9	1.181	
Total reduction	5,930.490	2	2,965.245	2,510.792**

Table C13. Analysis of variance for the linear regression of percent of total corn plant dry matter in the leaf on grain moisture content

Source	Sum of squares	DF	Mean square	F
Total	1,570.801	11	142.800	
Mean	1,507.896	1	1,507.896	239.691**
Residual	62.905	10	6.291	
Grain moisture	46.040	1	47.040	24.568**
Residual	16.865	9	1.874	
Total reduction	1,553.936	2	776.968	414.604**

Table C14. Analysis of variance for the linear regression of percent of total corn plant dry matter in the husk on grain moisture content

Source	Sum of squares	DF	Mean square	F
Total	780.940	11	70.995	
Mean	772.467	1	772.467	912.004**
Residual	8.473	10	0.847	
Grain moisture	1.259	1	1.259	1.570
Residual	7.214	9	0.802	
Total reduction	773.726	2	386.863	482.373**

Table C15. Analysis of variance for the regression of grain dry matter on grain moisture content for composite 20-plant samples from Schroeder (1968a)

Source	Sum of squares $X\ 10^{-4}$	DF	Mean square $X\ 10^{-5}$	F
Total	21,678.248	12	1,806.520	
Mean	21,577.302	1	21,577.302	2,351.27**
Residual	100.946	11	9.177	
Grain moisture	15.312	1	15.312	1.79
Residual	85.633	10	8.563	
$(\text{Grain moisture})^2$	56.826	1	56.826	17.75**
Residual	28.807	9	3.201	
$(\text{Grain moisture})^3$	12.768	1	12.768	6.37*
Residual	16.039	8	2.005	
Total reduction	21,662.208	4	5,415.552	2701.21**

Table C16. Analysis of variance for the linear regression of stalk dry matter yield on grain moisture content for composite 20-plant samples from Schroeder (1968a)

Source	Sum of squares X 10^{-4}	DF	Mean square X 10^{-4}	F
Total	5,571.192	12	464.266	
Mean	5,311.328	1	5,311.328	224.83**
Residual	259.864	11	23.624	
Grain moisture	235.657	1	235.657	97.35**
Residual	24.207	10	2.421	
Total reduction	5,546.985	2	2,773.492	1,145.60**

Table C17. Analysis of variance for the linear regression of cob dry matter yield on grain moisture content for composite 20-plant samples from Schroeder (1968a)

Source	Sum of squares X 10^{-3}	DF	Mean square X 10^{-3}	F
Total	13,272.860	12	1,106.072	
Mean	13,219.503	1	13,219.503	2,725.32**
Residual	53.357	11	4.851	
Grain moisture	27.496	1	27.496	10.63**
Residual	25.861	10	2.586	
Total reduction	13,247.000	2	6,623.500	2,561.29**

Table C18. Analysis of variance for the linear regression of leaf dry matter yield on grain moisture content for composite 20-plant samples from Schroeder (1968a)

Source	Sum of squares $\times 10^{-4}$	DF	Mean square $\times 10^{-4}$	F
Total	1,453.785	11	132.162	
Mean	1,358.865	1	1,358.865	143.16**
Residual	94.920	10	9.492	
Grain moisture	72.649	1	72.649	29.35**
Residual	22.271	9	2.475	
Total reduction	1,431.514	2	715.757	289.19**

Table C19. Analysis of variance for the linear regression of husk dry matter yield on grain moisture content for composite 20-plant samples from Schroeder (1968a)

Source	Sum of squares $\times 10^{-3}$	DF	Mean square $\times 10^{-3}$	F
Total	7,354.217	12	612.851	
Mean	7,246.302	1	7,246.302	738.63**
Residual	107.915	11	9.810	
Grain moisture	7.382	1	7.382	0.73
Residual	100.532	10	10.053	
Total reduction	7,253.685	2	3,626.843	360.77**

Table C20. Analysis of variance for the regression of corn silage dry matter yield on grain moisture content for composite 20-plant samples from Schroeder (1968a)

Source	Sum of squares $\times 10^{-5}$	DF	Mean square $\times 10^{-5}$	F
Total	10,241.784	12	853.482	
Mean	10,134.164	1	10,134.164	1,035.83**
Residual	107.620	11	9.784	
Grain moisture	72.254	1	72.254	20.43**
Residual	35.366	10	3.537	
$(\text{Grain moisture})^2$	18.261	1	18.261	9.61*
Residual	17.104	9	1.900	
Total reduction	10,224.678	3	3,408.225	1,793.37**

Table C21. Analysis of variance for the regression of corn refuse dry matter yield on grain moisture content for composite 20-plant samples from Schroeder (1968a)

Source	Sum of squares $\times 10^{-5}$	DF	Mean square $\times 10^{-5}$	F
Total	3,048.325	12	254.027	
Mean	2,939.500	1	2,939.500	297.12**
Residual	108.825	11	9.893	
Grain moisture	94.823	1	94.823	67.72**
Residual	14.002	10	1.400	
Total reduction	3,034.322	2	1,517.161	1,083.51**

