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Mechanization of the Selective Harvest of Broccoli

by

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(ABSTRACT)

An investigation was made of concepts for mechanizing the selective harvest of broccoli. Selective harvesting has advantages over once-over harvesting because of greater yield and reduced handling requirements. Results of a preliminary experiment measuring broccoli stalk cutting forces indicated that the blade speed for a broccoli cutting mechanism should be as fast as possible to minimize the required cutting force. A manually-directed, powered cutting device was designed to fit readily into existing broccoli harvest systems. In tests the first year with the device, the harvest rate was substantially faster than hand harvest rates measured at commercial farms, but the level of leaf-stripping achieved with the device was unacceptably low. A new cutting device included an added leaf-stripping mechanism and had a mounting arrangement that allowed the harvesting of two double rows at once. In tests the second year, leaf-stripping was much improved, but the overall harvest rate was only marginally better because of extra manipulation required to activate the leaf-stripping mechanism.

Measurements related to mechanical harvesting were made on broccoli plants both years. Head height, stalk diameter, and head weight were strongly affected by harvest time and in-row plant spacing. Height and stalk diameter were moderately correlated to head diameter. A regression model for predicting head diameter from height and stalk diameter indicated that potential exists for using a combination of the two parameters for sizing broccoli heads. Head weight was highly correlated to height and stalk diameter.

Two concepts for automatic mature head selection were evaluated. The results of an experiment measuring the force required to uproot broccoli plants indicated that physically sizing broccoli heads using spaced fingers would only be feasible if late season irrigations could be incorporated in a harvest system. Digital image processing for head selection appears more promising. An image processing algorithm based on the gray level run length method of textural analysis was developed for predicting broccoli head area. Accurate head classification was obtained with the model. For an automatic selective harvester, an image processing system can be coupled with a cutting device with the major advantage that leaf-stripping can be accomplished automatically during the harvesting action.

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Chapter I

INTRODUCTION

Broccoli (Brassica oleracea var. italica Plenck) is one of the vegetables that has benefitted most from the trend of health-conscious Americans toward eating more fresh vegetables. The demand for fresh broccoli, which has especially high concentrations of vitamin A and calcium (Peirce, 1987), has increased dramatically. The proportion of broccoli grown that is consumed fresh has risen from 35% in 1971 to 65% in 1984, and per capita grocery store purchases have increased from 0.14 kg in 1971 to 1.55 kg in 1986 (Anonymous, 1988), not including fresh broccoli consumed at increasingly popular restaurant salad bars.

The total fresh market production of broccoli in the United States is presently 254,061 t, with an additional 124,286 t produced for processing. The total area harvested in 1983 was 37,179 ha (91,800 acres). Commercial production is concentrated in California, which produces more than 75% of the nation's broccoli (Peirce, 1987). However, in recent years production has increased in other areas, especially the Midwest and the eastern part of the United States, as farmers have struggled to maintain profitability through diversification and reductions in product transportation costs. This increase in production outside of California has also been facilitated by the successful development of heat tolerant broccoli hybrids (Anonymous, 1988).

Alternate crops like broccoli became especially important in tobacco producing areas such as Virginia as the demand and price for tobacco dropped in the early 1980's. A pilot program was begun in 1983 to evaluate the potential for fall production of fresh market broccoli in south central Virginia. Fall broccoli does better than spring broccoli in this region, and a "market window" exists because California is the only other state producing fresh broccoli in October and November. Also, broccoli can withstand colder temperatures, extending the harvest time late into the fall when there is less competition with other farm operations. Commercial production of fall broccoli was promising, and a cooperative of growers, formed to market the broccoli, reached a peak production of nearly 200 ha (500 acres) after several years. Unfortunately, broccoli production in Virginia has dropped in the last few years because of the resurgence of tobacco as well as losses due to early hard freezes and high harvest labor requirements.

Brown (1980) estimated that 200 h/ha (80 h/acre) labor were required for harvesting broccoli. His estimate was an average for the entire country and included both fresh market and processed broccoli. In Virginia, where production is on a smaller scale than in California, it was estimated that 350 h/ha (143 h/acre) labor were required for harvesting fresh market broccoli (O'Dell et al., 1987). Time and management requirements associated with the harvest increase the competition with tobacco production, and high labor costs substantially reduce profits. Inefficient harvesting also contributes to cold weather losses because of reduced timeliness.

Harvest labor requirements are high because broccoli is harvested entirely by hand cutting. It must be harvested selectively, with three or four cuttings of the same planting typical, because the heads do not mature uniformly. Although the cutting of the heads is done by hand, other aspects of the harvest have been mechanized to a limited extent. Pneumatic bunching machines and field pack machines that move through the field with the cutters are now used extensively (Brown, 1980; Plumb, 1984). The bunching machines are mounted on the field pack machines and powered from air compressors.

Considering the increasing demand for fresh market broccoli, improvements in harvest efficiency that contribute to expanded production are needed. Improvements could be especially important for newer production areas like Virginia which are struggling to get established. Four main strategies for increasing the efficiency of the broccoli harvest are possible. Figure 1 shows an outline of the four strategies and points out constraints to each. The final objective of all the strategies is increased profitability to the grower through improved harvest efficiency, accomplished by mechanization.

The first strategy is to do a once-over machine harvest of the broccoli. The machine components required are relatively simple, and several such harvesters have been tried (Casada et al., 1988; Coffey et al., 1986; Borchers, 1989). The problem with this strategy is that the yield will be decreased and postharvest handling requirements increased due to the nonuniformity of maturity of the broccoli heads. For this approach to be practical, uniformly maturing varieties would have to be developed.

The second strategy relies on the economics of scale and improvements in machine components for handling and processing the broccoli after it has been cut. This strategy has been used in California, where large platforms carrying a dozen or more people and many bunching machines move through the field with a team of cutters. This strategy led to the development of the bunching machines, which are now standard for almost all fresh market broccoli production. In Virginia, fields are too small and uneven for this to be practical on such a large scale, although many growers have built or modified wagons equipped with bunching machines to move through the field with the cutters.

The third strategy is to partially mechanize the cutting process itself. Simple, powered cutting devices could allow workers to select and cut broccoli faster while eliminating some of the stooping and discomfort associated with hand cutting. This strategy has the advantage of being simple and low cost so that small-to-medium size producers could integrate the devices into their harvest systems without a large capital outlay.

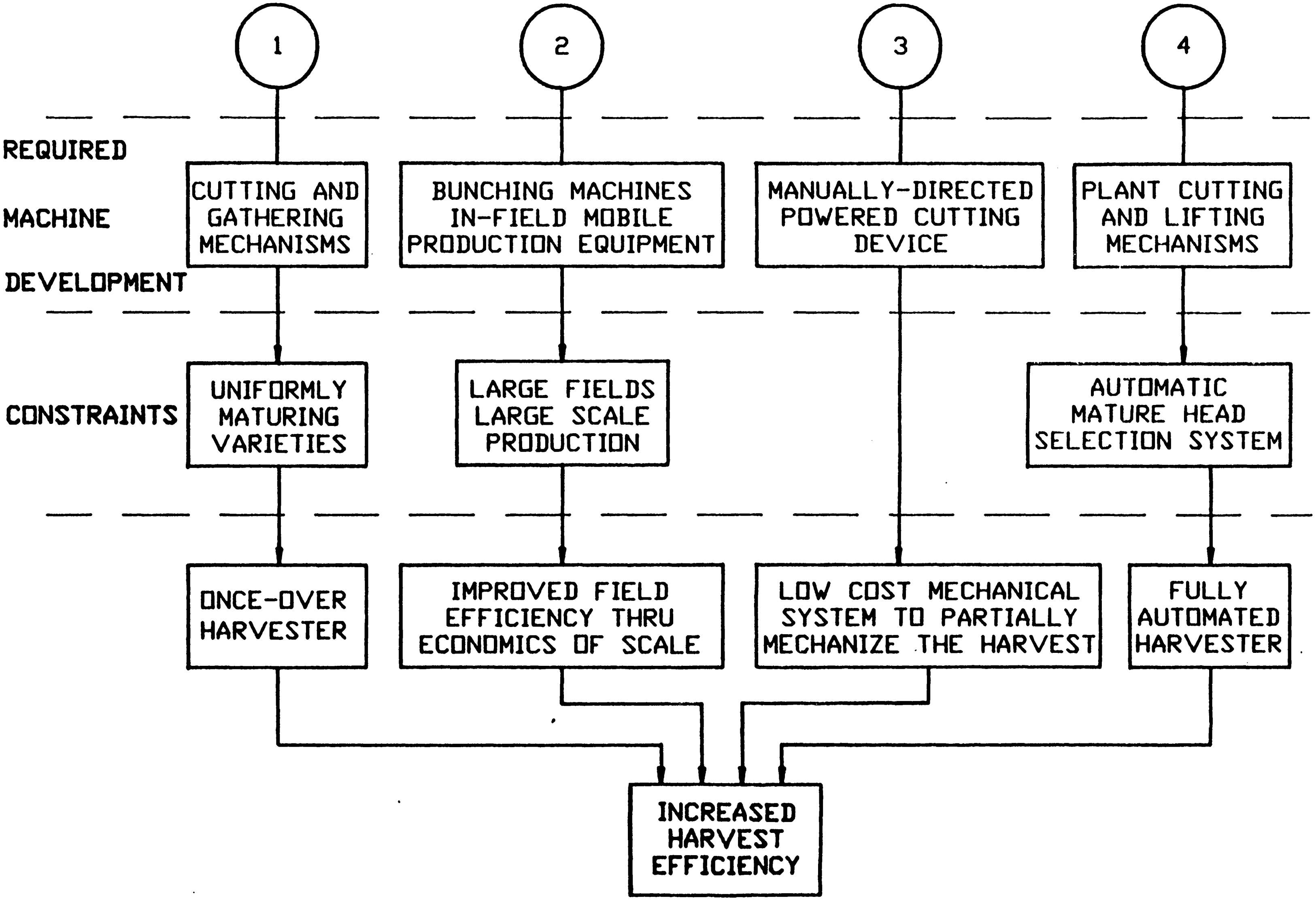


Figure 1. Outline of strategies for improving the efficiency of harvesting broccoli.

The fourth strategy is the complete mechanization of the selective harvest of broccoli. This strategy would require automation of the selection of the mature broccoli heads, using either physical or visual selection criteria, and the development of mechanisms to cut, lift, and collect the heads without damaging neighboring plants. Automating the head selection process would probably require sophisticated technology, making an automated selective harvester very expensive. Another disadvantage is that cutting would probably be most effectively done near the ground, requiring the machine to handle extra biomass and necessitating an added step for removing more leaves and stalk.

Of the four strategies for broccoli harvest mechanization, the biggest constraint is to once-over harvesting because of the requirement for uniformly maturing broccoli varieties. Much progress has already been made with the second strategy, but the benefits from this approach for small-scale production are limited. The third and fourth strategies are the most promising for helping broccoli producers in Virginia and other newer production areas. Research is needed on mechanization of the selective harvest of broccoli, both for the development of harvest aids that can benefit producers relatively quickly, and for the eventual development of fully automated harvesters. Mechanization of the selective harvest of broccoli can improve harvest efficiency, thereby improving profitability and management conditions through reduced harvest labor requirements and improved timeliness.

Chapter II

OBJECTIVES

The subject of this research was an investigation of ways to mechanize the selective harvest of broccoli. The primary objectives were to study physical and mechanical properties of broccoli plants related to mechanical harvesting, to develop a manually-directed, powered broccoli cutting device for partially mechanizing the harvest, and to evaluate the feasibility of automated selective broccoli harvesting.

The specific objectives of the research were:

1. To measure the forces associated with the high speed cutting of broccoli stalks.

2. To investigate physical properties of broccoli plants that relate to mature head selection and to the design of harvesting devices.

3. To design and construct a manually-directed, powered broccoli cutting device and to test the device in the field and optimize performance.

4. To conduct time studies of commercial broccoli harvesting for use as a basis of comparison for determining the effectiveness of the cutting device.

5. To conduct tests to evaluate a concept for automatically selecting mature broccoli heads by physically sizing them with spaced fingers.

6. To evaluate the feasibility of using a digital image processing system for automated mature broccoli head selection in the field.

Chapter III

LITERATURE REVIEW

3.1 Commercial Broccoli Harvesting Practices

A thorough understanding of commercial broccoli harvesting practices is essential to an investigation of harvest mechanization concepts. This investigation included a survey of commercial broccoli production practices in Virginia. Information was obtained from extension bulletins and other printed sources, from growers and extension personnel, and through the personal experiences of the author. The following is a review of broccoli harvesting practices necessary to an understanding of many of the concepts and results reported herein.

All fresh broccoli in the United States today is selected, cut, and packed by manual labor. In the past, the broccoli was handled in bulk and packed at a central packing shed, but there has been a strong trend in recent years toward field packing (Plumb, 1984). In California, field packing is accomplished with large tractor-drawn or self-propelled field pack machines with packing wings extending out as far as 6 m (20 ft.) on either side. Such a field pack machine may be equipped with 12 or more pneumatic bunching machines and employ a harvest crew of 23 people (Vigna, 1987).

Workers moving just ahead of or behind the field pack machines cut the individual broccoli heads with knives and place or throw them onto the field pack machine. The bunching machine operators then bunch the broccoli and place it in boxes. Bunching is accomplished by inserting the stem end of two or more broccoli heads into an opening in the top of the bunching machine and activating the machine to release a rubber band around the bunch while simultaneously slicing the bottom of the stalks off evenly. The bunching machines are connected to air compressors mounted on the field pack machines.

In Virginia, harvest crews are much smaller than in California, but the same field pack techniques have been adopted by most growers. A typical field pack machine in Virginia would be a modified trailer equipped with two bunching machines powered from a small PTO-driven air compressor.

The broccoli is typically planted in double rows, and one worker will usually harvest two double rows at once. Workers not only have to cut the broccoli, they must also strip the leaves from the stem. This leaf stripping is accomplished by either of two methods. By one method, the workers push their hands and knife down over the broccoli head to partially strip the leaves. They then cut the stalk and strip the remaining leaves off by hand while passing the head to the field pack machine. With the other method, the leaves are stripped in a separate operation using "leaf-breakers," which are 15 cm (6 in.) horizontal steel rings mounted on the end of long handles. Workers push the rings down over the broccoli head in an aggressive motion to break most of the leaves from the stalk. The stripped broccoli heads can then be cut very quickly in a separate pass. They can even be left in the field for cutting the following day if necessary. Figure 2 shows the leaf-breaking rings as well as some of the knives used for cutting broccoli with the bunching machines in the background. In Virginia, a typical harvest crew using the leaf-breaker method consists of seven people; two leaf-breakers walking in front, two cutters following the leaf-breakers, two riders bunching and boxing the broccoli, and one tractor driver (Maxey, 1987).

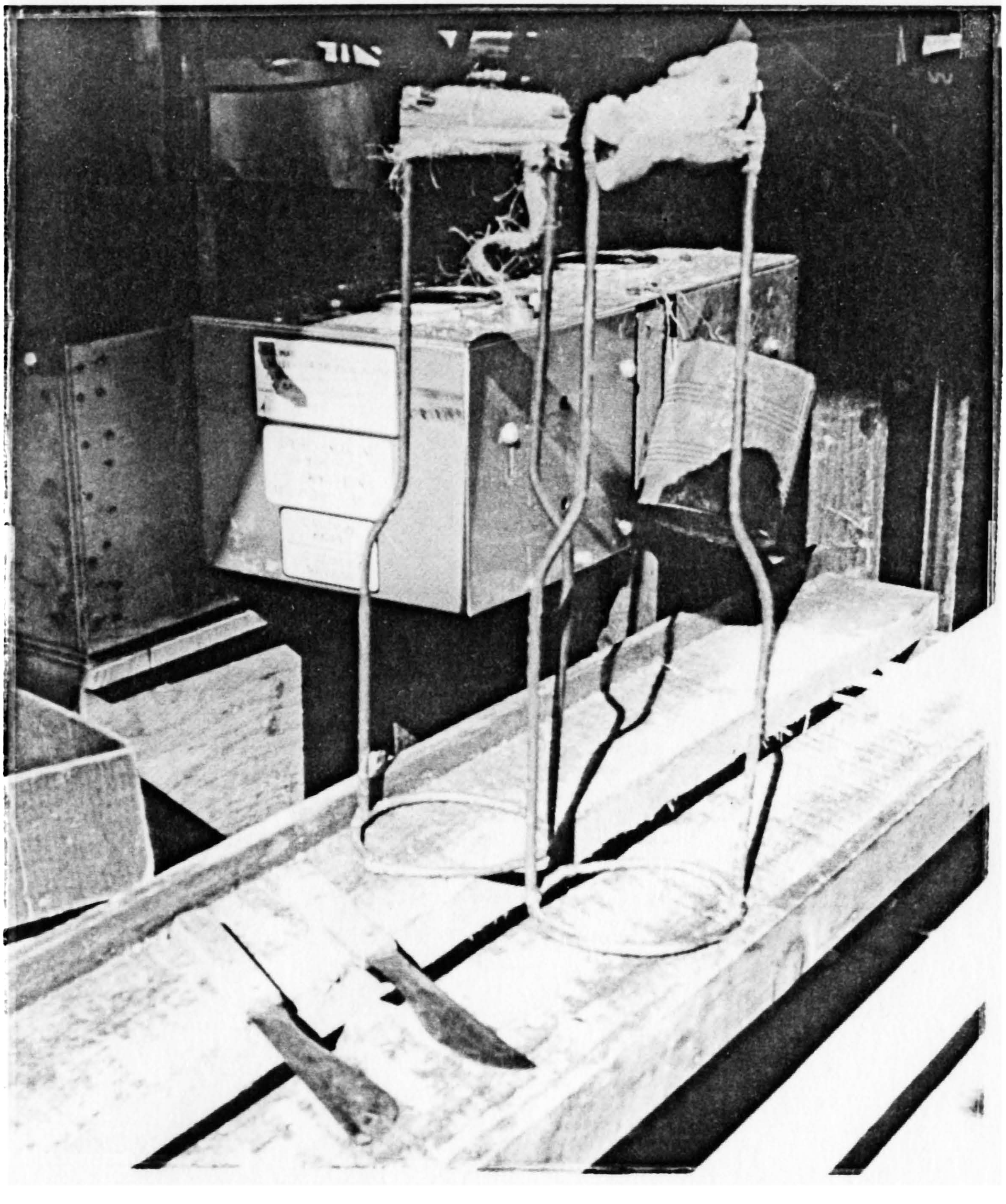


Figure 2. Leaf-breaking rings used to strip the leaves from broccoli stalks in the field.

By either method, the stalks are cut rather long, between 20 and 25 cm (8 and 10 in.) so that they can be trimmed evenly in the bunching machine. Cutting the broccoli with the stalk so long essentially destroys the plant. Fresh market broccoli is sold in bunches of 2 to 4 heads. Recommendations specify bunches weighing 0.57 or 0.68 kg (1.25 or 1.5 lb) with head diameters between 8 and 15 cm (3 and 6 in.). The boxes are packed either 14 (for the larger bunches) or 18 (for the smaller bunches) bunches per box, for an approximate box weight of 10 kg (22 lb) of broccoli, depending on buyer preference. Growers are advised to harvest heads when they first attain marketable size because the heads can overmature (flower) within several days, especially during hot weather (O'Dell et al., 1987).

3.2 Physical and Mechanical Properties

A study of the physical and mechanical properties of broccoli is needed in order to form a base of information for designing a selective harvester. Mohsenin and Gohlich (1962) stated "... to develop a machine for harvesting fruits and vegetables with minimum mechanical damage, it is essential to have a knowledge of those mechanical and physical properties which are significant in mechanically harvesting and handling the product." Mohsenin (1972) suggested size, shape, color, and surface conditions as physical characteristics that can be exploited for selective harvesting. Many mechanical properties of fruits and vegetables have been investigated, including modulus of elasticity, resistance to various types of loading, abrasion resistance, various types of stress or strength, cutting forces, coefficient of friction, and rolling resistance (Mohsenin and Gohlich, 1962; Mohsenin, 1972; Akritidis, 1974).

Chung (1982) evaluated yields of broccoli for the frozen market. His analysis included descriptive measurements of head diameter, butt diameter, evenness of bud size, cluster separation of the head, shape, and branching. These descriptors were scaled from 1 to 5 according to sketches and explanations of each rating. The measurements were used to summarize the quality and maturity of the broccoli spears grown under various planting conditions.

Salter et al., (1984) conducted an experiment to compare different agronomic treatments on a new cultivator of broccoli. His analysis included measurements of shoot fresh weight, trimmed head weight, head diameter, depth, and butt (stem) diameter. They did not mention how each measurement was taken, but they did reference Chung (1982) and probably based their measurements on his work.

Walton and Casada (1988) evaluated ten broccoli varieties for characteristics related to mechanical harvesting. They made several measurements of the broccoli plant and the cut head, including head height, plant width, head diameter, head length, stalk diameter, and head weight. The head diameter was taken as an average of the major and minor diameters. The stalk diameter was measured at the point of cutting. They did not report the criteria used to locate this point. They also determined the density of canopy, rating it by subjective visual observation with a 1 for low density, a 2 for medium density, and a 3 for high density.

Physical and mechanical properties related to mechanical harvesting have been investigated for other crops. Wright and Splinter (1966) reported on research conducted on the physical and mechanical properties of cabbage and on the development of an experimental cabbage harvester. Head diameter was measured as was plant stem diameter and length of leaf stem. Plant diameter, measured as the total width of the entire plant, was considered critical to the design of harvesting machinery gathering components. The force to cut the plant stem was described as "the force required to cut with knife-shaped blades through the region where the leaves are attached." The authors did not describe whether the force measurement was made in single shear or double shear or how the stem was supported.

Parsons and Rehkugler (1966) also investigated the physical properties of cabbage plants related to mechanical harvesting. They studied the geometrical relationship between the cabbage plant, ground location, and proper location for cutting. They measured head height, head diameter, stump diameter, and leaf stem thickness. They concluded that an automatically positioned cutter was not feasible due to irregularity in the measured geometrical relationship.

Stout et al., (1966) also worked on the development of a cabbage harvester. Physical measurements that they took included the force required to uproot a cabbage plant, head diameter, weight, distance from the soil surface to the bottom of lower leaves, and distance between the center line of the cabbage row to individual cabbage heads. They indicated that the force required to pull a cabbage plant from the soil depends on soil type, moisture content, cabbage variety, and direction of pull. They tried pulling the plant from the soil both horizontally and vertically. The maximum force that they measured was 498 N (112 lb) for pulling a cabbage horizontally from the ground, while the average required force from both directions was 334 N (75 lb).

Vick (1969) investigated the physical characteristics of okra plants and pods as they related to a specific mechanical harvesting method which involved the alteration of okra plants by pruning them to a central stem. He measured plant internode length, radial angle between successive okra pods, height of pods above the soil surface, and plant stem diameter at pod level on plants that had been subjected to the pruning culture. He found that the height of the first pod and the plant stem diameter were linear functions of plant density, while the angle between pods was affected by the okra variety.

Casada et al., (1966) studied the physical properties of burley tobacco related to harvester design. They measured the resistance of tobacco leaves to static and dynamic loads at different stages of wilting. They also determined the maximum angle that a leaf could be deflected without midrib breakage and measured the forces required to cause that deflection. Leaf resistance to loading was considered important relative to bruising that would show up after curing, while leaf deflection was considered a potential problem with any machine designed to harvest and handle tobacco stalks.

Hummel and Winn (1967) studied the cutting forces required to cut tobacco in the field and the relationship between stalk dimensions and recorded forces. Initial tests used three powered, notched counter blades with two blades mounted on one shaft spaced so that the other blade mounted on a second shaft passed between them. This double shear arrangement performed unsatisfactorily. The double coulter blades were replaced with a single smooth coulter blade. Strain gages were used to measure torques and the forces experienced by the coulter blades. They concluded that, as stem diameter increased, the torque on the notched coulter blade increased and components of force perpendicular and parallel to the direction of travel also increased.

Akritidis (1974) investigated the main mechanical factors influencing the cutting of maize stalks. He used a free-moving sharp blade to cut single maize stalks. Two springs provided the force to move the blade on a slider. The resistance force of the stalk and the cutting time were measured. He found that the energy required for the cut increased with the angle of inclination of the blade and with the age of the plant. The effect of the inclination angle of the blade indicated that compression rather than shearing was the prevailing phenomenon during the cutting process.

3.3 Mechanical Harvesting of Broccoli

Mechanizing the harvest of broccoli is very difficult because of the nature of the plant. Broccoli is a cole crop, which are vegetables of the species Brassica oleracea, including cabbage, cauliflower, brussel sprouts, kohlrabi, and kale (Ryder, 1979). Wilhoit and Vaughan (1988) listed four growth characteristics of cole crops that contribute to difficult harvesting requirements.

1. The harvested parts are vegetative rather than fruit, so the plant is usually destroyed during the harvest.

2. The plants do not mature uniformly, so they must be harvested selectively in several passes.

3. High plant populations are used for better yields, so harvesting must leave closely spaced neighboring plants unharmed.

4. Because the entire plant is harvested, further trimming of the harvested part is usually required to get it into marketable form.

Head lettuce is a high acreage crop with similar growth characteristics and harvesting requirements. Lettuce, cabbage, cauliflower, and broccoli all have similar requirements for some sort of butt and leaf trimming, although broccoli is unique in its requirement for leaf trimming along a stalk of some length.

The biggest constraint to mechanically harvesting broccoli is the requirement for selectivity due to nonuniform maturity. Selective multiple harvests are required to maximize yield. In Virginia, three or four harvests of the same planting over a period of four weeks or more are typical. Thompkins (1965) and Palevitch (1970) reported similar multiple harvest requirements in Washington and Israel, respectively. According to Cutcliffe (1975), six to nine cuttings were required for broccoli grown for processing in Prince Edward Island, while Brendler (1971) reported that broccoli grown for freezing in California was usually harvested two or three times over a two week period. Mechanizing the selective harvesting process is very difficult because an automatic selector is needed and because mature broccoli heads must be cut and collected without destroying adjacent immature heads that will be harvested later.

3.3.1 Once-Over Harvesting

Because of the difficulties of selective harvesting, broccoli harvest mechanization efforts have concentrated on once-over harvesting. Various studies have investigated ways of maximizing once-over harvest yields of broccoli through plant breeding, variety selection, and adjustments in cultural practices.

Borchers (1971) investigated uniformity of maturity and center head yield for selected broccoli varieties, inbreds, and hybrids. Center heads were harvested three times per week at the prime market stage of maturity. He used the standard deviation of the mean number of days from transplanting to harvest as a measure of uniformity of maturity. He found that hybrids bred from large headed inbreds generally had larger heads than their parents and that hybrids between uniformly maturing parents were also uniformly maturing. Borchers (1989) recently said that after many years working with broccoli, he believes that uniformity of maturity cannot be achieved even with a completely homozygous population because environmental effects are too strong.

Hulbert and Orton (1984) conducted breeding studies with direct-seeded broccoli. They used the standard deviation of the mean number of days from sowing to the mature marketable stage as a measure of uniformity of maturity. They found that genetic variation in uniformity of maturity was dependent on the environment. They also found that variation in maturity date under different environmental conditions could not be explained by temperature data. Their work pointed out the strong influence of environmental factors on uniformity of maturity in broccoli and the difficulty in characterizing these effects.

Palevitch (1970) investigated the effects of plant population and pattern on single harvest yields of broccoli. He found that higher yields were obtained by increasing the plant population density, especially through the use of spacings approaching equidistant arrangements. However, he also found that head size was generally smaller at higher plant population densities, particularly with reduced within-row spacing. His results showed no effect of changes in density on uniformity of maturity as measured by the percentage of marketable size heads in a single harvest.

Cutcliffe (1971) studied the effects of plant population, nitrogen, and harvest date on single harvest yields of broccoli. He found that plant population had only a slight effect on marketable yield while spear weight decreased and maturity was delayed as plant population increased. Uniformity of maturity, as measured by the percentage of marketable heads in a single harvest, was decreased as plant population density increased beyond 131,490 plants/ha (53,250 plants/acre). He used the percentage of heads that had flowered as an indicator of when to harvest and indicated that maximum single-harvest yields could be obtained when at least 11% of the plants had flowered. A later study by Cutcliffe (1975) found that single-harvest yields increased with decreased plant spacing for each of several varieties tested. His results also showed that spear weight and uniformity of maturity decreased with decreased plant spacing.

Chung (1982, 1985) investigated the effects of plant density and sowing time on once-over harvest yields of broccoli in Tasmania, Australia. He showed that there was an assymptotic yield-density relationship for three broccoli cultivators tested. He indicated that once-over harvesting at a stage when 10% less than the maximum marketable yield could be obtained would result in more efficient processing in the factory because of the minimization of the quantity of waste material harvested from over-mature plants.

Brendler (1970, 1971) reported the results of studies to evaluate the feasibility of using a once-over machine harvest for broccoli for freezing in California. The first year of the study, he used the Harvester variety of broccoli which was supposed to be especially good for mechanical harvesting because of quick maturity and long stems that would minimize the number of leaves attached to heads cut about 15 cm below the top of the head. He described the classes of broccoli used for freezing as spears, chop, and culls. For the first year, yields of spears and chop broccoli was slightly higher from plants spaced 14.5 cm (5.7 in.) than from plants spaced 8.6 cm (3.4 in.). The second year, the potential yield of spear grade broccoli from a once-over harvest reached 5835 kg/ha (5200 lb/acre) compared to an average yield of 5610 kg/ha (5000 lb/acre) for Ventura County, California.

Walton and Casada (1986) evaluated twelve different broccoli varieties for characteristics related to once-over mechanical harvesting. They measured several plant characteristics in the field, including head height, plant width, and density of canopy, and they also measured head diameter, stalk diameter and head weight after the head was cut. Uniform head height was considered desirable for mechanical harvesting. Several varieties showed good uniformity of head height and maturity, as measured by the percentage marketable heads harvested in a single cutting. Their study used transplanted broccoli at low population densities. As a result, head sizes were very large, with several varieties averaging as much as 0.45 kg (1 lb) per head.

Several attempts have been made to mechanically harvest broccoli nonselectively. According to Borchers (1989), brussel sprout harvesting machinery was tried on processing broccoli in Virginia in the 1960's. Apparently leaves were partially trimmed in a prior operation with a ring or circular cutting blade similar to that used for de-leafing brussel sprouts (Robertson, 1974). He did not know exactly how the harvesting machine functioned, but a later brussel sprout harvester used a rotating blade to sever the stalks near the ground, opposed lugged belts to support the stalks and hold them in an upright position, and a flighted elevator to convey the cut stalks for collection (Elridge, 1979).

An experimental one-row, once-over broccoli harvester was built and tested in Tennessee in 1985 (Coffey et al., 1988). In preliminary studies, a cutter bar on a greens harvester proved unsatisfactory for cutting broccoli. Circular saw blades worked much better, and the final unit used two 20 cm (8 in.) diameter saw blades. A conveyor received the broccoli after it was cut and elevated it onto another cross conveyor. The conveying system did not work satisfactorily because the 23 x 17 cm opening was not large enough to accommodate some of the larger broccoli heads. The development of this once-over harvester was discontinued after the 1986 season.

Casada et al., (1988) developed a tractor-mounted harvester for single pass harvesting of broccoli. This harvester also used a rotating circular saw (40 cm) to sever the heads and an elevating belt conveyor. An additional feature of the machine was an upper flight conveyor which swept the heads onto the elevating belt conveyor as they were severed from the plant. Harvest rates of 60 to 90 heads/min were reported, with only 2% of the heads unharvested by the machine. In two seasons of tests with the machine, the percentage of heads suffering discernible damage averaged 14.5%. Damage was confined to crushed florets and was considered to be generally slight.

The prospects for once-over mechanical harvesting of broccoli seem quite promising considering the simplicity of the mechanisms required for cutting and collecting the heads and the single-harvest yield results reported from several studies. The prospects seem especially promising for processed broccoli since each of these studies was conducted on broccoli for processing. Johnson and Zahara (1985) predicted that by 1990 20% of the broccoli grown for processing in the United States would be mechanically harvested. Yet at this time there has been no adoption of once-over mechanical harvesting of broccoli in the United States. The only reference worldwide to any commercial once-over mechanical harvesting is by Chung (1985) in Tasmania, Australia, but a recent inquiry indicated that once-over harvesting had not become prevalent there either.

The failure of once-over mechanical harvesting to be adopted may be due to several factors. The favorable single-harvest yields that have been reported may be misleading because broccoli for processing can be much smaller than would be acceptable for the fresh market. The wider acceptable size range would contribute to higher yields. Thompson and Taylor (1976) stated that spears with a head diameter as low as 25 mm (1 in.) were used for processing in Scotland. Brendler (1971) indicated that spear grade broccoli should have a stem diameter of only 18 mm (5/8 in.), and that even smaller size spears could be used for chop grade broccoli.

In the studies mentioned, high plant population densities were used to maximize single-harvest yields, but high population densities tend to increase competition. This increased competition leads to generally smaller heads and greater nonuniformity of maturity because individual plants are more likely to be subjected to growth limiting factors. Thus, even though single-harvest yields were maximized with high population densities, they are still likely to be substantially lower than multiple-harvest yields obtained with the same population densities.

Once-over machine harvested broccoli would probably require increased handling at the processing plant because of variable stalk length and leaves still attached to the stalk. If high plant population densities and once-over harvests are used, the yield will be composed of a much greater number of smaller broccoli heads, and a small head will require the same amount of handling for leaf and butt trimming as a larger head. With selective hand harvesting, the broccoli comes out of the field with most of the trimming already done, and the heads are larger and more uniform in size.

It may be that a combination of factors both at the producer end and at the processing end has kept once-over mechanical harvesting of processed broccoli from being adopted. For the producer, yields will be decreased with once-over harvesting because of the nonuniformity of maturity of the broccoli. For the processing plant, smaller, less uniform head sizes may contribute to increased handling requirements. Considering the dramatic shift in production from processed to fresh market broccoli, it now seems less likely that once-over mechanical harvesting of broccoli will become prevalent in the near future.

3.3.2 Selective Harvesting

Mechanization of the selective harvest of vegetables has proved to be very difficult. Mechanical harvesting has been successfully adopted for certain processed vegetables, including tomatoes, sweet corn, and cabbage (Johnson and Zahara, 1985), but once-over, destructive harvests are required. For fresh market vegetables, selective harvests are usually required. Attempts at mechanizing the selective harvest of several different vegetables have been made, although at this time no commercial vegetables are selectively harvested mechanically. Because so little research has been specifically directed at mechanizing the selective harvest of broccoli, a review of selective harvest concepts tried on certain other vegetables is useful in this study.

Two different concepts for selectively harvesting cantaloupes have been tried. O'Brien and Lingle (1965) reported on a selective cantaloupe harvesting concept that involved gently lifting vines trained to grow from one side of the bed and letting the mature melons detach themselves from underneath the vines by the force of their own weight. They developed a raking mechanism for training the vines in two or three passes throughout the growing season. In five harvests, the harvester recovered 72% as many marketable fruits as did five hand harvests.

Harriot et al., (1970) borrowed the above raking concept and used it not only to train the vines but to remove the mature melons from the vines as well. They used sloped beds and raked the melons down the slope. The fingers of the raking mechanism were made of stiff rubber. Their harvester recovered 67% as many marketable fruits as did eight hand harvests. A once-over mechanical harvest of cantaloupes has also been tried, although there is no processing of cantaloupes with the accompanying flexibility in size and quality requirements that make once-over harvesting practical. All of the mechanical harvesting concepts for cantaloupes involved considerable changes in cultural practices, and none of the concepts have been adopted.

The concept of using spaced fingers and a raking or stripping action to select mature fruit has been tried with different kinds of peppers. Fullilove and Futral (1972) investigated the use of horizontal spaced fingers mounted on roller chain and sprocket assemblies moving up an incline for harvesting the pimento, a medium-to-large variety of pepper widely grown for processing. Groundspeed was made equal to the rearward horizontal speed of the fingers so that the fingers only moved vertically relative to the pepper plants. Their work on this principle was abandoned due to various machine problems. However, Siow (1979) did further testing of this inclined raking concept applied to the selective harvest of smaller varieties of peppers. He conducted tests to study the effect of the diameter of the entry sprocket and to determine the optimum inclination angle and speed. Many problems were encountered with plant damage because all or most of a single plant tended to be squeezed between two fingers at the plant entry zone.

Lenker et al., (1973) investigated different systems for the selective mechanical harvesting of head lettuce. A system that used a knife powered by a hydraulic motor to cut the head and opposed rubber-fingered belts to collect the head proved most satisfactory. This system was incorporated into a prototype harvester and tried with two different selectors that had been developed earlier. One selector sized the heads mechanically with a pair of selection rollers, and the other used X-rays to sense a combination of size and density. The belts positioned above the head were able to lift the cut head up out of the row and caused no more damage to the head than hand harvesting. The complete harvesting system included extensive racks, platforms, and conveyors for carrying an entire crew to trim and package the lettuce. The lettuce cutting and collecting components could harvest the lettuce at a fast rate, but the harvester speed was limited by the trimming and packaging capacity of the crew. Turnaround time and uneven flow of lettuce also reduced the efficiency of the harvester. In tests with an experienced lettuce harvesting crew, the output per man hour with the harvester was only slightly better than for hand harvesting.

Lenker et al., (1978) developed a selective cauliflower harvester that used the same basic components as the selective lettuce harvester. The mechanical selector was used but the rollers were made much larger. An electrical signal from a potentiometer on the selection rollers indicated how far apart the rollers were opened by leaf-covered cauliflower heads. When the signal exceeded the adjustable threshold diameter, a solenoid value actuated a hydraulic motor which rotated a knife to cut the head. In tests the experimental cauliflower harvester selected and harvested heads as accurately and with as little damage to the harvested heads as a hand harvest crew. However, the harvester did damage unharvested plants during the harvest operation. In one test, an average of one leaf per unharvested plant was broken off, which was considered an acceptable level. In another test during a period when leaves were very succulent, an average of 6.8 leaves per unharvested plant were broken off by the harvester. This level of damage was considered severe.

The only other investigation that has considered the mechanization of the selective harvest of broccoli has been conducted in Maine (Soule et al., 1988; Soule and Sides, 1988). This investigation looked at engineering related to various aspects of the Maine broccoli industry and included the testing of leaf-stripping, stalk-cutting, and mature head sensing devices. A cage-like device was used for leaf-stripping by closing two inclined halves of a hexagonal plate just below the broccoli head and pushing downward to detach the leaves. The device proved to be awkward to position around the broccoli stem, although the stripping action was quick and effective once positioned. A simple hollow cylinder, 13 cm in diameter with padding on the lower edge and fitted with a long handle, was found to be just as effective as the more complicated device. A manually-directed cutting device with horizontal shears operated by squeezing a grip in the handle was also tried. Initial tests with the device showed it to be awkward to handle and rather slow. An additional problem was the difficulty in applying enough force by hand to fully sever the stalk (Soule, 1988).

Tests were also conducted to evaluate the potential for using light to sense the color of mature broccoli heads. A fiber-optic spectrophotometer was found to effectively sense differences in color under laboratory lighting conditions. However, no mention was made of how broccoli head color could be related to head size. Further testing of this system indicated that the use of color reflectance under the harsh light conditions in the field would not be feasible. Because of the lack of a feasible sensing system, the researchers in Maine plan to concentrate future efforts on the synthesis of a two-step harvesting system that includes a first selective harvest aided by some sort of cutting device followed by a second once-over mechanical harvest.

3.3.3 Mechanical Devices for Reducing Effort in Manual Operations

The work in Maine points out the difficulty in automating the selection of mature broccoli heads and the potential for using mechanical devices to augment rather than supplant the manual selective harvesting of broccoli. Mechanical devices that can reduce the effort required for manual operations, both harvesting and otherwise, have been developed for several crops. Chain saws for harvesting timber are an obvious example. Another example is the hand-held power equipment (electric, hydraulic, and pneumatic) that has been developed for pruning nut and fruit trees (Monroe and Peterson, 1977).

Swetnam et al., (1981) developed a self-propelled, self-steering burley tobacco harvesting aid with a powered circular sawblade for cutting the tobacco stalks. The harvesting aid held the tobacco sticks and allowed the operator to spear the tobacco stalks and dispose of the filled stick from a seated position. In tests with the machine, the harvest rate was about the same as by hand, but operators indicated that much less effort was required for machine harvest than for hand harvest.

O'Brien and Harriot (1975) developed a melon pickup machine for increasing the efficiency of harvesting cantaloupes in California. Before the use of tractor-drawn portable conveyor belts became prevalent, the harvest of cantaloupes involved pickers selecting mature fruits, placing them in a bag on their back, and carrying the bags over to a truck when they were full (34 kg). The work was so strenuous that most crews seldom worked past noon. The melon pickup machine had rubber-fingered pickup reels for collecting handpicked melons that had been placed in prepared furrows. Preliminary work with the machine indicated that it could substantially increase worker output by eliminating carrying and waiting time and reducing fatigue so that work could continue past midday.

The manual harvesting of broccoli can be difficult work. Although it does not involve activities that are especially strenuous, the repeated bending required to cut the broccoli heads can cause fatigue, and the leaf-stripping operation can be a strain on the hands if the leaf-stripping rings are not used. Cutting and leaf-stripping are two areas where mechanical devices could help to reduce the effort required for manually harvesting broccoli.

3.4 Digital Image Processing

The biggest constraint to the development of a fully automatic selective broccoli harvester is the mature head selection system. Recent decreases in computer costs and the development of specialized hardware and software have made digital image processing systems very promising for this application. Real-time digital image processing or machine vision systems have the potential to locate and identify broccoli heads against the background of plant foliage and decide if the head is large enough to be harvested.

A typical vision system consists of a high resolution camera, a frame grabber, an image processor, a host computer (minicomputer or microcomputer), and output modules for storage, access, and display. The camera senses the scene or the object and produces a continuous image. The frame grabber captures single images and digitizes them to form a matrix of discrete points or picture elements called pixels. The pixels are assigned gray levels to represent the light intensities of the image. The digitized image is then analyzed with image processing algorithms to yield information about the scene or object that is relevant to the requirements of the application (Cárdenas-Weber et al., 1988).

Resolution refers to the number of pixels used to digitize the image. Typical imaging devices have resolutions ranging from 64 x 64 to 512 x 512 pixels. The detail discriminating ability of the system improves as resolution increases, but the processing speed is reduced and the cost of the system increases due to additional hardware requirements (Awa, 1988).

With the advancement in electronics technology, digital image processing applications in agriculture have been receiving increasing attention. The applications can be classified into three main categories: 1) image analysis, 2) robotic vision, and 3) inspection (Kranzler, 1985). Image analysis involves the use of techniques to gain information from the digitized image itself. The first applications of digital image processing in agriculture, that of analyzing remotely sensed satellite data for information about land use, are examples of image analysis (Whittaker et al., 1984). Robotic vision refers to the use of camera-coupled image processing to provide real-time visual information for directing the actions of robots or robotic devices. Industrial applications of robotic vision abound, and there has been a lot of research recently into agricultural applications, especially related to fruit tree harvesting (Groover et al., 1986; Tutle, 1984). Inspection applications of digital image processing involve quality verification, defect removal, and sorting and grading of raw and processed products. Commercial systems have been developed for sorting cucumbers and detecting broken egg yolks and for several other food processing applications (Kranzler, 1985).

A great deal of research in recent years has been devoted to the development of robotic fruit and vegetable harvesters. For this type of application, a machine vision system must be able to identify and accurately locate the harvestable fruit with respect to a known coordinate system. To do this, the system must be able to distinguish the fruit from the background of leaves and branches. With fruit and vegetables, there are three main characteristics that have potential for use in distinguishing the fruit from the background; color, shape, and texture. For fruit tree harvester research, color, or spectral reflectance, is the parameter that has been used most often for fruit identification.

Parrish and Goksel (1977) tested the concept of automated apple harvesting by constructing a complete, working model of an automated harvesting mechanism and operating it on a three-dimensional apple tree model. They used color filters on a black-and-white television camera to enhance the contrast of the apples against the background. The video output from their TV camera was compared to a preset threshold level and put directly into binary form. The generated digital image was 144 (horizontal) by 82 (vertical) pixels. Because of the color difference between the apples and the leaves, the filtered image contained some unwanted background and noise but mainly only apples. Pattern recognition algorithms used the property of roundness, as quantified by the thinness ratio, to separate the apples from the remaining background and to locate the centroids. Their experimental system worked well on scenes arranged in arbitrary configurations. The picture-processing routine recognized all single apples and the model successfully simulated harvesting by touching these apples with a touch sensor at the arm tip. The picture-processing routine was less successful at locating overlapping apples.

Sites and Delwiche (1985) investigated the use of computer vision systems for locating fruit on peach and apple trees. They used a system with a resolution of 128 by 128 pixels that produced a 256 gray level image. They tested their system to find the best field of view resolution, the best color bandpass filters, and the best lighting techniques. They also investigated system flexibility by obtaining and processing images of different peach and apple cultivars at various stages of maturity. They used weighting, thresholding, and smoothing techniques to produce a binary image of fruit with some background and noise, and a segmentation technique to identify objects in the image. Algorithms using various characteristics, including area, perimeter, compactness, elongation, and several central invariant moments, were used to classify the objects in the image. Objects were classified as "single fruit", "multiple fruit", "poorly identified fruit", "leaf noise" and "noise". They found that 5 mm/pixel resolution, which allowed an image to cover a 0.64 m by 0.64 m portion of the tree, gave the best results. Red filters with passbands of 610 nm to 690 nm were found to work best. Night operation produced the best quality images due to better illumination control. Quality images were also obtained during the day when structured lighting was used. The system was able to distinguish peaches better than apples because of different spectral characteristics and leaf positioning. The system was not sensitive to differences in maturity of peaches.

D'Esnon et al., (1987) developed a robotic apple harvester that located individual fruit in a two-dimensional plane, directed a picking manipulator along the line of sight to the fruit until contact was made, picked the fruit using a suction action, and deposited the fruit on a conveyor. The harvester was mounted on a self-propelled frame that was automatically guided by ultrasonic telemeters. The harvester, designed to pick at the rate of two hand pickers, could pick one fruit every four seconds. The image processing system used three micro-cameras joined side by side which looked at the same image through optical filters of different wavelengths. Ratio's of the signals from the three cameras were compared with reference values to identify and locate objects that were apples. The reference values were adjusted at the beginning of the work by viewing objects known to be apples. The harvesting robot was designed to operate without added light sources. Harvesting results were good as long as natural lighting conditions were acceptable. Night operation with artificial lighting was tried with favorable results.

Whittaker et al., (1987) addressed the problem of locating green tomatoes under natural light conditions for possible robotic harvesting. Because spectral differences were likely to be insufficient for using color to distinguish the tomatoes, they investigated image analysis algorithms using a modified circular Hough transform to locate tomatoes based on shape. The transform searched images for curves contributing to an underlying circle. A gradient operator calculated the direction gradient for all edges. Circles were identified and located by checking the accumulation of intersecting vectors in the direction of the gradients for points within a specified radius range. A high accumulation indicated a high probability that a circle existed centered at that point in the original image. An advantage of this method was that arcs lying on the periphery of a circle did not have to be concurrent, so obscurations of the perimeter were acceptable. They tested the method on scenes of hydroponic tomatoes grown in a greenhouse filmed with a video camera without color filtering. Each scene was digitized into 256 gray levels in a 512 column by 480 row matrix of pixels. They found that the circular Hough transform method successfully located and identified a high percentage of the tomatoes under greenhouse lighting conditions. However, their algorithms were computationally intensive and could not yet be performed in real time.