Table C22. Analysis of variance for the regression of husk plus cob dry matter yield on grain moisture content for composite 20-plant samples from Schroeder (1968a)

Source	Sum of squares X 10^{-4}	DF	Mean square X 10^{-4}	F
Total	4,029.720	12	335.810	
Mean	4,004.042	1	4,004.042	1,715.23**
Residual	25.678	11	2.334	
Grain moisture	6.337	1	6.337	3.28
Residual	19.341	10	1.934	
Total reduction	4,010.379	2	2,005.189	1,036.81**

**Calculated F-statistic exceeds the tabulated value at the 1 percent level of significance.

Table C23. Analysis of variance for the regression of total grain dry matter per ear on grain moisture content, data from Schmidt (1968a)

Source	Sum of squares X 10^{-2}	DF	Mean square X 10^{-2}	F
Total	15,408.100	84	183.430	
Mean	12,980.210	1	12,980.210	443.74**
Residual	2,427.890	83	29.252	
Grain moisture	2,175.938	1	2,175.938	708.18**
Residual	251.953	82	3.073	
$(\text{Grain moisture})^2$	88.087	1	88.087	43.54**
Residual	163.865	81	2.023	
$(\text{Grain moisture})^3$	97.323	1	97.323	117.01**
Residual	66.542	80	0.832	
Total reduction	15,341.550	4	3,835.388	4611.11**

APPENDIX D: DRY MATTER YIELDS OF CORN PLANT PARTS

The data in Table D1 were taken from an unpublished report by Schroeder (1968a). He planted five hybrid corn varieties in replicated plots during 1967. At each harvest date listed in the table, four plants of each variety were harvested by hand. Wet and dry weights of each of five plant parts were obtained for each variety to investigate the relationship between kernel moisture content and grain moisture content.

Since Schroeder was interested only in the moisture content relationships, the dry matter values for the individual plant parts were not included in his thesis (1968b). He did include composite values for all 20 plants harvested on each date in an unpublished report (1968a). The values in Table D1 were obtained from that report, and were included here for use in estimating expected yields of forage.

Table D1. Dry matter yield and moisture content of corn plant parts from Schroeder (1968a)

Date	Dry matter (grams)[1]					Moisture content (%)				
	Grain	Stalk	Cob	Husk	Leaf	Grain	Stalk	Cob	Husk	Leaf
Sept. 9	3534	2802	1142	921	1671	41.42	68.90	48.26	60.53	60.44
Sept. 15	3904	2762	1089	583	1377	39.37	71.14	49.54	46.52	60.83
Sept. 20	4638	3767	1168	961	1523	34.91	60.21	48.57	57.01	63.24
Sept. 22	4466	2325	1074	800	1389	34.36	71.40	49.79	54.19	54.06
Sept. 25	4496	2356	1205	956	1349	31.75	66.78	44.24	41.03	46.75
Sept. 27	4495	2474	1058	807	1157	31.40	68.05	46.68	49.25	52.74
Sept. 29	4445	2418	1025	790	1128	32.25	68.06	47.90	49.36	33.53
Oct. 2	4327	1888	1025	796	686	29.70	65.51	45.02	39.10	5.64
Oct. 5	4279	1738	977	756	840	25.63	64.69	45.09	34.44	6.26
Oct. 6	4365	1670	1009	714	951	25.43	62.42	43.22	34.38	7.94
Oct. 11	4488	1933	1031	793	860	25.52	66.56	44.66	37.95	8.71
Oct. 13	3972	1599	992	718	818	25.43	65.01	40.75	34.13	13.26
Nov. 7	4114	1281	968	691		19.20	48.74	30.16	18.13	

[1] All weights are composite weights from 20 plants, 4 randomly selected plants from each of 5 varieties.

APPENDIX E: A CHI-SQUARE GOODNESS OF FIT TEST

The chi-square goodness of fit test is widely used as a criterion for accepting or rejecting a mathematical distribution for a data set. Difficulty in its use arises when the number of classes and the class boundaries must be selected, particularly when the number of values in the data set is small. Classes may be chosen to have either equal widths or equal probability densities. Kendall and Stuart (1961) and Kempthorne and Folks (1971) recommended choosing class boundaries to have classes with probability densities as nearly equal as possible. Kendall and Stuart (1961) also recommended that class boundaries be chosen so that the expected frequency of observations in the class is equal to or greater than five.

Cochran (1952 and 1954) recommended a more flexible approach. He argued that the discrepancy between an observed distribution and a theoretical distribution is often most apparent in the tails of the distribution, and that the sensitivity of the chi-square test was likely to be decreased by an overdose of pooling and an inflexible use of a minimum expected frequency of five. He reported that a single expectation as low as one-half may be allowed at the five percent level of significance, and that two expectations as low as one may be allowed without disturbing the test.

It has also been suggested that grouping data into classes for a chi-square test may result in a loss of information about the distribution of the data set. Tests which overcome this criticism are based on comparing the cumulative distribution function of the data set to the assumed distribution function. The Kolmogorov-Smirnov test (Massey, 1951) is a test of this type, and is based on the maximum deviation between the two distribution functions. Tables are available listing the maximum allowable deviations at various significance levels (Massey, 1951; Kempthorne and Folks, 1971). However, this test requires that the theoretical distribution function be completely specified independently of the particular data set being tested. Massey (1951) states that the distribution of the maximum deviation is not known when population parameters are estimated from the data set. Kempthorne and Folks (1971) also show that the deviations at various locations along the distribution function have unequal variances.