When color cannot be used to distinguish objects, shape may be an acceptable alternative if the objects have distinct edges and definable shapes. For certain image analysis and inspection applications, shape is not involved, and textural analysis methods have been used with digital image processing to obtain the required information. A textural analysis method that has been applied to measuring crop residue cover, analyzing aerial and satellite images, and identifying different plant cultivars is the co-occurrence matrix.

Haralick et al., (1973) studied the use of textural features in category-identification tasks with three types of image data: photomicrographs of sandstone, aerial photographs, and satellite images.

They used a co-occurrence matrix, also known as gray-tone, spatial-dependence matrix, to describe texture. The matrix is an estimate of the probability of pixel having a gray level i and a "nearest neighbor" pixel having a gray level j, dependent on the distance and angle between the pixels. One advantage of using this method to quantify texture is that it is computationally much more efficient than other methods such as Fourier transforms. They used textural features based on the co-occurrence matrices in classification algorithms and obtained good accuracy in category-identification tasks with all three types of image data.

Han and Hayes (1988) used co-occurrence matrices to discriminate textural differences between soil and residue/canopy to measure the percent soil cover. They used a three by three co-occurrence matrix so that each pixel had eight nearest neighbors and each image region had eight different co-occurrence matrices. The summation of these eight matrices was used as a template for textural features. Because the dimension of the co-occurrence matrix is the same as the number of gray levels, they reduced the original 256 gray levels down to eight gray levels using a gray level normalization process. They used learning sessions before analyzing images to classify different soil and residue/canopy areas with one of five different sample co-occurrence matrices. The use of textural differences was advantageous for analyzing scenes with little color difference between soil and residue/canopy areas, and it eliminated the need for a color imaging system. They found that the use of an image processing procedure based on textural features compared favorably with the photographic grid method for measuring percent soil cover and was subject to less human error.

Shearer and Holmes (1987) used co-occurrence matrices in conjunction with color image processing to discriminate between seven cultivars of containerized nursery stock. They included color in their textural analysis method, instead of just the variation of relative intensity of reflected light as was used for other textural analysis studies, to make the classification method even more accurate. They used a set of three filters of different spectral transmittance to obtain tristimulus values for each pixel. The tristimulus values are the relative intensities of three different primary color spectra required to produce the same color as that viewed. Three sets of color co-occurrence matrices, representing the attributes of intensity, saturation, and hue, were required instead of just one as with the gray-tone spatial-dependence matrix. Eleven different textural features were determined for each of the three attributes, and discriminant analysis was used to select the best set of features for classification models. Fifty observations from each of the seven cultivars were used for testing their system. The observations were divided into training and test data sets, each containing twenty five observations. Their results showed that a model containing only intensity features (nine of them) could accurately classify the plants 81.7% of the time, while the accuracy was improved to 90.9% when both intensity and hue features were included in the model (three intensity features, four hue features).

Another textural analysis method similar to the co-occurrence matrix involves the use of gray level run lengths. Galloway (1975) described the use of features based on gray level run length for visual texture analysis and reported on the use of those features for classifying a set of terrain samples similar to the one studied by Haralick et al. (1973). A gray level run length is a set of consecutive, collinear pixels having the same gray level value. The length of the run is the number of pixels in the run. A gray level run length matrix can be calculated for runs in any given direction. The matrix element specifies the number of times that a picture contains a run of a certain length and gray level in a given direction. Galloway computed five different functions, analogous to those used by Haralick et al. (1973) for co-occurrence matrices, to obtain numerical texture measures from the gray level run length matrices. The functions emphasized short runs, long runs, gray level nonuniformity, run length nonuniformity and structure nonlinearity. Images digitized into 64 x 64 pixels with 64 gray levels were analyzed. Gray level run length matrices, which were 8 x 6 arrays containing 8 gray levels groups and 6 run length groups, were calculated. Good results for the classification of different terrain types were obtained by plotting either different directions of the same function or the same direction of two different functions against each other.

Chapter IV

PHYSICAL AND MECHANICAL PROPERTIES

There are many physical and mechanical properties of broccoli plants that may affect the design of mechanisms for selectively harvesting broccoli. Among the most important are the forces required to cut the stalk, various plant size and geometric characteristics, and characteristics related to the visual selection of the mature head. Some of these properties relate directly to the design of a powered cutting device. Many properties are also important to the consideration of methods and machinery for completely automating the selective harvest of broccoli.

4.1 Broccoli Stalk Cutting Forces

Force requirements for cutting broccoli stalks are relevant to the design and operation of cutting mechanisms. Knowledge about cutting forces is especially important to the design of a manually-directed cutting device since the size and weight of such a device must be minimized. As a preliminary step to designing a powered broccoli cutting device, an investigation of the forces associated with the high speed cutting of broccoli stalks was conducted in the fall of 1986. High speeds were used in order to simulate a more realistic cutting action. An apparatus employing a hydraulic system and high speed transducers was used to conduct an experiment to measure broccoli stalk cutting forces. The specific objectives of this experiment were as follows:

1. To measure the forces required to cut broccoli stalks with a knife blade moving at high speeds.

2. To determine the effect of the knife speed on the cutting force.

3. To determine the effect of stalk dimensions on the cutting force.

4.1.1 Equipment

In order to simulate the high speed cutting of broccoli stalks, an apparatus capable of moving a knife at a high constant speed was needed. A method of measuring the forces on a knife moving at high speeds was also needed. A universal testing machine, with a maximum crosshead speed of 500 mm/min (0.83 cm/s), was much too slow, so a different apparatus for measuring the cutting force was required.

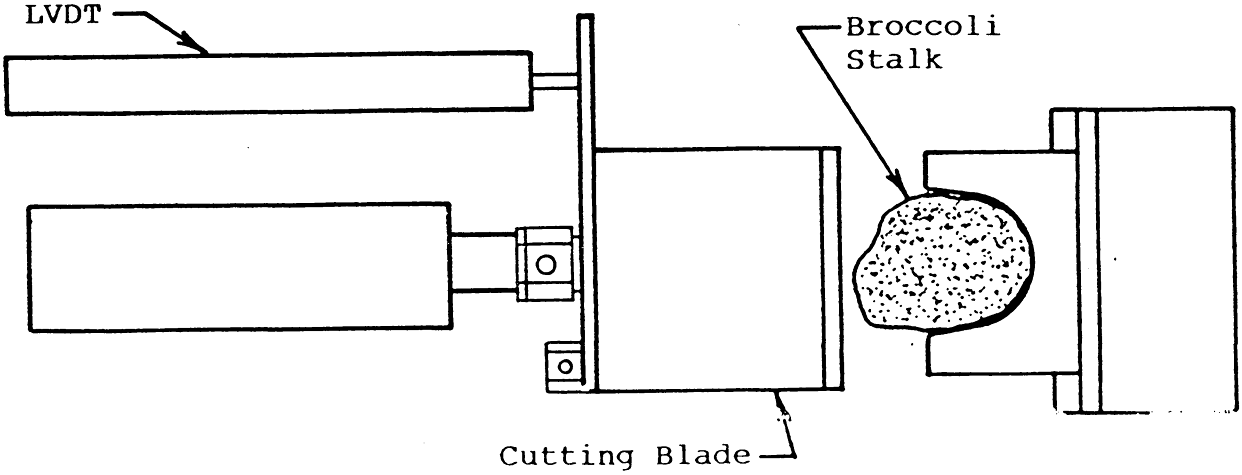
Brandon et al., (1986) investigated loading rate effects on soil strength parameters in order to improve past soil-tillage tool interaction models that have been mostly static or quasi-static in nature. They developed a test apparatus for conducting direct shear tests at high speeds (18 to 27 cm/s) while measuring acceleration, displacement, and force. A hydraulic cylinder actuated by a solenoid-operated, closed-center directional control valve provided nearly instantaneous movement of the upper half of a direct shear box at a constant velocity. Since this apparatus was very well suited to the measurement of forces associated with cutting broccoli stalks at high speeds, it was used after making major modifications to the shearing apparatus.

The modifications included mounting a knife on the end of the hydraulic cylinder to cut broccoli stems perpendicular to the longitudinal axis of the broccoli stalk (Figure 3). The knife had an even thickness of 3 mm (1/8″) and was beveled on both sides to give an edge angle of 45 degrees. The broccoli stalk was supported by a stationary countershear that consisted of wooden blocks with concave cavities attached to a metal backplate (Figure 3). The blocks were positioned so that the knife moved between them in what Persson (1987) described as a scissor cut. The stalks were placed within the cavities and pushed against the blocks for cutting. The knife moved in a plane 2.5 cm (1″) above a metal plate on which the end of the stalk rested.

A hydraulic system with a flow control valve was used to power the hydraulic cylinder at three different speeds. A solenoid-operated, closed-center, directional control valve was employed to actuate the hydraulic cylinder. The knife speed was kept constant from test to test by maintaining flow through the hydraulic system relief valve and by setting the flow control valve.

The transducers and associated instrumentation had to be capable of measuring knife forces and displacement at the required speed (up to 27 cm/s). A piezoelectric load cell (Kistler 9712A500) was mounted between the knife and the cylinder rod to measure the cutting force. Mounted on the vertical edge of the knife was a piezotron accelerometer (Kistler 818). Both of these transducers have very fast response times, with load cell response frequency equal to 15 kHz and that of the accelerometer equal to 5 kHz. Excitation for the load cell and the accelerometer was provided by piezotron couplers (Kistler 5112). A linear variance displacement transducer (LVDT) (Daytronic DS 500) was mounted rigidly to the stand and pushed against the vertical edge of the knife. LVDT excitation was accomplished with a converter (Sanborn 592-300). A waveform analyzer (Data Precision 6000) was used to record the data from the transducers. The LVDT was calibrated by measuring the transducer output at several displacements and then using linear regression techniques to provide a calibration curve.

TOP VIEW



SIDE VIEW

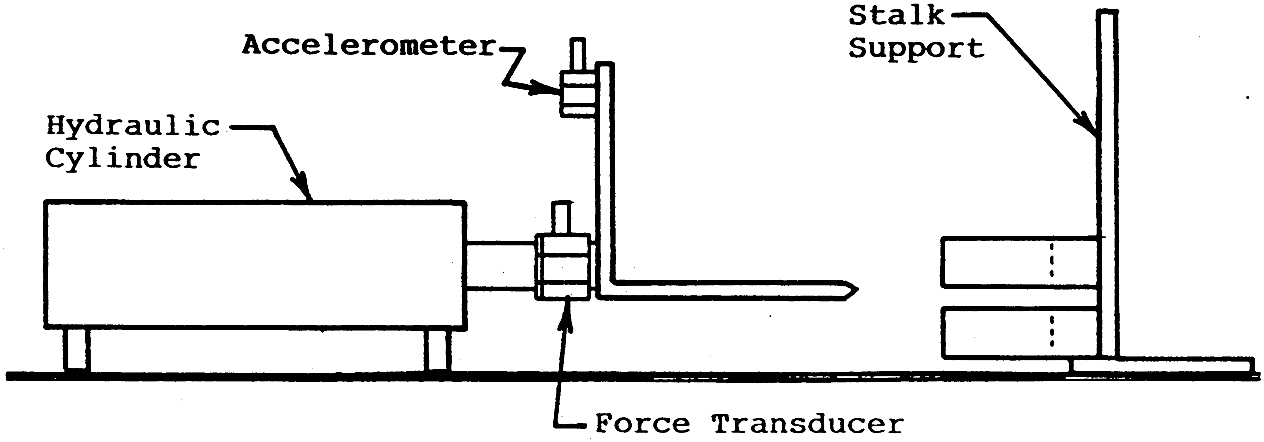


Figure 3. Stalk cutting apparatus for experiment to measure broccoli stalk cutting forces.

4.1.2 Experimental Procedure

The apparatus for measuring broccoli stalk cutting forces was tested by cutting a sample of broccoli stalks purchased from a local supermarket on the day of the test. Fresh field broccoli was not available at that time because it was so late in the season (December). Data collected from broccoli tested several days after harvest was not considered to accurately reflect field conditions, but it was assumed to be acceptable for showing the effects of certain variables on the cutting force and for estimating cutting force magnitudes for machine design purposes.

To test for the effect of speed on the cutting force, broccoli stalks were cut at three different knife speeds, and the results were statistically analyzed using a single factor analysis of variance. Five stalks, randomly selected from the sample purchased from the store, were cut at each speed for a total of fifteen cut stalks. Each stalk was placed in the cutting apparatus and held firmly against the base and the wooden blocks. The cylinder was then activated by the directional control valve to make the cut. Data were recorded and scrutinized on the screen of the Data Precision 6000. Graphs of displacement, speed, acceleration, and force were examined to determine if all of the transducers were functioning properly. Data for critical areas were then transmitted to the printer.

After the stalk was cut, the cut end was placed on paper and the perimeter traced. The axial direction of the hydraulic cylinder was noted with an arrow on this trace. The trace was used to find several stalk dimensions for use as possible covariates for statistically analyzing the results of the tests. A representative stalk trace with the dimensions obtained is shown in Figure 4. A planimeter was used to find the cross-sectional area of each stalk. The other dimensions that were measured are as follows:

D1 = Stalk diameter in the direction of blade travel.

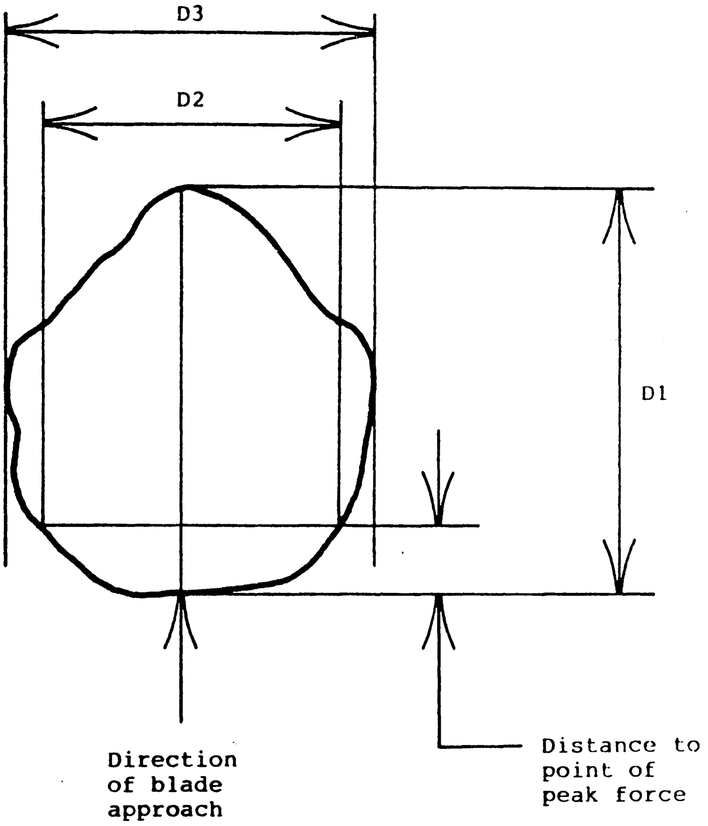


Figure 4. Stalk perimeter trace and characteristic dimensions.

D2 = Stalk diameter perpendicular to the direction of blade travel at the point of peak force.

D3 = Maximum stalk diameter perpendicular to the direction of blade travel.

The three blade speeds were set by adjusting the valve controlling the flow to the hydraulic cylinder. The settings were selected to give a range of speeds appropriate for a realistic cutting process. The tests were denoted A(1-5) for the slower speed, B(1-5) for the middle speed and C(1-5) for the higher speed. The speed for each test was calculated by two different methods. A regression was done on selected points from the displacement data measured by the LVDT to find the slope of a line, giving the average speed for the test. The acceleration data measured by the accelerometer were integrated to give another measure of the speed. Points from the same time period were used for all of the speed calculations. The standard deviation for the speeds within each treatment was calculated for the two methods, and the speed results are shown in Table 1. Since displacement speeds had a lower standard of deviation, they were used in the analysis.

4.1.3 Results and Discussion

Force results for one of the tests (B3) are shown in Figure 5. The force, as measured by the load cell and plotted as a function of time, clearly shows a peak of 78.3 N (17.6 lbf) near 30 ms. The peak force, recorded for each test, ranged from 59.2 N (13.3 lbf) for test C2 to 114 N (25.6lbf) for test B1 (Table 2). The average peak force for each of the three knife speeds was 94.6 N, 93.1 N and 73.4 N for speed levels A, B and C, respectively. These levels correspond to average knife speeds of 9.40, 16.2 and 25.6 cm/s. The time at the peak force was also recorded so that the location at which the peak force occurred could be calculated from the displacement data. The peak force occurred near the front of the stalk in all of the tests (Figure 4).

Table 1. Knife speed obtained by integrating acceleration and differentiating displacement for broccoli shear tests.

Test	Acceleration Speed (cm/s)	Displacement Speed (cm/s)
A1	9.45	8.76
A2	12.5	9.04
A3	8.84	8.69
A4	8.84	11.3
A5	9.14	9.09
	Mean = 9.75	Mean = 9.40
	S[1] = 0.61	S = 0.43
B1	18.0	15.5
B2	14.6	16.1
B3	14.6	16.1
B4	18.6	16.3
B5	21.3	16.9
	Mean = 17.4	Mean = 16.2
	S = 1.1	S = 0.20
C1	18.3	26.0
C2	24.4	25.4
C3	20.4	25.5
C4	24.7	25.7
C5	25.3	25.5
	Mean = 22.61	Mean = 25.6
	S = 3.1	S = 0.25

[1] Standard deviation.

Table 2. Summary of broccoli shear tests results.

Test	Area (cm^2)	D1 (cm)	D2 (cm)	D3 (cm)	Peak Force (N)
A1	6.33	2.84	2.24	2.82	101.0
A2	6.60	3.05	2.34	2.84	92.3
A3	5.20	2.57	1.65	2.59	97.8
A4	8.48	3.51	3.05	3.56	104.0
A5	3.45	2.06	2.03	2.13	77.8
Mean	6.01	2.81	2.26	2.79	94.6
B1	5.52	2.62	2.36	2.62	114.0
B2	6.70	2.57	3.12	3.40	101.0
B3	4.00	2.18	2.08	2.41	78.3
B4	5.76	2.39	2.29	3.12	99.5
B5	3.90	2.31	2.03	2.24	73.4
Mean	5.18	2.41	2.50	2.76	93.1
C1	5.72	2.82	1.96	2.64	69.9
C2	4.58	2.41	1.78	2.51	59.2
C3	6.92	3.02	2.16	3.07	82.4
C4	4.68	2.16	2.34	2.97	85.6
C5	4.75	2.54	1.93	2.26	69.9
Mean	5.33	2.59	2.03	2.76	73.4

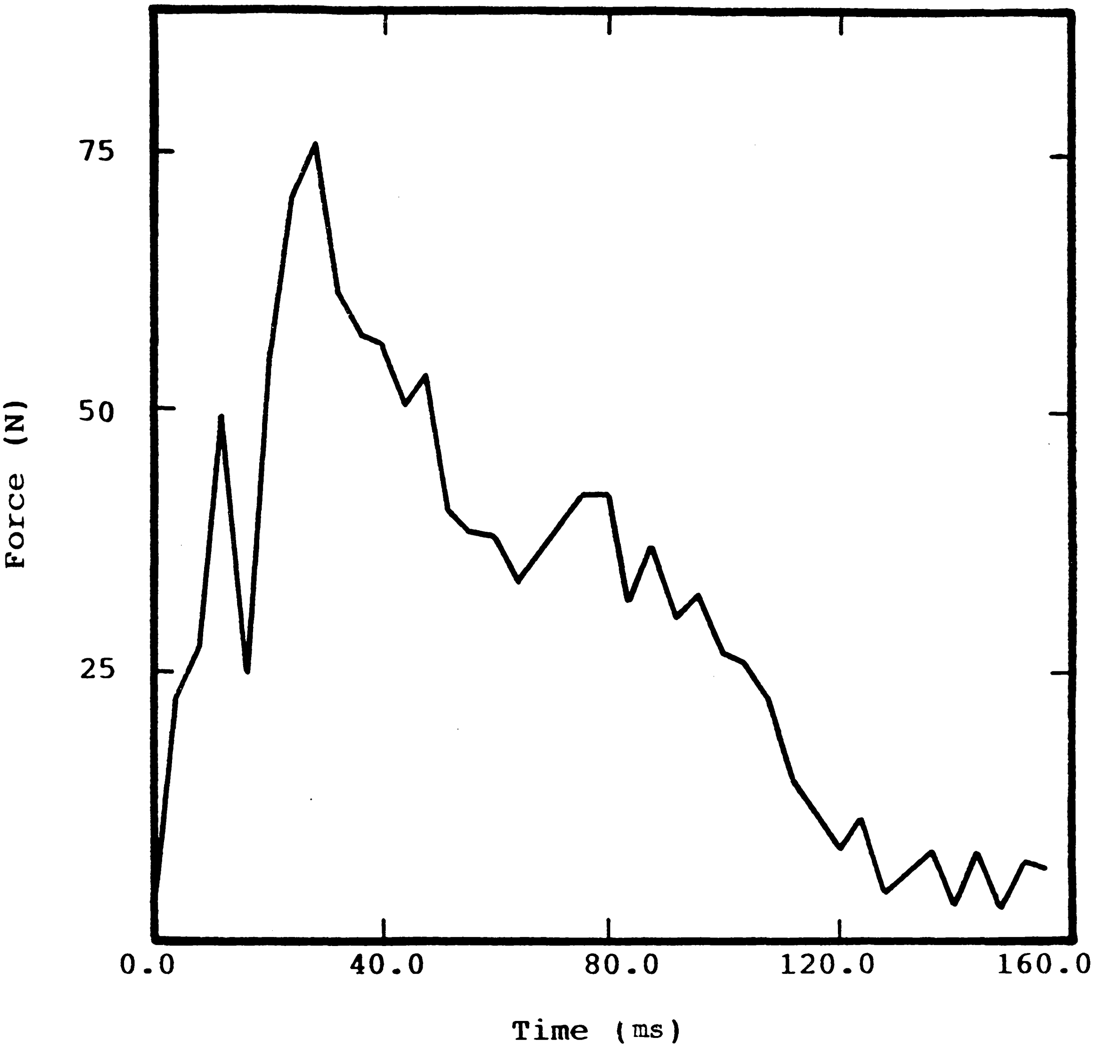


Figure 5. Plot of force versus time for broccoli shear test B3.

Peak force, speed, and stalk dimension results are shown in Table 2. An analysis of variance on models containing the speed with each of the covariates separately showed no significance for the interaction terms, indicating that each of the stalk dimensions could be used as covariates. However, none of the stalk dimensions could be included together as covariates in the same model because of the high correlation between area and diameter measurements.

The analyses of variance for each of the individual models containing speed and one of the covariates are shown in Table 3. The effect of speed was significant at the 5% alpha level in all cases. The effects of all the covariates except D1 were significant at the 5% alpha level. Among the different stalk dimensions, D3 gave the highest significance for the speed treatments. Area gave the next highest significance. Plots of the peak force versus area and the perpendicular diameter D3, and their corresponding linear regression lines, are shown in Figures 6 and 7, respectively, for the three speed levels A, B and C.

The statistical analyses show that the blade speed had a significant effect on the force to cut a broccoli stalk. It is interesting to note from Figures 6 and 7 that the first two speed treatments, at 9.40 and 16.2 cm/s, gave about the same force results. But the force decreased when the speed was increased to 25.6 cm/s. The effect of blade and cylinder inertia would account for an inverse relationship between speed and force if the knife speed decreased during the cut. Displacement data however, showed that the knife speed remained relatively constant during the cut, so this was not the case. A lower force requirement above a certain speed, such as 20 cm/s, could be important for machine design purposes.

Results for the covariates indicate that the resistance to cutting the stalk comes from a combination of the effects of the tough outer fibers of the stalk and the friction of the blade sliding across the stalk. For a larger measurement of the perpendicular diameter D3, the blade should be presented with a blunter section of stalk so that there are more of the outer fibers to cut at one time. The fact that the peak force occurred near the front edge of the stalk rather than at the middle supports this conclusion. On the other hand, the larger the cross-sectional area, the greater the

Table 3. Analysis of variance table for broccoli shear tests.

Model	Source	Degrees of Freedom	Type III Sum of Squares	F	Prob(F)
Force = Area, Speed	Area	1	46.57	9.25	.0112
	Speed	2	61.24	6.08	.0166
Force = D1, Speed	D1	1	24.73	3.52	.0873
	Speed	2	71.38	5.09	.0273
Force = D2, Speed	D2	1	37.37	10.52	.0101
	Speed	2	39.44	5.55	.0269
Force = D3, Speed	D3	1	49.99	10.59	.0077
	Speed	2	69.10	7.32	.0095

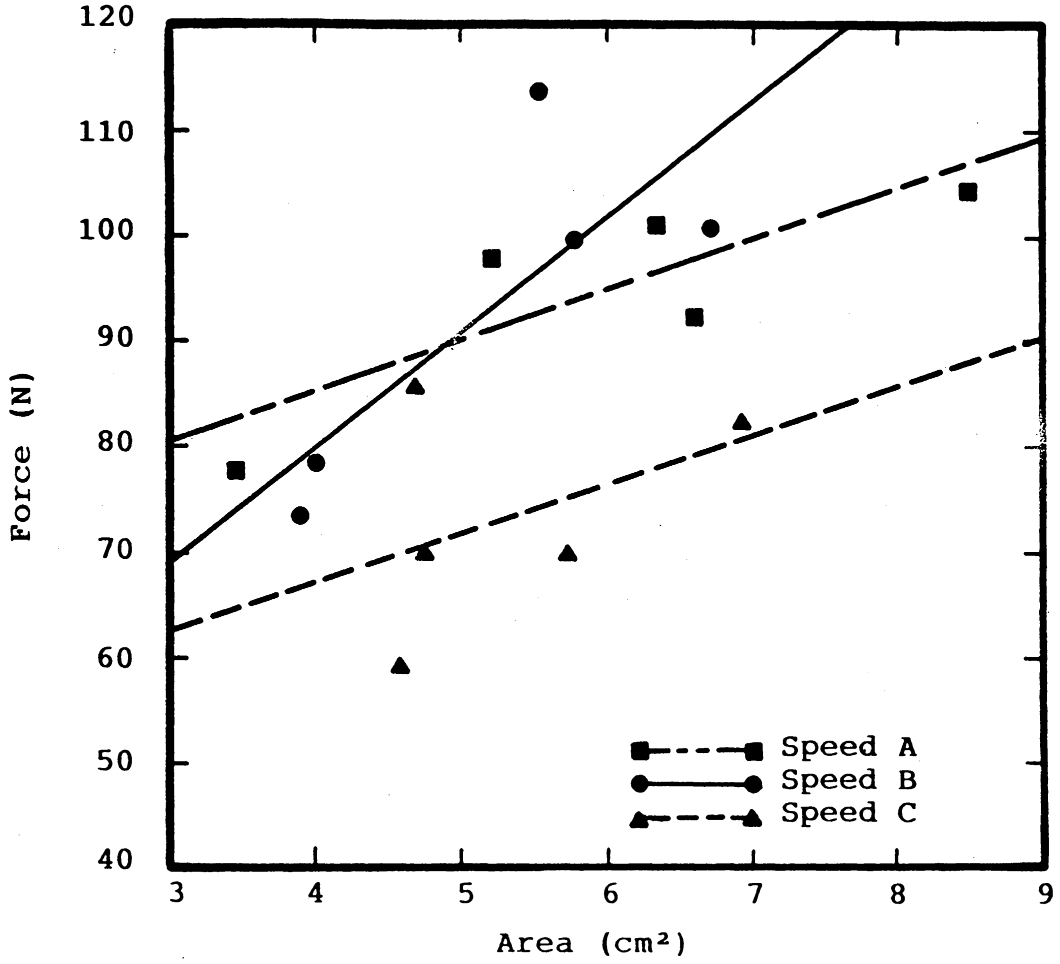


Figure 6. Plot of force versus stalk cross-sectional area for three speed levels.

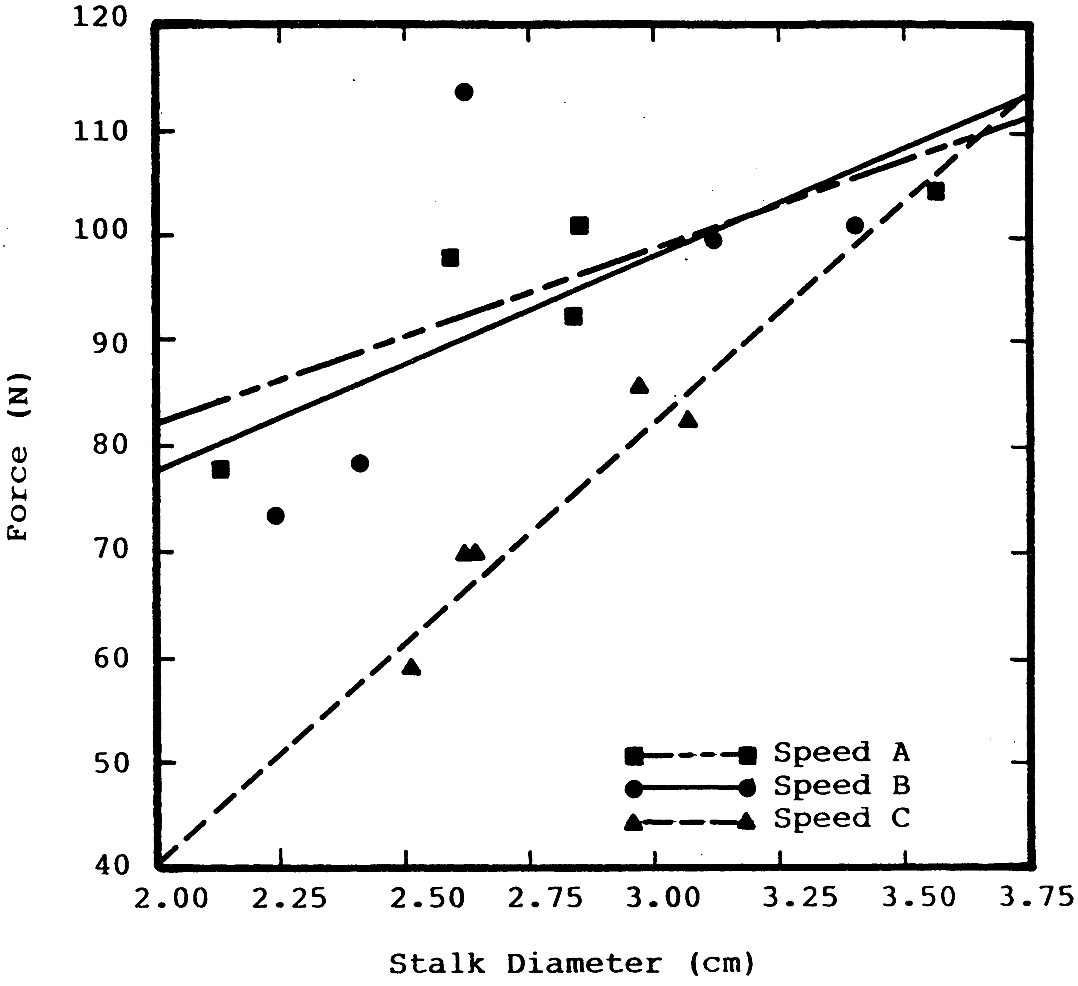


Figure 7. Plot of force versus the perpendicular diameter D3 for three speed levels.

contact area and the friction force between the stalk and the blade. The fact that the cutting force was lower at the highest speed may reflect a change in the coefficient of kinematic friction above a certain speed. The effect of speed had a higher statistical significance for the model containing the perpendicular diameter D3 as a covariate, possibly indicating that the resistance due to the outer fibers is more significant than that due to friction.

4.1.4 Conclusions

The apparatus used for this experiment worked very well. The arrangement of the hydraulic cylinder and piezoelectric load cells provided a means of measuring the forces associated with a high speed cutting process. The results of this experiment cannot be taken as directly representing field conditions because the test material was not fresh from the field. However, the results do give an indication of the factors involved in the cutting process as well as force and knife speed magnitudes.

The following conclusions were reached based on the results of this experiment:

1. The force required to cut a broccoli stalk was significantly affected by the speed of the cutting blade.

2. The smallest force required was for the highest blade speed (25.6 cm/s).

3. The cutting force peaked when the blade was near the front edge of the stalk cross-section.

4. The cutting force was significantly affected by the stalk diameter measured perpendicular to the direction of blade travel.

5. The cutting force was significantly affected by the cross-sectional area of the stalk.

Some of these results are directly applicable to the design of a powered broccoli cutting device. The fact that the cutting force decreased as the blade speed increased above 25 cm/s indicates that the blade speed for a cutting device should be as fast as possible. This result is consistent with the need for near instantaneous blade motion in an intermittently operating cutting device designed to speed up the manual harvesting process. The probable effect of the tough outer fibers on the required cutting force indicates that the edge angle of the blade should be as small as possible. This assumption is consistent with the results of Akritidis (1974) with maize stalks.

4.2 Broccoli Plant Measurements

There are many characteristics of broccoli plants growing in the field that may affect the design and operation of harvesting mechanisms. Broccoli head and plant dimensions and their relationships may be important to the size and orientation of machinery components for harvesting and handling broccoli in the field. These relationships may also be important in evaluating the feasibility of different concepts for automated mature head selection. Visual characteristics of the broccoli head in the field also relate to mature head selection, either by human or machine vision. Finally, the effects of different planting arrangements or densities on plant characteristics may be important in considering the feasibility of different principles for mechanical selective harvesters.

Physical properties measurements were made on broccoli plots used for harvest tests with the powered cutting device in 1987 and 1988. In 1987, a preliminary investigation of physical properties was made on the guard rows of broccoli plots planted in three different patterns for harvest tests. In 1988, a more complete set of measurements was taken on broccoli planted in different arrangements and densities. In 1988, the measurements were made on a separate plot from the ones used for harvest tests, although measurements were also taken on a large number of heads from one planting arrangement that were harvested with the cutting device. The objectives of the field study on the physical characteristics of broccoli were as follows:

1. To measure height, head diameter, stalk diameter and weight of broccoli heads and to determine the effects of different planting arrangements, population densities and harvest times on these dimensions.

2. To determine how well different physical characteristics were correlated in order to evaluate alternate criteria for mature head selection.

3. To assess the visual accessibility of broccoli heads in the field viewed from above and to determine the effects of different planting arrangements, population densities and harvest times on this parameter.

4.2.1 1987 Season

4.2.1.1 Procedure

Physical properties measurements were made on broccoli (cv. Emperor) in the fall of 1987. The broccoli was planted in three blocks at the Virginia Tech Horticulture Farm, with three different planting patterns within each block, for harvest tests with the broccoli cutting device described in Chapter 5. The three planting patterns were A) double rows 30 cm (12 in.) apart with an in-row spacing of 15 cm (6 in.), B) triple rows 53 cm (21 in.) apart with an in-row spacing of 15 cm (6 in.) and C) triple rows 30 cm (12 in.) apart with an in-row spacing of 23 cm (9 in.). The plots were overseeded and hand-thinned to the desired spacing. Planting patterns A and C were on 106 cm (42 in.) centers, and the rows of planting pattern B represented a solid planting across the field, so the plant population density was the same for all three patterns.

The plots used for the harvest tests were 12.2 m (40 ft.) long. Samples of marketable size broccoli heads were taken from guard rows of these plots three times, at approximately the same time as the harvests with the broccoli cutting device. Two samples of five adjacent mature heads were taken from the guard rows. The height to the top of the head was measured and the visual accessibility rating given for each head prior to cutting. The visual accessibility refers to how easily a broccoli head can be distinguished from the foliage around and above it when viewed from above. A rating of 0, 0.5, or 1 was given corresponding to the head being completely obstructed from view, partially obstructed but substantially visible, and completely visible, respectively. After being cut, each head was marked, and head and stalk diameter measurements were made in the lab. Heads were kept in refrigerated storage until the measurements were made. Marking the heads allowed records to be kept of all the measurements corresponding to each individual head. Head diameter measurements were made in the directions of the major and minor axis. The stalk diameter measurements, made at the point where the stalk was cut, were also made in the directions of the major and minor axis.

For the samples taken at the time of the first harvest, heads were cut at a point 18 cm (7 in.) below the top of the head. This point corresponds to the location where stalks are usually cut in the bunching machines. For the second and third harvests, the heads were cut at a uniform level 13 cm (5 in.) above the ground. The method of measurement was changed because of the nonuniform shape of the broccoli stalk. As shown in Figure 8, the stalk starts out very narrow near the ground, increases in size moving up the stalk, and then decreases again before a final increase in size where the branching of the stalks begins. Because of the variability in head height, a stalk diameter measurement made at a uniform distance below the top of the head would not be representative of actual stalk size because of the dependence on the proximity of the point of maximum girth.

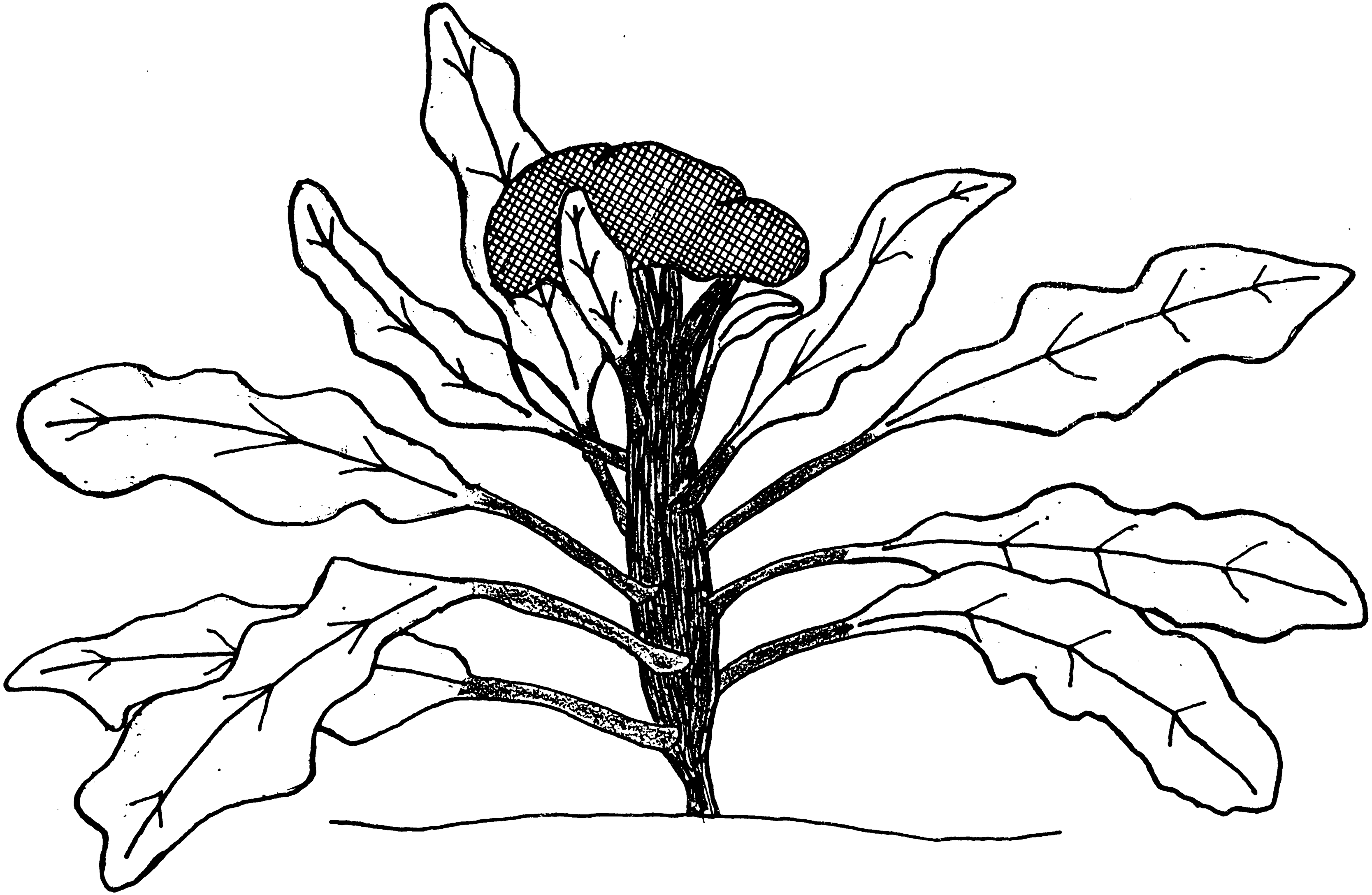


Figure 8. Broccoli plant side view showing stalk shape and leaf positioning.

4.2.1.2 Results and Discussion

The physical properties investigation conducted in 1987 was an initial attempt at measuring broccoli physical properties, and because of various difficulties, only abbreviated results were obtained. Complete sets of samples were not obtained for each of the three planting pattern treatments in a block over all three harvests. Therefore, the effect of the three harvest times could not be statistically analyzed. However, two sets of complete samples for an entire block for one of the harvests were obtained. The results of these samples are useful in examining the effects of the planting patterns on the physical properties.

Table 4 shows the results for the first harvest from block 2. The results were analyzed statistically as a one-way analysis of variance with three planting pattern treatments and a sample size of ten heads for each treatment. The physical properties measurements for this block and harvest are shown in Appendix A. Only the height was significantly affected by the planting pattern $[P(f) = 0.0113]$. There were no statistical differences in head diameter, stalk diameter, or visual accessibility among the planting arrangements. The tallest heads were in planting pattern A, which had the closest spacing of the plants. Closer spacing would tend to force the plants to grow taller because of the competition for sunlight.

The results for block 3 for the third harvest are shown in the lower part of Table 4. The physical properties measurements for this block and harvest are also shown in Appendix A. None of the physical properties were significantly affected by the planting pattern. Only height came close to being significant $[P(f) = 0.1016]$. Planting pattern A had the tallest heads, the same as for the first harvest in block 2.

Looking at the two sets of results for the planting patterns, it appears that the heads were taller, the stalk diameter lower and the visual accessibility higher for the third harvest than for the first. However, these data are from different blocks, so a valid comparison cannot be made. Since

Table 4. Broccoli physical properties results for different planting patterns for the 1987 season.

	Planting Pattern	Height (cm)	Head Diameter (cm)	Stalk Diameter (cm)	Visual Accessibility[1]
Block 2, First Harvest	A	38.4 a[2]	10.0 NS[3]	3.32 NS	0.50 NS
	B	35.3 b	10.0	3.27	0.70
	C	36.8 b	10.1	3.19	0.60
Block 3, Third Harvest	A	40.6 NS	10.4 NS	2.82 NS	0.85 NS
	B	37.3	9.9	2.94	0.75
	C	39.4	10.4	3.05	0.95

[1] Ratings of 0, 0.5, or 1 were given for totally obstructed, partially obstructed, or totally unobstructed view of the broccoli head in the field.

[2] Values followed by the same letter are not significantly different ($\alpha = 0.05$) by Duncan's Multiple Range Test.

[3] Factor effect nonsignificant at the $\alpha = 0.05$ level.

there are not complete sets of samples from a single block over all three harvests, these apparent trends cannot be validated statistically. However, there are some incomplete sets of samples that can be used for comparing two out of the three harvests.

Table 5 shows the results for measurements made from some of the plots in block 3 for the first and third harvests and block 2 for the first and second harvests. The results for the stalk diameter were not included because of the different methods used for measurement. In block 3, the heads were substantially taller for the third harvest. Head diameter and visual accessibility were also greater by the third harvest, although to a much lesser extent. In block 2, all three parameters increased somewhat from the first harvest to the second. The results parallel those from block 3, with height, head diameter and visual accessibility increasing with successive harvests, although the increases were smaller because only one harvest had been completed.

Of all the physical properties measurements, only the height showed much of a response to changes in planting pattern. The heads were tallest in planting pattern A, which had the closest spacing of plants. Planting pattern C had the second tallest heads and planting pattern B the shortest heads in both sets of planting pattern results. The fact that planting pattern B had the same in-row plant spacing (15 cm) as pattern A, but much wider row spacing (53 cm) than either pattern A or C, indicates that the height was more strongly affected by the between row spacing than the in-row plant spacing.

The heads also appeared to be taller later in the season. Increased height later in the season would be expected considering the competition among the plants. Heads harvested later in the season were from plants that were slower to mature. Those plants would be crowded out initially by the faster maturing plants, and they would not receive the sunlight they needed to achieve full head development until they had grown taller.

The other parameters showed very little response to either changes in planting pattern or different harvest times. Visual accessibility was not significantly affected by the planting pattern.

Table 5. A comparison of broccoli physical properties results for different harvests for the 1987 season.

	Harvest	Plant Measurements		
		Height (cm)	Head Diameter (cm)	Visual Accessibility[1]
Block 3	1	34.9	9.9	0.70
	3	40.0	10.4	0.88
Block 2	1	37.6	10.1	0.55
	2	38.9	10.6	0.58

[1] Ratings of 0, 0.5, or 1 were given for totally obstructed, partially obstructed, or totally unobstructed view of the broccoli head in the field.

For these tests, the density was constant for all three planting patterns, even though the spacing and configuration were different. Visual accessibility may be more responsive to differences in plant population density. Visual accessibility did appear to increase with successive harvests, but a more substantial increase would have been expected considering the clearing out of the plots that occurred with successive harvests.

The lack of response of head and stalk diameter measurements is an indication of the extreme variability in broccoli growth and maturity, but it also reflects problems in measurement methods. To look at the effect of harvest time on stalk diameter, the method of measurement must be kept constant from harvest to harvest. Head diameter measurements were made only on mature heads, and therefore may not be representative of the actual response of head size to factors such as planting arrangement and harvest time because the number of heads harvested was not considered. If one plot yields many more mature heads than other, that plot obviously has larger heads overall at the time of that harvest even if the average mature head diameter is the same.

There are physical properties results other than factor effects that may relate to the mechanization of the selective harvest of broccoli. The distribution of visual accessibility ratings gives an indication of the feasibility of using machine vision for automated mature head selection. For block 2, first harvest, only 5 of 30 heads received a visual accessibility rating of 0, for totally obstructed view. For block 3, third harvest, only 1 of 30 heads received a 0 (see Appendix A). Assuming that a machine vision system can determine head size even if the view is partially obstructed, a high percentage of heads receiving a 0.5 or 1 rating indicates good potential for the application of machine vision.

Correlations between different parameters may be important in determining whether alternate criteria can be used for mature head selection. The determination of head maturity (or harvestability) is based primarily on head diameter, but if parameters such as height or stalk diameter were closely correlated to head diameter, it might be possible to develop selection systems based on these parameters instead of head diameter. Correlations were checked between the various parameters for each of the samples of 10 broccoli heads from 1987 season. No high correlations, as measured by Pearson's correlation coefficient, resulted between any two of the physical properties. A better determination of correlations could have been made with a much larger number of head measurements, but the various samples could not properly be pooled because of the different planting patterns, blocks and harvests.

4.2.2 1988 Season

4.2.2.1 Experimental Procedure

Physical properties measurements were made on broccoli (cv. Packman) during the 1988 season. The broccoli was planted at the same time as broccoli grown for testing the cutting device, but this year a separate block was planted specifically for the physical properties measurements. The factors used in 1988 included double-row spacings of 30 and 46 cm (12 and 18 in.) and in-row plant spacings of 15, 23 and 30 cm (6, 9 and 12 in.), as well as three different harvest times. The three in-row spacings gave plant population densities of 109,300, 71,300 and 54,600 plants/ha for double-rows planted on 122 cm (48 in.) centers.