Lilliefors (1967) developed a table of critical values for the Kolmogorov-Smirnov distance for a theoretical normal distribution when the mean and variance are estimated from the data set. But similar tables could not be found for the rectangular and Weibull distributions, so the chi-square test was used to choose a theoretical distribution for data sets considered in this dissertation. Class boundaries were chosen to have equal probability densities with minimum expected frequencies of five except for the first and last classes. Based on Cochran's suggestion, these classes were chosen to have minimum expected frequencies of one. Acceptance or rejection of a particular theoretical distribution for a data set was based on the tabulated value of the chi-square statistic at a five percent level of significance. Whenever the chi-square test indicated that the normal distribution could not be rejected, a Kolmogorov-Smirnov test was also made with the maximum deviation being compared to the critical values in Lilliefors' table.

APPENDIX F: MARKOV CHAIN PROBABILITY EXPRESSIONS

The following are the expressions for computing the probability of 0-7 days suitable for field operations during any climatic week.

$$P(7\text{ good days}) = P(G)P(G/G)^6$$

$$P(6\text{ good days}) = P(G)P(G/G)^5P(B/G) + 5P(G)P(G/G)^4P(B/G)P(G/B) + P(B)P(G/B)P(G/G)^5$$

$$\begin{aligned}P(5\text{ good days}) = {} & P(G)P(G/G)^4P(B/G)P(B/B) + P(B)P(G/B)P(G/G)^4P(B/G) \\ & + P(B)P(B/B)P(G/B)P(G/G)^4 + 4P(G)P(G/G)^3P(B/G)^2P(G/B) \\ & + 4P(G)P(G/G)^3P(B/G)P(B/B)P(G/B) \\ & + 6P(G)P(G/G)^2P(B/G)^2P(G/B)^2 + 4P(B)P(G/B)^2P(G/G)^3P(B/G)\end{aligned}$$

$$\begin{aligned}P(4\text{ good days}) = {} & P(G)P(G/G)^3P(B/G)P(B/B)^2 \\ & + 6P(G)P(G/G)^2P(B/G)^2P(G/B)P(B/B) \\ & + 2P(B)P(G/B)P(G/G)^3P(B/G)P(B/B) \\ & + 3P(G)P(G/G)P(B/G)^3P(G/B)^2 + 3P(B)P(G/B)^2P(G/G)^2P(B/G)^2 \\ & + 3P(G)P(G/G)^2P(B/G)P(B/B)^2P(G/B) \\ & + 6P(G)P(G/G)P(B/G)^2P(G/B)^2P(B/B) \\ & + 6P(B)P(G/B)^2P(G/G)^2P(B/G)P(B/B) + P(G)P(B/G)^3P(G/B)^3 \\ & + 3P(B)P(G/B)^3P(G/G)P(B/G)^2 + P(B)P(B/B)^2P(G/B)P(G/G)^3\end{aligned}$$

$$\begin{aligned}P(3\text{ good days}) = {} & P(B)P(B/B)^3P(G/B)P(G/G)^2 \\ & + 6P(B)P(B/B)^2P(G/B)^2P(B/G)P(G/G) \\ & + 2P(G)P(B/G)P(B/B)^3P(G/B)P(G/G) \\ & + 3P(B)P(B/B)P(G/B)^3P(B/G)^2 + 3P(G)P(B/G)^2P(B/B)^2P(G/B)^2 \\ & + 3P(B)P(B/B)^2P(G/B)P(G/G)^2P(B/G) \\ & + 6P(B)P(B/B)P(G/B)^2P(B/G)^2P(G/G) \\ & + 6P(G)P(B/G)^2P(B/B)^2P(G/B)P(G/G) + P(B)P(G/B)^3P(B/G)^3\end{aligned}$$

$$+ 3P(G)P(B/G)^3P(B/B)P(G/B)^2 + P(G)P(G/G)^2P(B/G)P(B/B)^3$$

$$P(2 \text{ good days}) = P(B)P(B/B)^4P(G/B)P(G/G) + P(G)P(B/G)P(B/B)^4P(G/B)$$

$$+ P(G)P(G/G)P(B/G)P(B/B)^4 + 4P(B)P(B/B)^3P(G/B)^2P(B/G)$$

$$+ 4P(B)P(B/B)^3P(G/B)P(G/G)P(B/G)$$

$$+ 6P(B)P(B/B)^2P(G/B)^2P(B/G)^2 + 4P(G)P(B/G)^2P(B/B)^3P(G/B)$$

$$P(1 \text{ good day}) = P(B)P(B/B)^5P(G/B) + 5P(B)P(B/B)^4P(G/B)P(B/G)$$

$$+ P(G)P(B/G)P(B/B)^5$$

$$P(0 \text{ good days}) = P(B)P(B/B)^6$$