The plots for the six planting treatments were randomly located in the block. Each of the plots was 4.9 m (16 ft.) long. Marketable size broccoli heads were harvested from the plots three times, at approximately the same times as the harvests with the broccoli cutting device. All of the mature heads were harvested each time, rather than just a sample as was done the previous season, so that the number of heads harvested from each treatment could be considered in the analysis. Height, visual accessibility, and head diameter measurements were made on each broccoli plant in the same way as in the 1987 investigation. All broccoli stalks were cut long in the field and trimmed to a length of 18 cm (7 in.) after they were brought into the lab. The stalk diameter measurements were made at the point where the stalk was trimmed. This length is approximately the lower limit of the length of broccoli stalks that have been bunched and trimmed in a bunching machine. An additional measurement made in 1988 was the weight of each head. The weight was determined after the stalk was trimmed to the uniform length.

No records were kept on corresponding measurements in the separate plot because these measurements were to be used only for analyses of variance for determining the effects of various factors. Another set of measurements, made on broccoli plants from the cutting device harvest test plots, was used to investigate correlations between measured parameters. These measurements were made on broccoli from the three plots used for the treatment combination of 30 cm double-row spacing and 15 cm in-row spacing. This treatment combination is the planting arrangement most commonly used commercially, although commercial fields are usually not overseeded and hand-thinned, and therefore have somewhat lower plant populations. Measurements of height and visual accessibility were made on all the mature broccoli heads from one of the two double-rows in each of the three plots just prior to the cutting device harvest tests. The heads were marked by attaching a numbered sticker to the underside of the broccoli head. After harvesting with the cutting device, the marked broccoli heads were separated from the other heads and brought into the lab for head diameter, stalk diameter, and weight measurements. The same methods were used for these measurements as were used with the broccoli from the separate plot.

4.2.2.2 Results and Discussion

The results of the factorial experiment investigating broccoli physical properties conducted during the fall of 1988 are summarized in Table 6. The physical properties measurements are shown in Appendix B. The results for each of the broccoli plant measurements (height, head diameter, stalk diameter, weight and visual accessibility) were analyzed as a three-way analysis of variance with the factors harvest, plant spacing (or population density) and double-row spacing.

Table 6. Broccoli physical properties results for 3 different factors (harvest, plant spacing, and spacing) for the 1988 season.

Factors	Plant Measurements				
	Height (cm)	Head Diameter (cm)	Stalk Diameter (cm)	Weight (g)	Visual Accessibility[1]
Harvest					
1	30.45 a[2]	10.18 NS[3]	3.40 a	183 a	0.68 a
2	34.42 b	10.53	2.91 b	177 a	0.72 a
3	35.91 b	10.24	2.58 c	145 b	0.84 b
Plant Spacing (cm)					
15	36.24 a	10.13 NS	2.73 a	152 a	0.70 NS
23	33.58 b	10.65	2.97 b	178 b	0.74
30	31.20 c	10.33	3.15 b	183 b	0.81
Row Spacing (cm)					
30	34.37 a	10.40 NS	2.90 NS	169 NS	0.73 NS
46	33.46 b	10.33	2.95	169	0.76

[1] Ratings of 0, 0.5, or 1 were given for totally obstructed, partially obstructed, or totally unobstructed view respectively, of the broccoli head in the field.

[2] Values followed by the same letter are not significantly different ($\alpha = 0.05$) by pairwise t-test of the least squares means.

[3] Factor effect nonsignificant at the $\alpha = 0.05$ level.

Where factors had a statistically significant effect on the measured parameter at the $\alpha = 0.05$ level, a pairwise comparison of the least squares means of individual factor levels was done using a t-test. The t-test and least squares means were used to account for differences in sample sizes.

Looking at the different measured parameters, the height was the most strongly affected by all three factors. The effect of the harvest was very highly significant $[P(f) = 0.0001]$, with the heads getting taller later in the season. The effect of the plant spacing was also very highly significant $[P(f) = 0.0001]$, with the heads taller at the closer plant spacing (or higher plant population). The effect of the double-row spacing was also significant $[P(f) = 0.0092]$, although to a lesser extent. At the closer double-row spacing (30 cm), the heads averaged only about 1 cm taller than at the wider row spacing (46 cm). The statistical significance of all of the possible interactions between the factors was also checked. Only the in-row plant spacing by double-row spacing interaction was significant $[P(f) = 0.0151]$. A plot of the height versus the in-row plant spacing for each of the two double-row spacings is shown in Figure 9. The interaction is due to the change in the relationship between the heights at the two double-row spacings over the three plant spacings. The plants were taller at the closer double-row spacing for all three plant spacings, but the difference was much greater at the 23 cm plant spacing than at the 23 cm or 30 cm plant spacings.

The head diameter was the least affected of all of the measured parameters by the three factors. None of the factors significantly affected the head diameter, and the results suggest no trends in the measured head diameter due to the factors. None of the interactions between factors were significant either.

The stalk diameter and weight showed high levels of response to all the factors except row spacing. The stalk diameter was very significantly affected by the harvest $[P(f) = 0.0001]$, with the diameter decreasing substantially with each harvest. The response of the weight to harvest was nearly the same $[P(f) = 0.0001]$, although the weight decreased more from the second to the third harvest. Stalk diameter and weight were also similarly affected by the plant spacing. For the stalk diameter, $P(f) = 0.0133$, and the stalk diameter increased as the plant spacing increased, especially

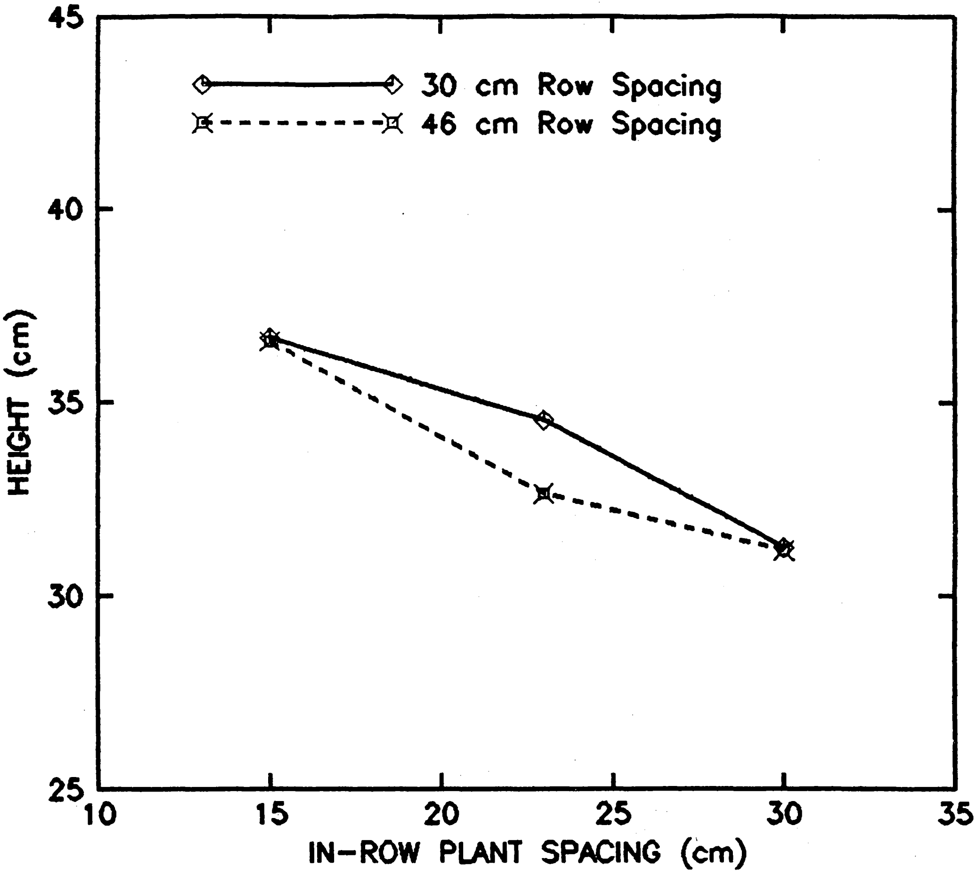


Figure 9. Height versus plant spacing for broccoli planted in two double-row spacings.

from 15 to 23 cm. For the weight, $P(f) = 0.021$, and the weight also increased as the plant spacing increased, especially from 15 to 23 cm. Neither of the parameters were affected by the row spacing. Of all the possible interactions for these two parameters, only the harvest by double-row spacing interaction for the weight was close to being statistically significant [$P(f) = 0.0564$]. A plot of weight versus harvest for each of the two row spacings is shown in Figure 10. The overall decrease in weight with each successive harvest can be seen. The interaction is due to the reversal of the average weights for the two double-row spacings. The closer double-row spacing (30 cm) had the heavier heads during the first and third harvests, but the wider spacing (46 cm) had the heavier heads during the second harvest.

The only factor to significantly affect the visual accessibility was the harvest [$P(f) = 0.0074$]. The visual accessibility increased with successive harvests, especially from the second to the third harvest. The visual accessibility was not significantly affected by either the in-row plant spacing or the double-row spacing, although the results indicate a trend toward increased visual accessibility as the plant spacing increased, as would be expected. The harvest by row spacing interaction was the only interaction close to being statistically significant [$P(f) = 0.0540$] for this parameter. Figure 11 shows a plot of visual accessibility versus harvest for the two double-row spacings. Interestingly, the visual accessibility shows a strong, uniform increase with successive harvests for the closer double-row spacing (30 cm), but little or no increase with successive harvests for the wider spacing (46 cm).

The harvest had the greatest effect on the measured parameters of all of the factors. Height and visual accessibility increased with successive harvests, and stalk diameter and weight decreased. The height and visual accessibility results confirm the trends indicated from the 1987 results. The fact that the physical properties of the broccoli plants were so strongly affected by the harvest may be very important to the design of selective harvest machinery because certain machinery components may require adjustment from one harvest to the next. The big change in physical properties from the beginning to the end of the harvest season may be especially important to the consider-

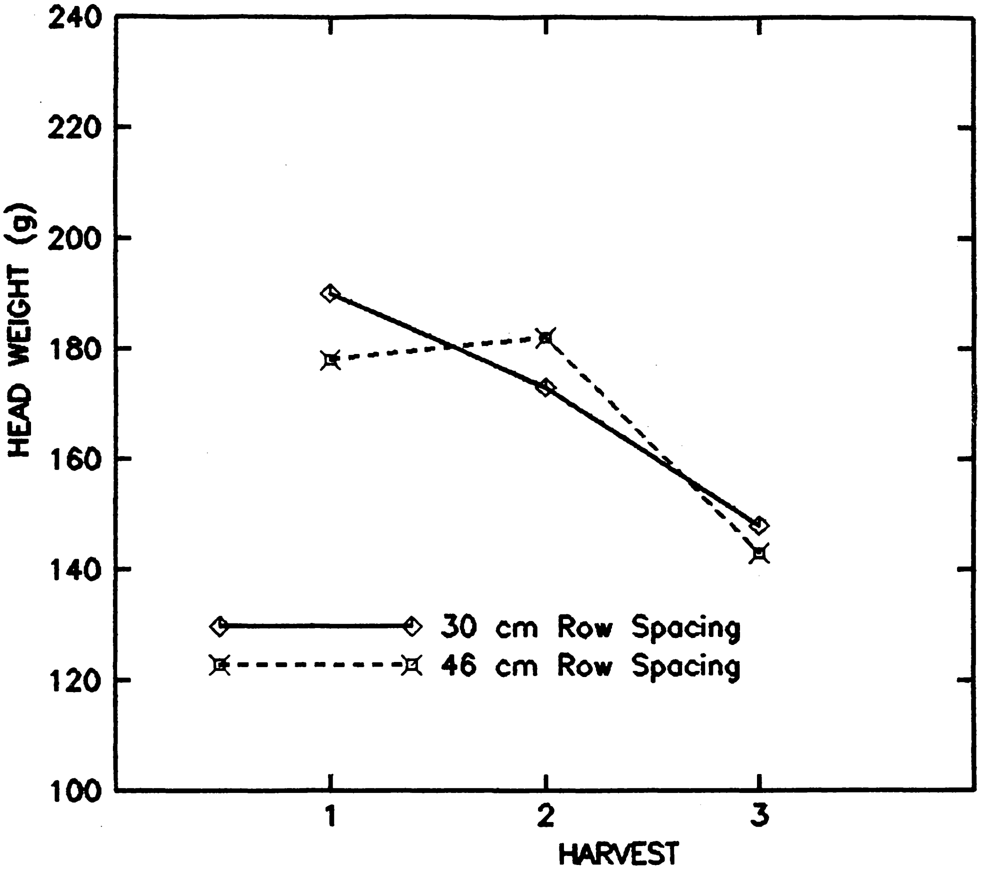


Figure 10. Head weight versus harvest for broccoli planted in two double-row spacings.

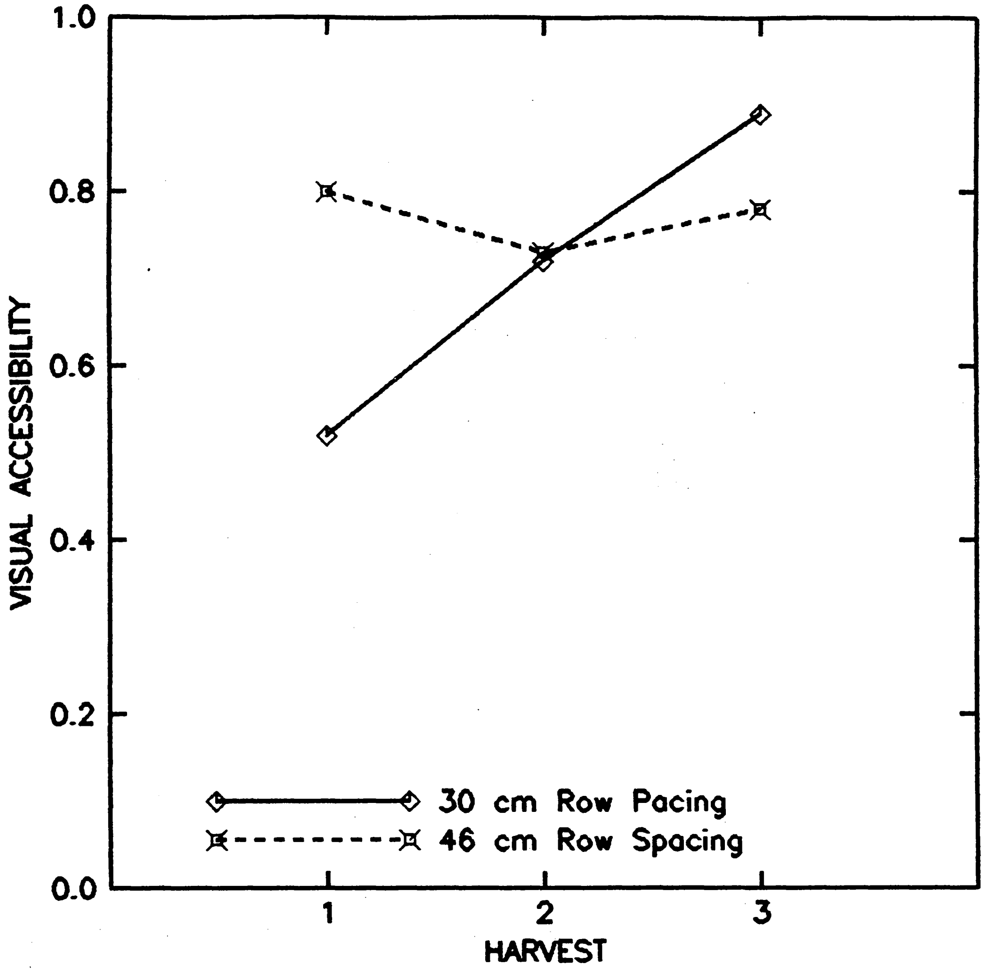


Figure 11. Visual accessibility versus harvest for broccoli planted in two double-row spacings.

ation of a two-step harvesting system where the final harvest is done with a once-over mechanical harvester.

The in-row plant spacing also strongly affected several of the measured parameters. The height decreased substantially as the plant spacing increased, and the stalk diameter and weight increased, especially as the plant spacing increased from 15 to 23 cm. The double-row spacing, on the other hand, had little effect on the measured parameters. Only the height was significantly affected, with the heads somewhat taller at the closer row spacing. These results seem to contradict the 1987 results, when the row spacing appeared to have a stronger effect on the height than the in-row spacing. However, the plant population was held constant for the different planting arrangements in 1987, while the plant population decreased from 109,300 to 71,300 to 54,600 plants/ha as the in-row plant spacing increased from 15 to 23 to 30 cm in 1988. It is the plant population, rather than the spacing, that so strongly affected the physical properties. This result is consistent with past studies (Palevitch, 1970; Cutcliffe, 1971). The increased competition at higher population densities led to taller, lighter heads with thinner stalks. These results could be important to the consideration of certain selective harvesting techniques, if there were advantages to taller heads or thinner stalks for instance, although other effects due to population density or spacing would have to be considered as well.

The lack of apparent response of the head diameter to any of the factors has already been mentioned. This lack of response is partially due to the subjective nature of mature broccoli head selection. Selection is based solely on subjectively chosen size criteria. As such, head diameter measurements are likely to reflect the accuracy of the selection process and the amount of time between harvests regardless of different factors. The lack of response is also indicative of the problem inherent in comparing head diameter averages without considering the number of heads. Head diameter measurements were made only on mature heads, and the different treatment combinations yielded different numbers of heads. As an additional indication of the effects of the factors, it is important to look at the results for the number of heads harvested from the different treatment combinations.

Table 7. Number of heads harvested for different treatment combinations of harvest, plant spacing, row spacing for the 1988 season.

Factors	Plant Spacing (cm) 15	 23	 30	Total
Harvest				
1	11[1]	22	23	56
2	40	38	32	110
3	41	22	7	70
Row Spacing (cm)				
30	45	40	32	117
46	47	42	30	119
Total	92	82	62	236

[1] Average number of broccoli heads harvested from each block for that treatment combination.

Table 7 shows the results for the number of heads harvested for the harvest by in-row plant spacing and double-row spacing by in-row plant spacing combinations as well as the totals for the three factors. The number of heads harvested was very different for the different plant spacings, as would be expected because of the differences in population. The harvest appears to have had a substantial effect on the number of heads, but the effect was different for the different plant spacings. A graph of the number of heads versus the harvest for each of the three plant spacings is shown in Figure 12. For the 15 cm plant spacing, very few heads were harvested during the first harvest, and then the number of heads increased substantially for the second and third harvest. For the 30 cm plant spacing, the results are the reverse of the 15 cm results, but with a lower number of heads overall. A lot of heads were harvested during the first and second harvests, and very few were harvested during the third harvest. At the 23 cm plant spacing, the number of heads harvested was more evenly distributed among the three harvests, although it peaked during the second harvest.

It appears that head maturity was delayed but uniformity increased at the 15 cm plant spacing, since 81 out of 92 heads (88%) were harvested during the last two harvests. Actually, the apparent increased uniformity is somewhat misleading since only 80% (92 out of 115) of the possible heads were harvested during the three harvests at the 15 cm spacing. Head maturity increased and uniformity increased at the 30 cm spacing, since 55 out of 62 heads (90%) were harvested during the first two harvests. Overall, 89% (62 out of 70) of the possible heads were harvested during the three harvests at the 30 cm spacing. The 23 cm spacing had the highest total percentage of possible heads harvested during the three harvests with 91% (82 out of 90).

The yield results are shown in Table 8 and Figure 13. The yield results for the different plant spacings parallel the results for the number of heads, with reversed trends for the 15 and 30 cm spacings for the different harvests. The overall yield was much higher for the second harvest than for the first and third. The 23 cm plant spacing gave the highest overall yield. The yield for the 15 cm spacing was almost as high, and that of the 30 cm spacing was much lower.

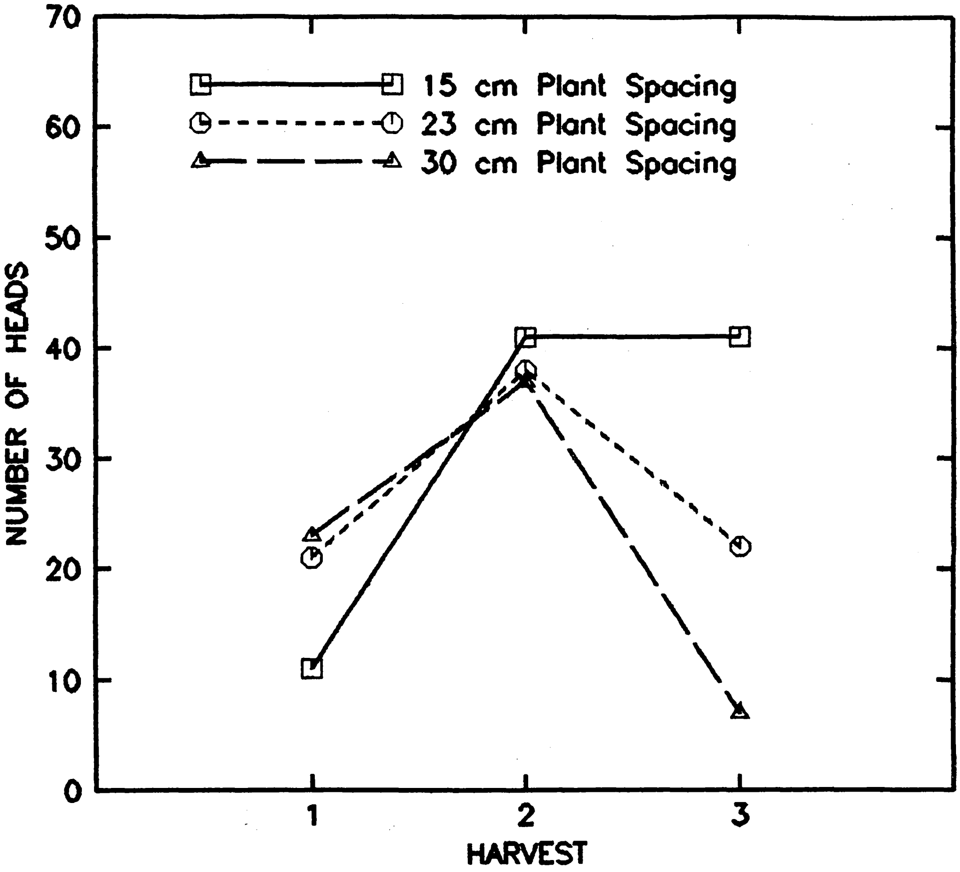


Figure 12. Number of heads versus harvest for broccoli planted in three in-row spacings.

Table 8. **Plot yield for different treatment combinations of harvest, plant spacing and row spacing for the 1988 season.**

	Plant Spacing (cm)			
Factors	15	23	30	Total
Harvest				
1	1.89[1]	4.18	4.20	10.22
2	6.66	7.00	6.00	19.66
3	5.62	3.42	1.15	10.19
Row Spacing (cm)				
30	6.65	7.27	5.89	19.81
46	7.47	7.33	5.46	20.26
Total	14.12	14.60	11.35	40.07

[1] Yield in kilograms (kg).

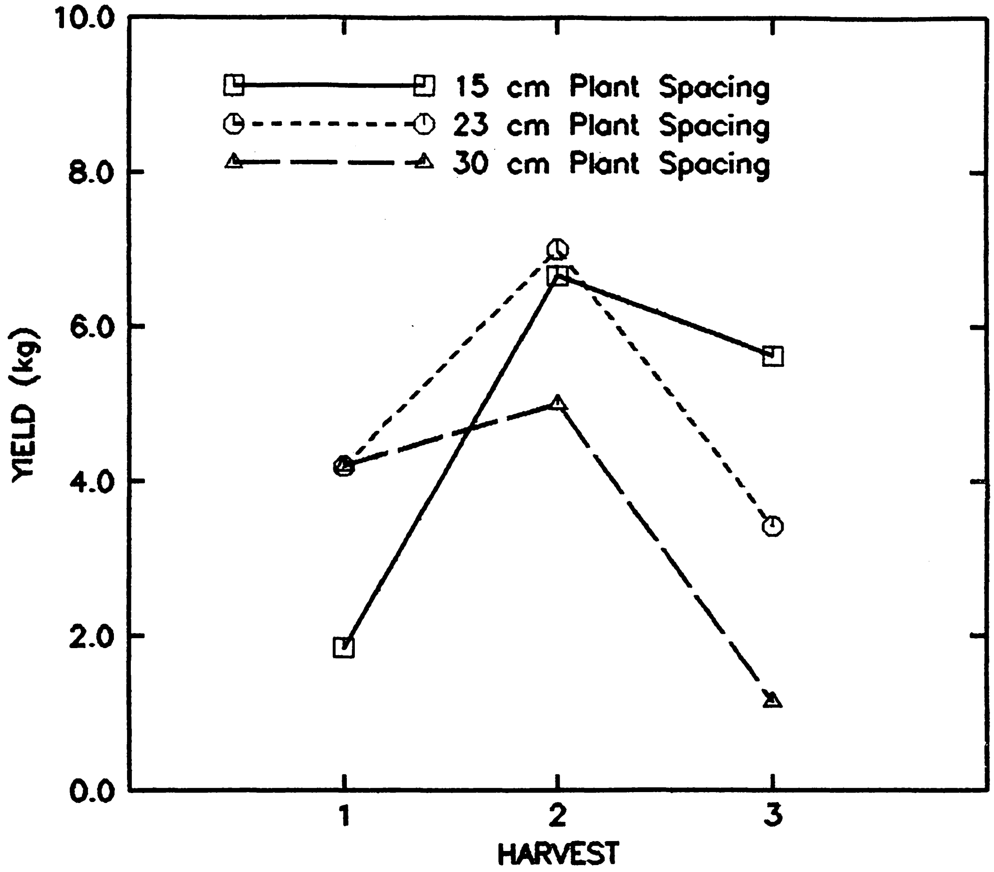


Figure 13. Plot yield versus harvest for broccoli planted in three in-row spacings.

Measurements for investigating correlations were made on 34 broccoli plants during the first harvest, 40 broccoli plants during the second harvest and 56 broccoli plants during the third harvest. Correlations were evaluated between pairs of plant measurements for each of the harvests separately. The data from the three harvests were not combined because of the strong effect of the harvest time on plant measurements in the factorial experiment. The correlation results are shown in Tables 9, 10 and 11 for the first, second and third harvest, respectively. The correlation data is shown in Appendix C.

Looking at the various parameters, the visual accessibility showed surprisingly little correlation to any of the other parameters, and the results were not consistent from one harvest to the next. The correlation with height was negative for the first harvest, positive for the second and negative for the third. The correlations with head diameter, stalk diameter and weight were positive for the first harvest and negative for the second and third. Since tall or large heads would seem to favor improved visual accessibility, a high positive correlation between visual accessibility and height or head diameter would have been expected, but this was not the case.

Correlations between head diameter and other parameters were of interest because of the possibility of using a mature head selection system based on selection criteria other than head diameter. For instance, if stalk diameter were highly correlated to head diameter, head maturity could be determined by sizing the broccoli stalk from the side of the row, either by mechanical or machine vision means, instead of sizing the broccoli head from above. In fact, the head diameter was somewhat correlated to the stalk diameter. During the first harvest, the Pearson's correlation coefficient between the two parameters was only 0.2083, with a probability of 0.1970. However, the coefficient increased to 0.4246, with a probability of 0.0123, for the second harvest, and 0.4080, with a probability of 0.0016, for the third harvest. The height also showed some correlation to the head diameter, although the results were not consistent from one harvest to the next. For the first harvest, the correlation coefficient between the two parameters was 0.4683, with a probability of 0.0023, and for the third harvest it was 0.3014, with a probability of 0.0240. But for the second harvest, the correlation coefficient was only 0.0325, with a probability of 0.8553.

Table 9. Correlations between pairs of plant measurements for the first harvest, 1988 season.

	Plant Measurements				
Plant Measurements	Visual Accessibility	Height	Head Diameter	Stalk Diameter	Weight
Visual Accessibility	1.0000	-0.1931[1]	0.1036	0.1876	0.1845
	0.0000	0.2326[2]	0.5245	0.2465	0.2545
Height		1.0000	0.4683	-0.2725	0.1552
		0.0000	0.0023	0.0689	0.3391
Head Diameter			1.0000	0.2083	0.8584
			0.0000	0.1970	0.0001
Stalk Diameter				1.0000	0.6106
				0.0000	0.0001
Weight					1.0000
					0.0000

[1] Pearson's Correlation coefficient, r.

[2] Probability of the R value under the null hypothesis ($r = 0$).

Table 10. Correlations between pairs of plant measurements for the second harvest, 1988 season.

Plant Measurements	Plant Measurements				
	Visual Accessibility	Height	Head Diameter	Stalk Diameter	Weight
Visual Accessibility	1.0000 0.0000	0.1105[1] 0.5337[2]	-0.0715 0.6679	-0.0275 0.8771	-0.0825 0.6428
Height		1.0000 0.0000	0.0325 0.8553	-0.4414 0.0090	-0.2653 0.1294
Head Diameter			1.0000 0.0000	0.4246 0.0123	0.7240 0.0001
Stalk Diameter				1.0000 0.0000	0.8853 0.0001
Weight					1.0000 0.0000

[1] Pearson's Correlation coefficient, r.

[2] Probability of the R value under the null hypothesis (r = 0).

Table 11. Correlations between pairs of plant measurements for the third harvest, 1988 season.

Plant Measurements	Plant Measurements				
	Visual Accessibility	Height	Head Diameter	Stalk Diameter	Weight
Visual Accessibility	1.0000 0.0000	0.0659[1] 0.6294[2]	-0.2158 0.1102	-0.2515 0.0616	-0.2128 0.1154
Height		1.0000 0.0000	0.3014 0.0240	-0.2433 0.0708	0.1491 0.2726
Head Diameter			1.0000 0.0000	0.4080 0.0018	0.8597 0.0001
Stalk Diameter				1.0000 0.0000	0.7046 0.0001
Weight					1.0000 0.0000

[1] Pearson's Correlation coefficient, r.

[2] Probability of the R value under the null hypothesis (r = 0).

The correlations with stalk diameter and height were probably not high enough for either parameter to be used by itself as a selection criteria alternative to head diameter. Stalk diameter and height were somewhat correlated to each other, however, and this fact may explain why more of the variation in head diameter was not accounted for by either of the individual parameters. The correlation coefficient between stalk diameter and height was negative for all three harvests, indicating that the stalks were generally smaller for taller heads. The extent of correlation between the two parameters indicated that a model containing both parameters might do a better job of predicting head diameter than either parameter by itself. A linear regression was done on the head diameter, stalk diameter, and height data from each of the three harvests, and the results were as follows:

$$\text{1st harvest,} \quad HD = -8.75 + 1.90SD + 0.412H, \quad r = 0.584 \tag{1}$$

$$\text{2nd harvest,} \quad HD = 2.66 + 1.52SD + 0.0727H, \quad r = 0.490 \tag{2}$$

$$\text{3rd harvest,} \quad HD = 1.86 + 1.73SD + 0.0986H, \quad r = 0.581 \tag{3}$$

where HD = head diameter (cm)
SD = stalk diameter (cm)
H = height (cm)
r = correlation coefficient.

The correlation coefficients were higher than any of those between head diameter and stalk diameter or height, indicating that the models were better at predicting head diameter. A further indication of how well the models predict head diameter is the 95% confidence limits on the predicted values. In most cases, the 95% confidence limits were within ± 0.6 cm. Whether or not these models predict head diameter accurately enough cannot yet be known because no system of head selection that could use this information exists or has even been proposed. These results, however, show that the potential exists for using a combination of stalk diameter and height as a selection criteria alternative to head diameter.

The weight was the parameter most strongly correlated to other parameters. The head diameter was strongly correlated to the weight for all three harvests, with a correlation coefficient of 0.8584 and a probability of 0.0001 for the first harvest, 0.7240 and a probability of 0.0001 for the second harvest, and 0.8597 and a probability of 0.0001 for the third harvest. The stalk diameter was also strongly correlated to the weight, with a correlation coefficient of 0.6106 and a probability of 0.0001 for the first harvest, 0.8853 and a probability of 0.0001 for the second harvest, and 0.7046 and a probability of 0.0001 for the third harvest. The high correlation between stalk diameter and weight was expected considering the strong similarity in stalk diameter and weight results for the factorial experiment. The height was not correlated to the weight, but this result was also expected since the broccoli heads were trimmed to a uniform length before weighing.

Since weight was so highly correlated to both head diameter and stalk diameter, and since these parameters were somewhat correlated to each other, an investigation of weight models containing combinations of both of these parameters was made. The first model investigated included the head diameter, stalk diameter, head diameter squared and stalk diameter squared. The squared terms were used because weight seemed likely to depend on the amount of material in the head and stalk, which should be roughly proportional to the cross-sectional area. The results of linear regressions containing the four terms done for each of the three harvests were as follows:

1st harvest, $W = 149 - 9.40HD + 1.38HD^2 - 83.3SD + 25.3SD^2,$ $r = 0.974$ (4)

2nd harvest, $W = 145 - 5.34HD + 3.56\,HD^2 + 65.2SD + 0.233SD^2,$ $r = 0.968$ (5)

3rd harvest, $W = -27.2 - 19.6HD + 16.2\,HD^2 + 80.7SD - 8.07SD^2,$ $r = 0.948$ (6)

where W = weight (g).

As indicated by the high correlation coefficients, these models were able to predict head weight with good accuracy. However, the analysis of variance results indicated that in some cases the higher order terms were adding very little to the models. Models were tried with one or the other of the squared terms left out and with only the first order terms included. The simpler models containing only head diameter and stalk diameter were found to predict the head weight with nearly as good accuracy as the more complex models. The results of linear regressions containing the two terms done for each of the three harvests were as follows:

1st harvest, $W = -224 + 20.0HD + 62.1SD$, $r = 0.965$ (7)
2nd harvest, $W = -171 + 14.0HD + 65.2SD$, $r = 0.965$ (8)
3rd harvest, $W = -193 + 21.4HD + 44.8SD$, $r = 0.943$ (9).

These models are much simpler than the models containing the higher order terms, and they are more consistent from harvest to harvest.

Weight predicting relationships are of no immediate practical use in mechanizing the selective harvest of broccoli. However, models relating weight to other geometric parameters could be useful for future studies in areas such as automated handling and processing of broccoli and selective harvest scheduling optimization. These results show that weight can be accurately related to head and stalk diameters using linear regression models.

Since the data used for the correlations investigation included measurements from such a large number of heads all from the same treatment combination, it was used to check for the distribution of visual accessibility ratings. During the first harvest, 9 out of 40 heads (22.5%) received a 0 rating, for totally obstructed view. During the second harvest, 5 out of 34 heads (14.7%) received a 0. During the third harvest, 1 out of 56 heads (1.8%) received a 0. These results are favorable to the use of a machine vision system for automated head selection.

4.2.3 Summary and Conclusions

Physical properties measurements were made on broccoli grown for cutting device harvest tests during the 1987 and 1988 seasons. Measurements made during the preliminary physical properties investigation of 1987 included the height to the top of the head, head diameter, stalk diameter, and visual accessibility. An additional parameter measured in 1988 was the weight of the trimmed heads. The measurements were used both to determine the effects of different factors on the physical properties and to investigate correlations between the different physical properties. In 1987 the factors included three harvests (early, middle and late season) and three planting patterns. The 1988 factors included three harvests, three plant spacings or population densities (109,300, 71,300 and 54,600 plants/ha), and two double-row spacings (30 and 46 cm). Measurements for the investigation of correlations in 1988 were made on a large number of broccoli heads harvested with the cutting device from one of the treatment combinations of the harvest test plots.

The following conclusions were reached based on the results of this investigation:

1. The harvest had a considerable effect on most of the measured parameters, with height and visual accessibility increasing and stalk diameter and weight decreasing with successive harvests.

2. The population density significantly affected several of the measured parameters, with height increasing and stalk diameter and weight decreasing as population density increased.

3. The double-row spacing had little effect on the measured parameters. Only the height was significantly affected, with the heads somewhat taller at the closer row spacing.

4. Plant height was strongly affected by most of the factors each year, especially the harvest and the population density.

5. Head diameter showed no response to any of the factors either year, indicating problems inherent in comparing head diameter averages without taking the number of heads into account.

6. The distribution of visual accessibility ratings was somewhat favorable to the use of a machine vision system since a low percentage of heads received a 0, for totally obstructed view.

7. The head diameter showed a moderate positive correlation to both height and stalk diameter.

8. The head diameter could be predicted with linear regression models containing both height and stalk diameter. These models had higher correlation coefficients than models containing either parameter separately.

9. Weight showed good correlation to both head diameter and stalk diameter, with correlation coefficients for head diameter ranging from 0.61 to 0.89 and those for stalk diameter ranging form 0.72 to 0.86 for the three harvests.

10. Weight could be predicted with very good accuracy with linear regression models containing both head diameter and stalk diameter. These models had correlation coefficients ranging from 0.95 to 0.97 for the three harvests.

These results can be useful in mechanizing the selective harvest of broccoli in several ways. Distributions of head and plant dimensions may be important to the design or adjustment of machinery components. The response of parameters to different factors may be helpful in determining the optimum planting arrangement or population for a specific concept. For example, taller plants and increased visual accessibility should both be advantageous to the use of a powered cutting device. Parameter responses may also be important in evaluating the feasibility of selective harvest concepts. Visual accessibility and its importance to the consideration of the use of machine vision for mature head selection is a good example. Correlations between parameters are important to the consideration of selection criteria alternatives to head diameter. Based on the results of this investigation, neither height nor stalk diameter alone would be a viable selection criterion alternative, but there may be potential for collectively using the two parameters for head selection. Finally, modeling of the relationships among broccoli physical properties may be useful in the future as other aspects of the handling and processing of broccoli are automated. The results of this investigation indicate that such modeling, especially related to head weight, can be done.

Chapter V

POWERED BROCCOLI CUTTING DEVICE

Mechanization of the harvest of broccoli would substantially reduce harvest labor requirements for fresh market broccoli. Total mechanization, however, will be difficult because of unsatisfactory results or prohibitive costs. Once-over mechanical harvesting would require a considerable increase in handling for sorting, trimming, and leaf-stripping, and would also reduce yields. Automated selective harvesters may take many years to develop and require sophisticated technology that would make them very expensive.

Partial mechanization of the harvest, through the mechanization of the cutting process only, has the potential to benefit producers relatively quickly because of low cost and ready integration into existing harvest systems. This strategy uses a manually-directed, powered cutting device to do the actual cutting of the broccoli. The cutting device concept combines the leaf-stripping and stalk cutting operations into a single operation by having a powered cutting mechanism on the end of an apparatus similar to the leaf-breaking rings. By combining the two operations, harvest labor requirements can be reduced, and since the stooping involved with hand cutting is eliminated, the work should be less strenuous. Because the device is manually-directed and used for selective harvests, handling requirements for the broccoli will be unchanged, making the device fit into existing production systems especially well.

A powered broccoli cutting device was designed and built in 1987. After extensive testing with the device, design modifications were made and a new device was built for testing in 1988. This chapter explains some of the analysis and design involved with the development of the device and reports the results of two years of field testing with it.

5.1 Analysis and Design

5.1.1 Harvesting Principle

One of the most important considerations in mechanizing the harvest of fresh market broccoli is the requirement that the stalks be free of leaves. Whether the broccoli is mechanically harvested selectively or in one pass, an additional operation, most probably manual, is going to be required to strip the leaves from the stalk unless the cutting and gathering operation accomplishes this leaf-stripping automatically. The leaf-breaking rings commonly used for broccoli harvesting in Virginia are very important because they can be used to strip the leaves from the stalk without manual handling of the broccoli head. The concept for a hand-held, powered broccoli cutting device was inspired in large part by the use of these leaf-breaking rings.

Figure 14, a schematic of a broccoli plant viewed from above, illustrates the principle of the leaf-breaking rings. The dark circle represents a leaf-breaking ring with a 15 cm diameter opening. Also shown as dashed lines are the broccoli stalk and the portions of attached leaf stems hidden from view by the broccoli head. As the ring is pushed down over the head, leaves caught outside the ring are bent downward and hopefully broken off. The ring may be pushed down in a single,

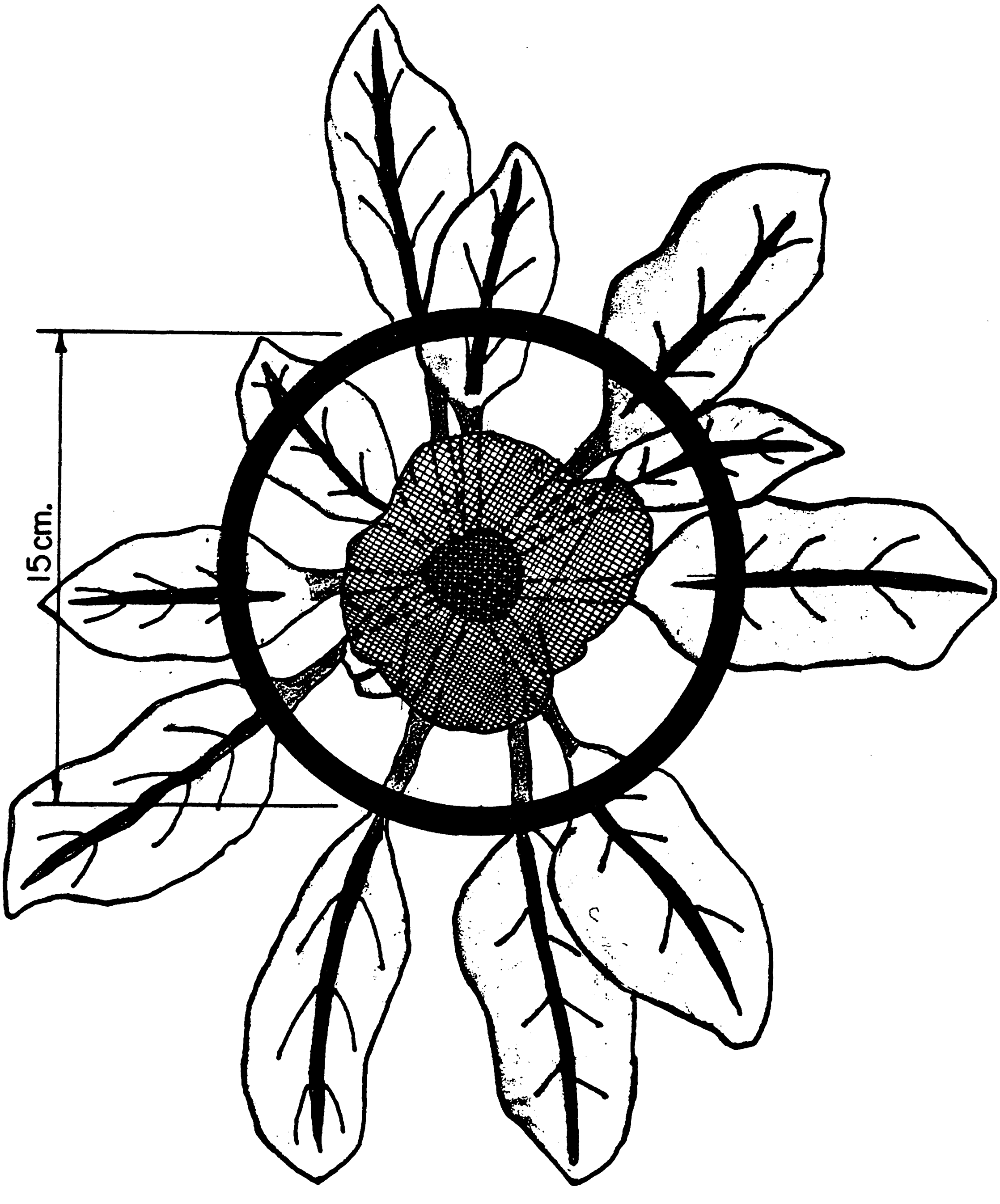


Figure 14. Broccoli plant viewed from above illustrating the principle of the leaf-breaking rings.

vigorous motion in an attempt to break most of the leaf stems off cleanly near the stalk. Or the ring may have to be pushed down several times, with the edge scraping along the sides of the broccoli stalk.

The powered broccoli cutting device is essentially a leaf-breaking ring equipped with a cutting mechanism on the bottom. The device is operated by workers moving through the field in the same way as they would for hand cutting. The sequence for cutting and collecting a broccoli head with the cutting device is as follows. The device is pushed down over the broccoli head from above. It is pushed far enough down that the desired length of broccoli head protrudes through the opening, and then the cutting mechanism is activated to sever the broccoli stalk from the plant. After the broccoli head is cut, it is retained in the device. The operator raises the device, removes the head with his free hand, tosses it into a collection hopper, and continues on to the next head.

5.1.2 Power Source

Weight, size, and simplicity were primary considerations in selecting a power source for the cutting device. The device must be as light and small as possible for manual handling and maneuvering. The device should be simple, making use of readily available technologies, in order to be reliable and inexpensive enough for adoption by Virginia broccoli producers.

The gripping force of the human hand was a possible power source for the cutting device, but a consideration of the conditions required for operating the device made its use seem impractical. From the results of the stalk cutting force experiment, it was known that the force required to cut a stalk under laboratory conditions ranged from 60 to 115 N. Actual cutting forces under field conditions are likely to be somewhat higher. While the hand may be capable of delivering this much gripping force, it would be difficult to deliver such a force intermittently several times a minute, over a period of several hours a day. Therefore, an outside power source was needed.

Pneumatic, hydraulic, and electrical power were all possible sources for the cutting device. Because compressed air was already being used to operate bunching machines in the field, pneumatic power was the most obvious choice. A consideration of the other power sources pointed out other advantages of pneumatic power. Hydraulic power, while available in the field from the tractor hydraulic system, was not suited for use with a hand-held device because of heavy components and hoses. Electrical power could have been delivered to the cutting device with flexible, lightweight connecting lines. However, electrical components which are light enough and capable of delivering the required force are not readily available at low cost. Pneumatic components are lightweight, readily available, and relatively inexpensive. Air hoses made of small diameter, self-coiling plastic tubing meet the criteria for flexible, lightweight connecting lines. Small pneumatic cylinders operating at standard pressures (up to 150 psi) can deliver a substantial amount of force, yet are relatively light weight.

5.1.3 Cutting Mechanism

Weight, size, and simplicity were also important in the design of the cutting mechanism. These factors were considered in making decisions about the type, configuration, and position of several components before the actual design was begun. Especially important were decisions concerning the following:

1. Number and configuration of blades to be used for the cutting mechanism,

2. Positioning of the pneumatic cylinder,

3. Type and configuration of the linkage to transmit power from the cylinder to the blades.

Double opposing blades were chosen for the cutting device instead of a single blade because double blades can rotate through a much smaller angle to make the required cut, allowing the use of a lower cylinder stroke and a smaller power transmission linkage. The blades were curved so that they had a ring shape when open prior to the cut. A single blade would have to rotate through an angle of at least 90° to cut through the entire circular area inside the ring (see Figure 14), and they would have to protrude substantially outside the ring area, either prior to or after the cut, depending on the blade configuration. Protrusion of the blades had to be minimized in order to reduce resistance to pushing the device down over the broccoli head and to minimize the possibility of damage to neighboring plants. With two curved blades, each blade had to rotate only to the center of the circular area, so there was very little protrusion outside the ring area when the blades were closed.

Minimizing the projected area of the device was also a main consideration in how the cylinder was mounted. To mount the cylinder horizontally, a longitudinal mounting would have been required to get equal movement from the two opposing blades. In this position, the cylinder would project a long way out from the device. The cylinder was mounted vertically in order to minimize the projected area.

A linkage was needed that was capable of converting the vertical motion of the cylinder to the horizontal motion of the blades. A combination of slider crank mechanisms was chosen for transmitting the motion in this way. Figure 15 shows a representation of the two blades of the cutting mechanism as a pair of slider crank mechanisms in the horizontal plane. The blades are the cranks (link 2), and the input of a force on the slider at point A produces the cutting action, which is a rotation of the cranks. The slider is connected to both cranks by connecting rods (link 3).

Another slider crank mechanism was needed to transfer the output from the vertically-mounted cylinder to the horizontal, linear force input at point A. Figure 16 shows two possible configurations of slider crank mechanisms for accomplishing this transfer. In both cases, the input

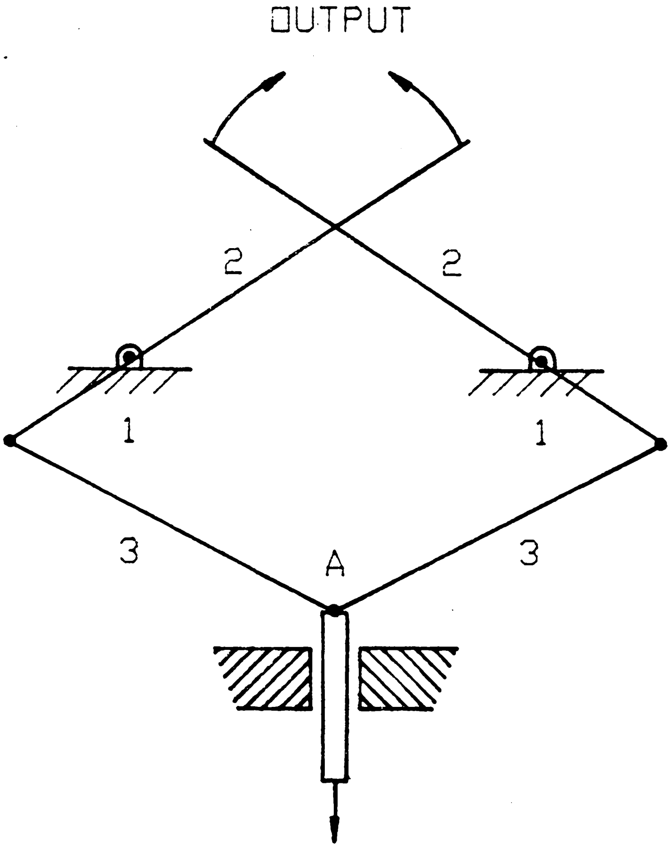


Figure 15. Cutting mechanism representation using slider crank mechanism.

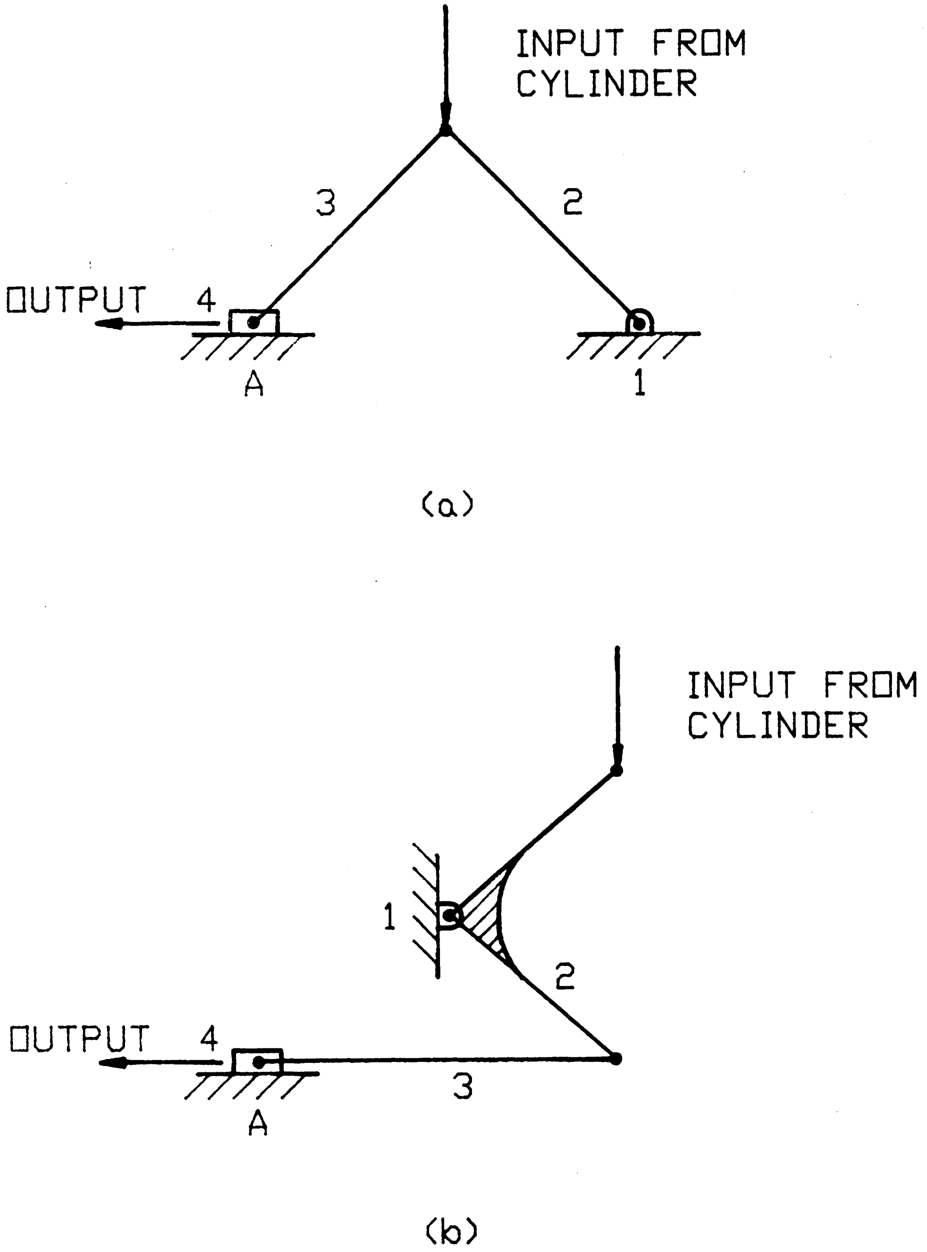


Figure 16. Two configurations of slider crank mechanisms for transfering cylinder output to the blades.

to the mechanism is the rotation of the crank (link 2) caused by the force from the cylinder applied somewhere on link 2. The output is the linear motion of the slider at point A.

In Figure 16a, the cylinder force is applied at the connecting point between links 2 and 3. With this configuration, it is difficult to get much stroke from the slider unless link 3 is more vertical. However, when link 3 is more vertical, the vertical component of the reaction force at point A is greater. It was necessary to minimize this vertical reaction force because the connecting rods of the mechanism for moving the blades are unsupported in the vertical direction (Figure 15). A vertical force on these connecting rods would tend to bend them downward at the points where they are connected to the blades.

With the slider crank mechanism shown in Figure 16b, the location of the input and output points of link 2 can be adjusted to maximize the transmission of force from the cylinder to the slider while minimizing the vertical reaction force at point A. The reaction force is minimized as link 3 becomes more horizontal. If the configuration of link 2 is such that initial and final positions of the link are symmetric with a vertical line drawn through point 1, then link 3 can be made horizontal in its initial and final positions. Most of the vertical reaction force will be at point 1, which is rigidly supported in the frame. This slider crank mechanism configuration was selected to transfer the output of the vertically mounted cylinder to the horizontal mechanism for moving the blades.

5.1.4 Experimental Apparatus

5.1.4.1 Cutting Mechanism

A prototype broccoli cutting device was designed and fabricated in 1987. The cutting mechanism for the device employed a vertically-mounted, double-acting pneumatic cylinder to power a pair of horizontal curved blades in a scissor action. Figure 17 shows an isometric view of the cutting mechanism with the blades open and the cylinder in the retracted position. Note the triangular-shaped link that rotates about a pin secured to the frame. Two of the legs of the triangle are 90° apart and equal in length. The other leg has a length equal to the stroke of the cylinder so that the link rotates exactly 90° when the cylinder is extended. Figure 18 shows a bottom view of the cutting mechanism with one of the blades removed. Dotted lines show the linkage when the cylinder is extended to close the blades. Because of the configuration of the triangle link, the pivot pin moves a distance equal to the stroke of the cylinder. As the pivot pin moves, the connecting links pull the blades closed.

Certain other design features of the cutting mechanism should be pointed out. Each of the blades had its own pivot point, located across the centerline of the device from the blade itself (see Figure 18). A single pivot point common to both blades could have been used for a simpler design, but the blades would have had to rotate through a larger angle to reach the center of the circular area. When the blades rotate through a smaller angle, the cylinder stroke and linkage can be smaller, and the blades will protrude less outside the ring area when closed. Reducing blade protrusion reduces the potential for damage to neighboring plants and injury to the operator.

5.1.4.2 Cylinder Requirements

In choosing the cylinder for the cutting device and the air compressor to power it, consideration was given to the results of the broccoli stalk cutting force experiment reported in Chapter 4. According to these results, the blade velocity needed to be greater than 25 cm/s to reduce the force required to cut through the stalk, and the required force was likely to be greater than the maximum of 114 N measured with non-fresh broccoli stalks. Analyses were done on the cutting mechanism to determine the air compressor capacity required to achieve the desired blade speed and the size of the cylinder required to achieve the desired cutting force.

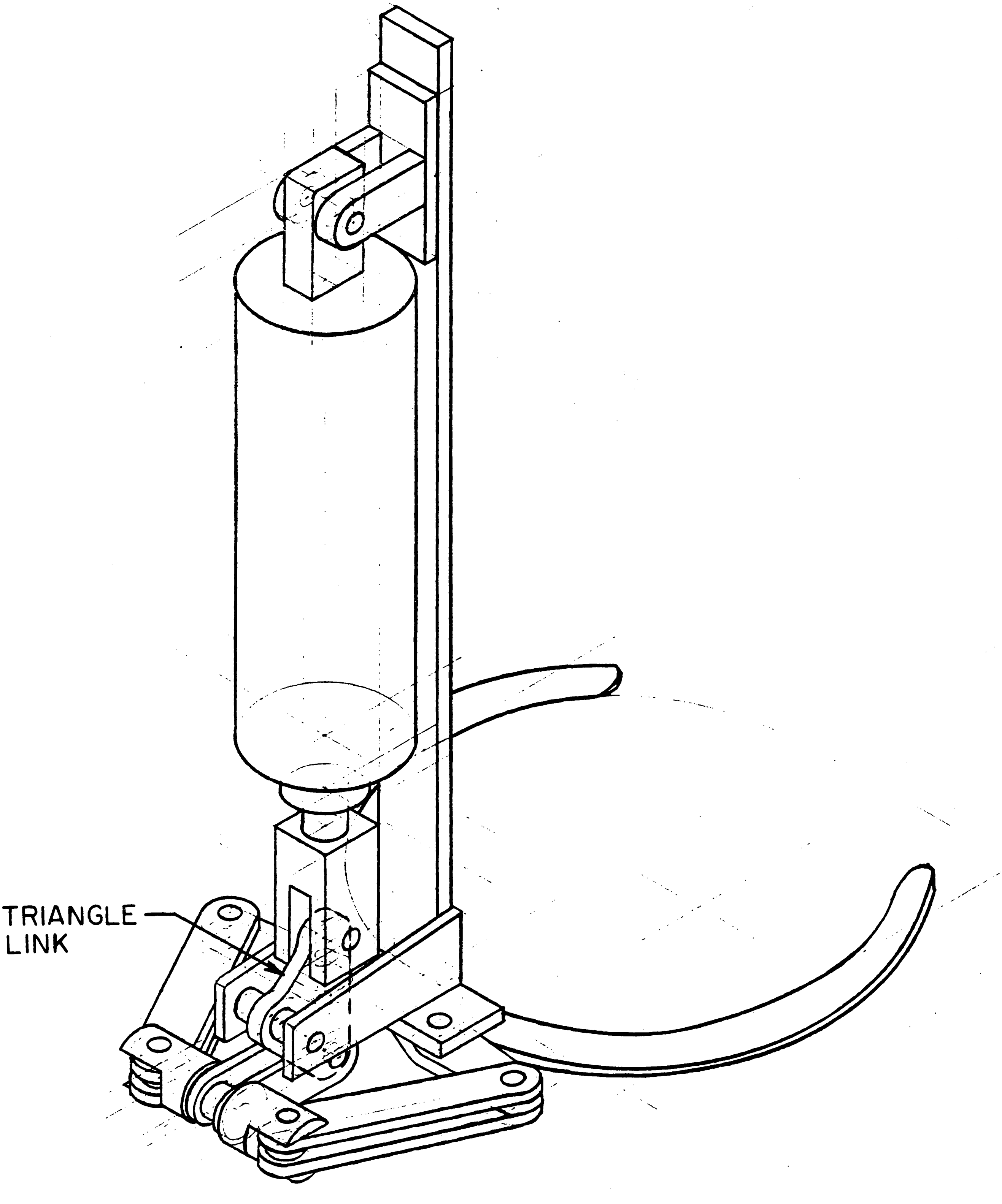


Figure 17. Isometric view of the cutting mechanism with the cylinder retracted.

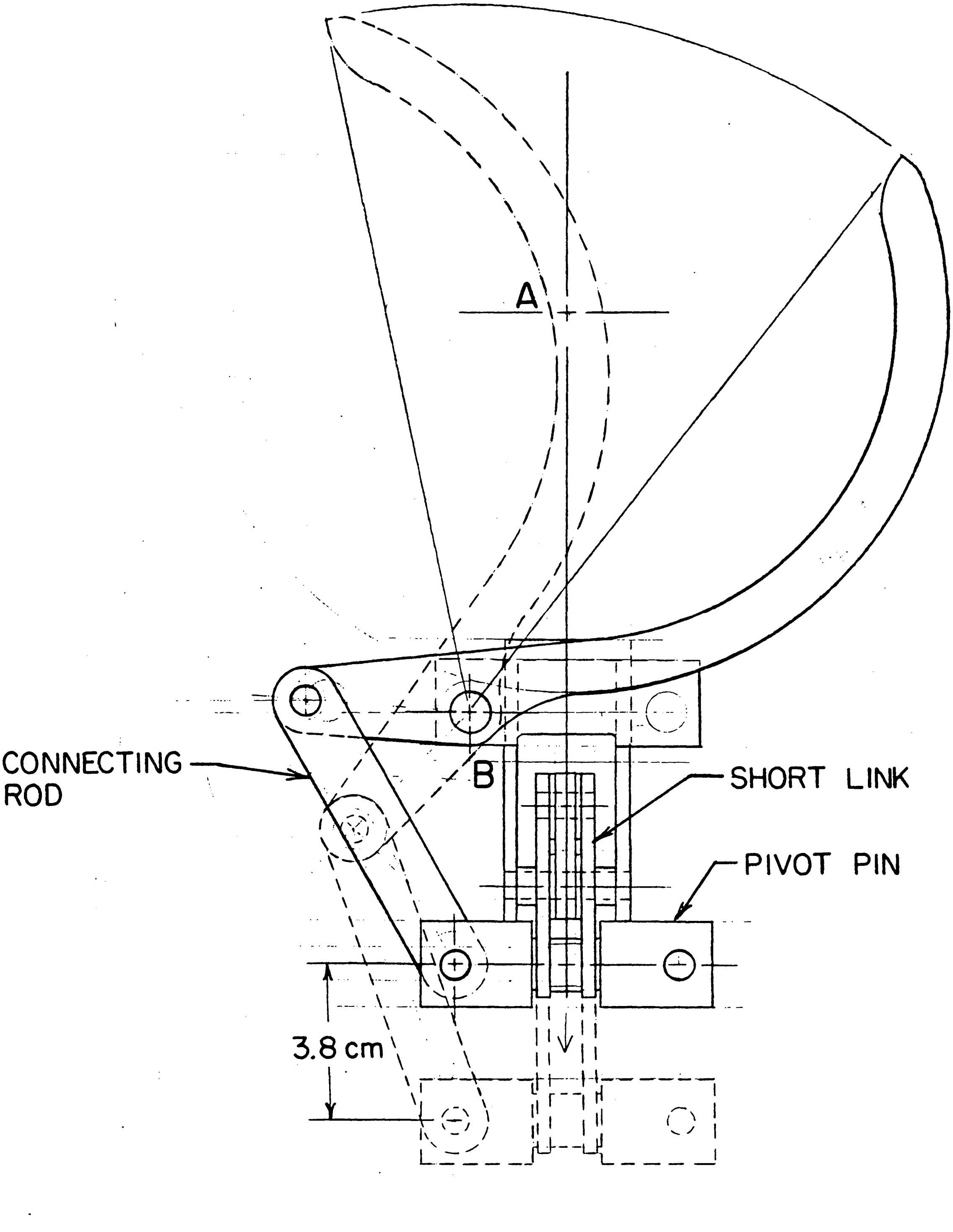


Figure 18. Bottom view of the cutting mechanism with one of the blades removed.

The broccoli stalk is most likely to be cut at the center of the circular ring area, shown as point A in Figure 18. The average tangential velocity of the blade at point A can be calculated from the following equation:

$$V_t = \overline{AB}\dot{\theta}_{AVG} \tag{1}$$

where V_t = average tangential velocity at point A. (cm/s),

$\overline{AB}$ = distance from blade pivot B to point A (cm),

$\dot{\theta}_{AVG}$ = average angular velocity (rad/s).

If the angle through which the blade rotates is known, the time it takes for the blade to rotate can be calculated.

$$t = \frac{\theta}{\dot{\theta}_{AVG}} \tag{2}$$

where t = time for rotation (s),

θ = angle of rotation (rad).

The cylinder must extend in the time required for blade rotation. For a given cylinder stroke and diameter, the required flow from the air compressor is given by,

$$Q = \frac{60\pi SD^2}{4000t} \tag{3}$$

where Q = flow from air compressor (L/min),

S = cylinder stroke (cm),

D = cylinder diameter (cm).

Combining Eqs. (1), (2), and (3),

$$Q = \frac{60\pi S D^2 V_t}{40000\theta AB} \tag{4}$$

For the 1987 prototype of the cutting device, the distance $\overline{AB}$ was 10 cm, the angle that the blades rotated through was 50° (0.87 rad), and the stroke was 4.1 cm (1.625 in.). With these dimensions, the air compressor flow required to achieve an average tangential blade velocity of 25 cm/s was 4.56 L/min if a 2.9 cm (1.125 in.) diameter cylinder was used, and 14.4 L/min if a 5.1 cm (2 in.) diameter cylinder was used. The air compressor chosen to power the cutting device was the same type used by several Virginia broccoli producers for operating bunching machines in the field. The compressor (SpeeCo model AC 440101) was PTO-driver and had no air storage. It could develop a maximum pressure of 0.9 MPA (130 psi) and had a rated capacity of 25 L/min (0.9 cfm) at 0.7 MPA (100 psi). The flow was more than sufficient to achieve the desired blade tangential velocity with a cylinder 5.1 cm in diameter.

A static force analysis was done on the cutting mechanism linkage to determine what size cylinder was required to achieve the desired cutting force. Figure 19 shows a line representation of the linkage for transmitting force from the cylinder to the blades. The top view shows the horizontal part of the linkage, including the blade, the connecting rod, and the pivot pin. A representation of the linkage for only one of the blades is shown because the two blades are symmetrical with respect to the pivot pin. The linkage is shown in the closed position because the maximum force will be required where the stalk is cut, which is mostly likely to be in the center of the circular ring area (point A in Figure 18). The side view shows the vertical part of the linkage, including the triangle link, the short link, and the pivot pin. The triangle link is shown in its final position, corresponding to the blades in the closed position and the cylinder fully extended.

In the side view, F_{cyl}, the force input from the cylinder, is vertical. The force on the pivot pin, F_D, is horizontal and therefore fully transmitted along the horizontal short link to the triangle link. Because the triangle link is a 45° triangle and symmetric about a vertical line through point E in this position, a summation of moments about point E gives the result that $F_{cyl} = F_D$. Therefore, the

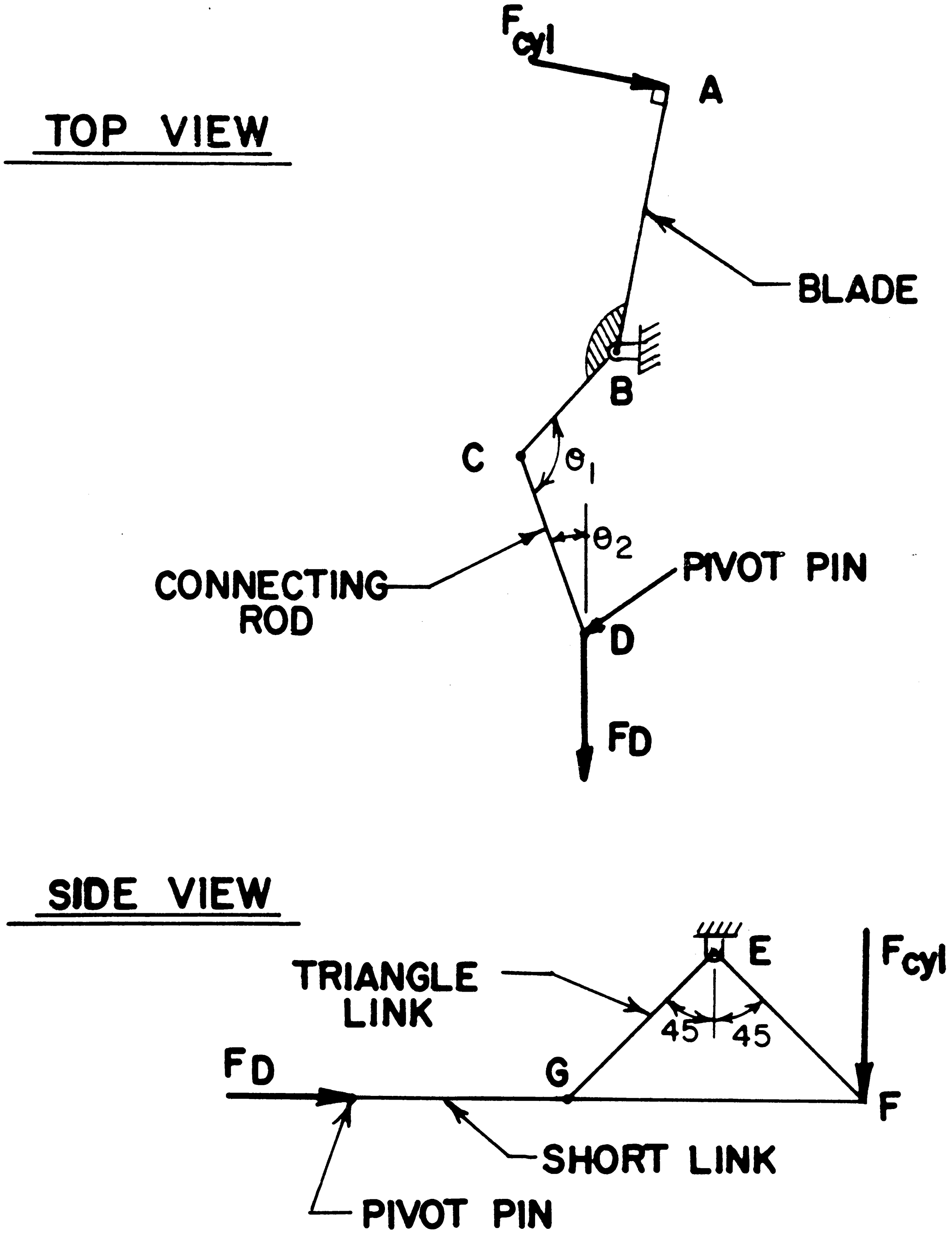


Figure 19. Line representation of the linkage for transmitting force from the cylinder to the blades.

force F_D on the pivot pin in the top view is the same as the cylinder force, and no further analysis of the vertical part of the linkage is required.

In the top view, F_{cut} is the force required to cut the broccoli stalk. The connecting rod exerts a force on the blade at point C to produce the required cutting force. The two forces can be related by summing moments about point B.

$$\sum M_B = O, \qquad F_{cut}\overline{AB} = F_{con}\overline{BC}\cos\left(\theta_1 - \frac{\pi}{2}\right) \tag{5}$$

where
F_{con} = connecting rod force (N),
$\overline{AB}$ = distance from blade pivot to cutting point (cm),
$\overline{BC}$ = distance from blade pivot to connecting rod (cm),
θ_1 = angle between blade and connecting rod (rad).

The force along the connecting rod can be related to the force on the pivot pin, F_D, by the following equation:

$$F_{con} = F_D \cos\theta_2 \tag{6}$$

where θ_2 = angle between connecting rod and vertical (rad). Substituting Eq. (6) into Eq. (5) and solving for F_D,

$$F_D = \frac{F_{cut}\overline{AB}}{\overline{BC}}\cos\left(\theta_1 - \frac{\pi}{2}\right)\cos\theta_2 \tag{7}$$

Because $F_{cyl} = F_D$, solving Eq. (7) gives the required cylinder force for a given cutting force F_{cut}.

For the 1987 prototype of the cutting device, the angles and lengths were as follows:

$$\theta_1 = 117^\circ$$

$$\theta_2 = 20^\circ$$

$$\overline{AB} = 10\,\text{cm}$$

$$\overline{BC} = 4\,\text{cm}$$

Substituting these values into Eq. (7) and assuming a required cutting force of 114 N, the cylinder force must be at least 337 N.

A 2.5 cm (1 in.) diameter cylinder operating at a standard pressure of 0.7 MPa (100 psi) develops a force of 347 N. A 2.9 cm (1.125 in.) diameter cylinder develops a force of 440 N. Because the force required to cut broccoli stalks in the field was assumed to be somewhat larger than the force measured in the lab with non-fresh broccoli, the 2.9 cm diameter cylinder was initially chosen for operating the cutting device. With this cylinder in place, the cutting device cut through broccoli stalks with ease during early trials in the lab. However, when the cutting device was tested in the field on some of the first broccoli to mature in the fall of 1987, it was not able to cut through the broccoli stalks. The 2.9 cm diameter cylinder was replaced by a 3.8 cm (1.5 in.) diameter cylinder, but still the cutting device was unable to cut completely through all of the broccoli stalks. Finally, a 5.1 cm (2 in.) diameter cylinder was tried, and the device was able to cut through all broccoli stalks in the field.

The force required to cut the broccoli in the field was unexpectedly high compared to the forces measured in the lab. Several factors may have contributed to the large difference in required cutting force. Friction due to the numerous pivot points of the cutting mechanism would have reduced the force delivered to the blades. Also, duller blades than the ones used in the stalk cutting experiment may have increased the required cutting force. The blades of the cutting device were somewhat difficult to sharpen because the cutting edge was on a concave side. While these factors probably increased the required cylinder force somewhat, they were not the primary factors in the large difference in cutting force requirements, as evidenced by the fact that the cutting device was able to cut through non-fresh broccoli in the lab with the 2.9 cm diameter cylinder in place.

The two factors that may have contributed most to the higher cutting force requirement in the field were the foliage that had to be cut through in addition to the broccoli stalk and differences in stalk characteristics between non-fresh and field broccoli. The leaves that were bent back as the cutting device was pushed down over the head tended to be gathered inside the curved blades as they closed. These leaf stems not only provided extra plant material for the blades to cut through, they tended to slow down the blades as well. Stalk characteristics of plants in the field were expected to be somewhat different than those of non-fresh broccoli heads, but it is not known what differences would have contributed to lower cutting force requirements for non-fresh broccoli. It may be that the tough outer fibers of the stalk experience some sort of morphological change due to prolonged (up to two weeks) refrigerated storage that lowers the cutting force requirement.

5.1.4.3 Other Cutting Device Features

In addition to the cutting mechanism and the cylinder, other components of the cutting device included a housing above the blades, a long handle attached to the cutting mechanism, and a valve located in the handle grip for activating the cylinder. The cutting device had an overall height of approximately 80 cm which could be adjusted by changing the length of the handle. The handle was made of a 13 mm diameter aluminum tube attached to a steel channel that served as the grip. A miniature 4-way valve was housed inside the steel channel. The grip was held in the transverse position, and the cylinder was activated by pressing a pushbutton on the side of the value with the thumb.

5.1.4.4 Harvesting Aid

A three-wheeled vegetable harvesting aid (Four Star, Inc.) was modified for use in field testing the device. The harvesting aid had a 9 kW (12 HP) engine in the rear that delivered power to the single rear wheel through a four-speed transaxle and could move at very slow speeds. This feature is very important for vegetable harvesting applications. The front axle of the harvesting aid was adjustable in width from 1.5 to 3.5 m (60 to 140 in.), another important feature for field tests with the cutting device. The air compressor used to power the cutting device was installed on the harvesting aid and powered by a V-belt drive from the engine.

The first broccoli cutting device prototype, having a weight of approximately 3 kg, was too heavy for unsupported, continuous operation in the field. For this reason, a pivoting boom was mounted on the harvesting aid frame, and the cutting device was suspended from the boom with an elastic cord. The boom and elastic cord arrangement fully supported the weight of the cutting device while allowing complete freedom of movement for the operator. The boom, 1.2 m long and adjustable in height, could be used for suspending the cutting device either in front of or behind the harvesting aid. The cutting device and harvesting aid arrangement was designed so that the cutting device could be operated from a seated position over the broccoli in front of the harvesting aid, as shown in Figure 20, or from a standing position walking behind the harvesting aid.

Broccoli heads harvested with the cutting device were collected by lifting the head from the top of the housing with the free hand. The broccoli head was then placed in or tossed to a collection bin in the same manner as with hand cutting. The collection bin could be positioned behind the harvesting aid frame for walking operation of the cutting device, or it could be positioned to the side of the frame for seated operation (see Figure 20).

A final modification required for the harvesting aid was a foot-operated clutch located below the seat of the cutting device operator. This clutch was operated by pivoting the left foot on a bar to depress a lever which was attached by a small cable to the harvesting aid clutch. This feature was required because the harvesting aid had to slow down or stop each time a broccoli head was harvested with the cutting device. Stop-and-go operation of the harvesting aid could have been avoided by using an extremely slow forward speed, but then excessive time would have been lost between harvested heads. The foot clutch allowed the cutting device operator to start and stop the

Figure 20. Vegetable harvesting aid with the cutting device operated from the seated position.

harvesting aid as needed when harvesting from the seated position. For walking operation, there was no way for the cutting device operator to control the harvesting aid, so the harvesting aid driver had to watch the harvesting operation and start and stop the harvesting aid as needed.

5.2 1987 Season

5.2.1 Experimental Procedure

Harvest tests were conducted during the fall of 1987 to evaluate the performance of the broccoli cutting device. The main objectives of the tests were to determine which method of operation (seated or walking) worked best and to evaluate the effects of different planting patterns and harvests on the harvest rate with the device. The following planting patterns were used:

A. Double rows 30 cm (12 in.) apart, 106 cm (42 in.) center to center, with an in-row plant spacing of 15 cm (6 in.).

B. Triple rows 53 cm (21 in.) apart, with an in-row plant spacing of 15 cm (6 in.).

C. Triple rows 30 cm apart, with an in-row plant spacing of 23 cm (9 in.).

Planting pattern A is most commonly used commercially. Planting patterns B and C were designed to achieve the same plant population densities as pattern A. For the tests, the cutting device was operated on one double row of pattern A, two of the rows of pattern B, and all three of the rows of pattern C so that the density was constant over all three of the planting patterns.

Broccoli plots (cv. Emperor) were direct-seeded at the Virginia Tech Horticulture Farm on July 24, 1987. Standard recommendations regarding cultural practices such as irrigation, cultivation, and fertilization were followed (O'Dell et. al., 1987). Plots were overseeded and thinned to the desired in-row spacing approximately three weeks after planting. A split plot, randomized block design was used for the main experiment. There were three blocks, with plots of each of the three planting patterns within each block. Each plot was split for the two methods of operation (walking and seated). The plots were 15.2 m (50 ft.) long.

Tests consisted of harvesting the mature broccoli heads with the cutting device from a 12.2 m (40 ft.) section marked within each plot and measuring the time required. After each test, the number of mature heads harvested was counted. The number of heads damaged by the cutting device and the number of heads missed was also counted. Each of the plots was harvested three times with the cutting device using the same method of operation each time. The first harvest was from October 9 to 13, the second was from October 16 to 21, and the third was from October 28 to November 2.

Plots were also hand harvested before and after the three main tests so that the total number of broccoli heads harvested from each plot over the entire season would be known. Guard rows in each plot were also hand harvested over the entire season. After all of the mature heads were cut from each plot, either by hand or using the cutting device, a count was made of the plants left uncut in the plot so that the total stand in each plot could be determined. The percentage of mature broccoli heads harvested from cutting device plots and from guard rows was compared to determine if there was any yield reduction due to mechanical harvesting.

In addition to the three blocks used for the main experiment, a fourth block was planted and used both for practice with the cutting device and for a separate test. Because the cutting device was being tried for the first time, extensive preliminary practice was done before the harvest tests in order to minimize possible operator learning curve effects. The separate test was conducted to evaluate the possibility of operating the cutting device on two double rows at once. This possibility was considered important for adoption of the cutting device by broccoli producers because only half as many passes through the field would be required. Only the walking method could be used for harvesting two double rows at once because it was impossible to reach both double rows from the seated position. There were three replications of the two double rows, and each replication was harvested three times, at approximately the same times as the harvests for the main experiment.

Time studies of commercial broccoli harvest operations were conducted during the fall of 1987 for use as a basis of comparison for evaluating the performance of the cutting device. Broccoli cutting operations were timed at two farms on the same day. At one farm, the leaf-stripping was done by the person cutting the broccoli. At the other farm, the leaf-stripping was done in a separate operation using the leaf-breaking rings. At both farms, the times to strip the leaves and to cut the heads were measured with a stop watch as workers harvested the broccoli from 7.6 m (25 ft.) lengths of row marked within the field. Harvests from six locations were timed at each farm.

5.2.2 Results and Discussion

The results of the harvest test using the cutting device were analyzed as a 2 x 3 x 3 factorial experiment. The factors were two methods of operation, three planting patterns, and three harvests. The harvest rate results for each of the factors are shown in Table 12. The harvest test data are shown in Appendix D. Overall, the average harvest rate with the cutting device was about 11.1 heads/min. The harvest rate was not significantly affected by either the method of operation or the planting pattern. However, the harvest rate increased significantly with each successive harvest.

The average number of heads harvested in the plots for each factor has been included in Table 12 to illustrate the probable effect of the number of heads harvested on the harvest rate. The number of heads harvested was relatively constant for both the method of operation and the planting pattern, but it increased substantially with successive harvests. With more heads to harvest, there is less lost time between heads, so the harvest rate should be faster. In order to account for the possible effect on the harvest rate, the number of heads was included as a covariate in the

Table 12. Harvest rate results with the broccoli cutting device for three different factors for the 1987 season.

Factor		No. Heads[1]	Harvest Rate (heads/min)
Method	Walking	25.2	10.8 Ns[2].
	Seated	24.4	11.4
Planting Pattern	A	22.0	10.8 Ns
	B	23.9	11.4
	C	28.2	11.1
Harvest	1	17.1	8.7 a[3]
	2	26.1	11.3 b
	3	30.4	14.1 c

[1] Average number of heads harvested in the plots for each factor.

[2] Factor effect nonsignificant at the $\alpha = 0.05$ level.

[3] Values followed by the same letter are not significantly different ($\alpha = 0.05$) by Duncan's Multiple Range Test.

statistical model analyzing the results. The effect of the number of heads harvested was found to be highly significant [$P(f) < .004$], but its inclusion as a covariate did not change any of the other results. Including the covariate allows the use of the method of least squares means to adjust the results for the number of heads. Table 13 shows the adjusted results.

The fact that the adjusted harvest rate still increased significantly with successive harvests indicates that factors other than the number of heads had an effect. The clearing out of the plots that occurred from previous harvests probably had the biggest effect. The heads became more visible and therefore easier to select with successive harvests, and there was less resistance to pushing the device down because of reduced foliage. Also, the heads were taller later in the season, as shown by the results of the physical properties study, and this contributed to reduced resistance because the device did not have to be pushed down as far. The faster harvest rate may have reflected some operator learning curve effect, because this was the first time that the device had been used. However, a substantial amount of practice was done with the cutting device before the tests were started, so the learning curve effect should have been minimal.

The results for the damaged and missed heads are shown in Table 14. None of the factors had any significant effect on damage. Heads were rated as damaged if they showed any signs of damage from the cutting device. They did not have to be unmarketable to be counted as damaged. Observations of commercial harvests showed that most of the heads rated as damaged in these tests would have been acceptable to commercial producers. Less than 2% of the heads harvested in the tests were damaged severely enough by the cutting device to be unmarketable. Commercial hand harvesting appeared to leave a greater percentage of the heads damaged to the point of unmarketability. The only factor that significantly affected the percentage of heads missed was the harvest. The percentage decreased significantly with successive harvests. This result parallels the harvest rate results and reflects both the increased visibility within the plots and the learning curve effect. It is interesting to note that commercial hand harvesting was observed to leave an occasional mature broccoli head unharvested. The number of heads missed by hand cutting was estimated to be 1 in 20 (5%), which is in the range of the percentage missed with the cutting device.

Table 13. 1987 broccoli cutting device harvest rate results adjusted for the number of heads harvested.

Factor		Harvest Rate, LSMeans (heads/min)
Method	Walking	10.7
	Seated	11.4
Planting Pattern	A	11.0
	B	11.4
	C	10.7
Harvest	1	9.4
	2	11.2
	3	13.1

Table 14. Percentages of heads damaged and missed during the 1987 broccoli cutting device field test.

Factor		Damaged (%)	Missed (%)
Method	Walking	8.6 Ns[1]	3.6 Ns
	Seated	7.8	5.6
Planting Pattern	A	10.1 Ns	4.8 Ns
	B	6.3	4.5
	C	8.3	4.6
Harvest	1	7.4 Ns	8.5 a[2]
	2	11.0	4.0 b
	3	6.2	1.7 b

[1] Factor effect nonsignificant at the $\alpha = 0.05$ level.

[2] Values followed by the same letter are not significantly different ($\alpha = 0.05$) by Duncan's Multiple Range Test.

The results for the percentage of heads harvested are shown in Table 15. Included in the table are the results for the different blocks and planting patterns as well as a comparison of hand harvesting with the two methods of operation with the cutting device. One of the blocks had a significantly lower percentage of heads harvested, indicating that the plants in that block were less mature overall because fewer of them reached marketable size by the end of the harvest season. The percentage of heads harvested was also significantly lower for planting pattern A. Pattern A had a closer spacing of the plants than the other planting patterns which probably delayed maturity. The closer spacing may have also contributed to damage to unharvested plants by the cutting device, which could have reduced yield. The percentage of heads harvested from the hand-harvested guard rows was only slightly higher than from the cutting device plots using either method of operation. The difference was not statistically significant, indicating that any yield reduction due to mechanical harvesting was negligible.

The results of the separate test to determine if the cutting device could be operated on two double rows in one pass are shown in Table 16. The results for planting pattern A using the walking method have been included in the table for comparison since pattern A was the pattern used for the tests on two double rows. The harvest rate for two double rows was faster for all three harvests, although the advantage decreased with each successive harvest. This decreasing advantage supports the conclusion that the harvest rate was significantly affected by density of harvestable heads. Twice as many heads should be available with two rows instead of one, and the increased number of heads would have a greater effect earlier in the harvest season when fewer mature heads are present. The fact that the harvest rate advantage was so small by the last harvest indicates that there is a limit to the advantage of more heads. The advantage comes from a decrease in the time required to locate and move to the next head to be harvested. If the time to locate and move to the next head is eliminated, there is still a base time required for cutting and collecting the head.

At the farm where the leaf-breakers were not used, the harvest rate ranged from 9.60 to 3.95 heads/min, with an average of 7.11 heads/min. At the farm where the leaf-breakers were used, the rate ranged from 12.5 to 4.04 heads/min, with an average of 7.62 heads/min. The average hand

Table 15. Percentages of total heads harvested from 1987 plots.

Factor		Percentage Heads Harvested
Blocks	1	90.6 a[1]
	2	91.1 a
	3	84.6 b
Planting Pattern	A	85.4 a
	B	89.8 b
	C	90.6 b
Method	Hand Harvested	89.9 NS[2]
	Walking	88.9
	Seated	87.4

[1] Values followed by the same letter are not significantly different ($\alpha = 0.05$) by Duncan's Multiple Range Test.

[2] Factor effect nonsignificant at the $\alpha = 0.05$ level.

Table 16. Comparison of harvest rates for cutting device operated on one double row and two double rows.

Harvest	Harvest Rate (heads/min)	
	One Double Row[1]	Two Double Rows
1	8.7	10.3
2	10.6	11.5
3	13.8	14.2

[1] Results are for walking operation of the cutting device on planting pattern A.

harvest rate by both methods was about 7.4 heads/min. The average harvest rate with the cutting device (11.1 heads/min) was approximately 50% faster than the average measured hand harvest rate.

Overall, the cutting device performed very well for a first prototype. It was easy to operate either walking or seated, and the suspension system satisfactorily supported the weight with no interference to operation. It proved to be a natural and easy motion to lift the cut head out of the top of the housing for collection after letting the cutting device spring back up due to the tension of the elastic cord. The harvest rate with the cutting device was substantially faster than the hand harvest rate measured at two different farms.

There were some problems, however. The device caused some discomfort to the hand after a period of operation. This discomfort seemed to be due mainly to the design of the handle grip. It was difficult to push the device far enough down over the broccoli head because of the resistance of the foliage of the closely spaced plants. Because of this difficulty, there was a tendency to cut the heads too short, and leaves were often left attached to the stalk. A comparison between four broccoli heads harvested with the cutting device (top) and four broccoli heads cut, stripped, and trimmed by hand (bottom) is given in Figure 21. The heads harvested with the cutting device are no longer than the hand cut heads which were trimmed to the approximate length that they would be cut in the bunching machine. Most of the leaves were broken by the cutting device, but they were not completely detached from the stalk. The broccoli heads shown in Figure 20 would require an additional operation to remove leaves still attached to the stalk. An additional operation would certainly offset to some extent the harvest rate advantage with the cutting device.

The stop-and-go harvesting aid operation that was required was also a problem. This problem was easily overcome for seated operation by using the foot-clutch, but the use of a foot-clutch would not be practical if more than one cutting device were being operated from the same harvesting aid. For walking operation, the harvesting aid driver had to watch the harvesting operation and stop and start the harvesting aid as needed. This situation would be unacceptable for a commercial harvesting system no matter how many cutting devices were being used. Because of the

Figure 21. Broccoli heads harvested with the cutting device (top) and cut and trimmed by hand (bottom).

advantage of covering more ground in one pass, and considering the results of the harvest test on two double rows at once, walking operation of the cutting device seems to be the best method. However, the problem of stop-and-go harvesting aid operation must be overcome for the walking method to be practical.

5.3 1988 Season

5.3.1 Cutting Device Modifications

A new cutting device, incorporating several modifications based on the 1987 results, was designed and fabricated in 1988. The basic design of the cutting mechanism was the same, although the linkage components were changed somewhat to make the cutting action more effective. A cylinder with a longer stroke, 5 cm (2 in.), was used so that the blades would overlap more in the center when they were closed. The linkage end of the blades was made longer to give the blades a bigger lever arm, thereby increasing the cutting force. The linkage end of the blades was also positioned differently so that its rotation was symmetric about a line through the two blade pivot points. As shown in Figure 22, this feature makes the connecting links have a parallel position when the blades are open or closed. If these links hold their relative position, then design changes such as lengthening the blade lever arm or changing the size of the pivot pin can be made without affecting the initial and final positions of the blades. Also, the angle between the connecting link and the linkage end of the blade can be made nearer to 90° to maximize force transmission.

The most important modifications made to the cutting device were a new handle grip design, a new mounting arrangement on the harvesting aid, and the addition of spring-loaded leaf-stripping arms. The new handle grip was made from a 3.2 cm (1 1/4 in.) diameter aluminum tube that was held in the longitudinal direction. A miniature valve attached to the end of the tube was activated

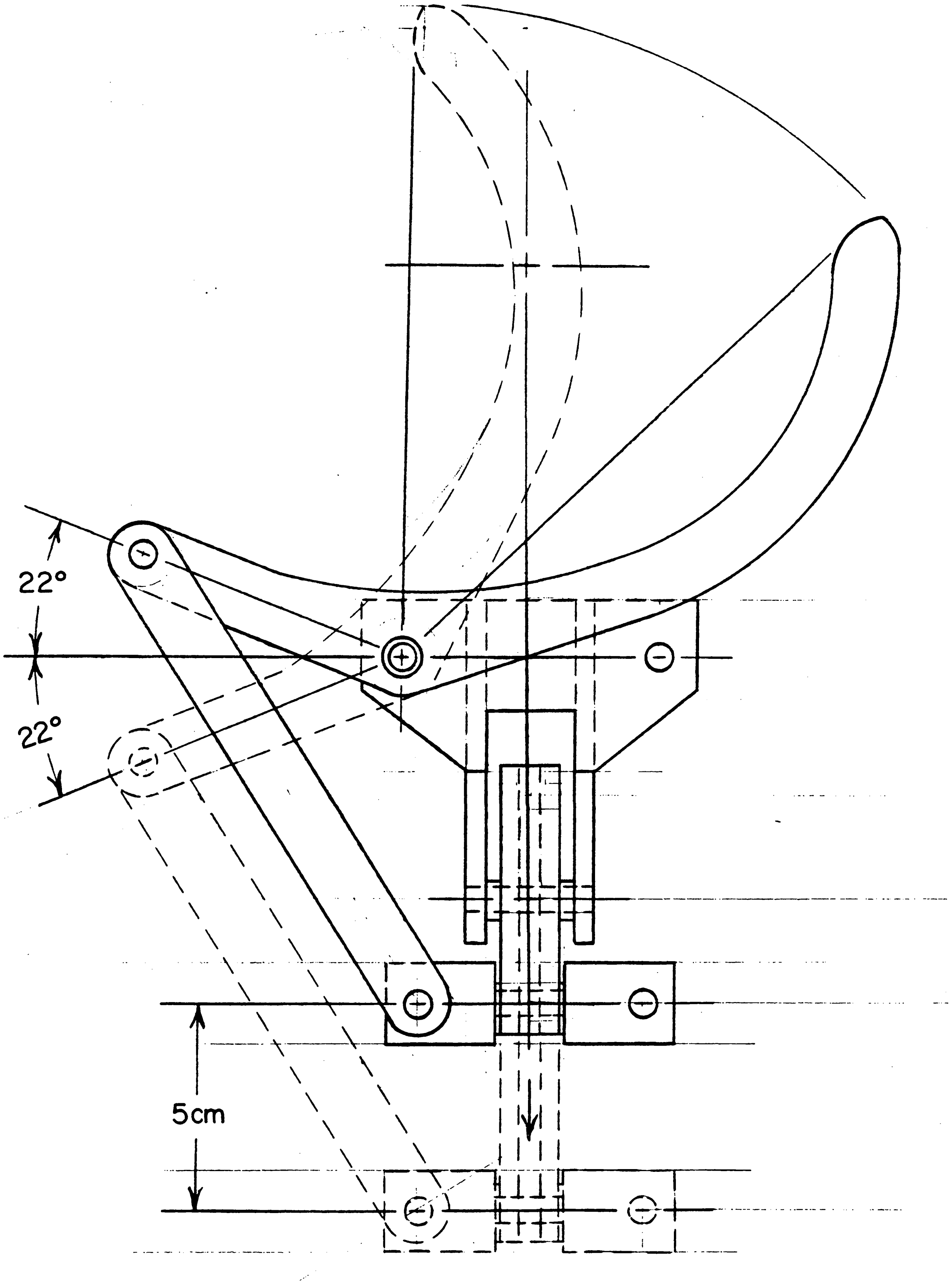


Figure 22. Bottom view of the cutting mechanism, second prototype.

by a trigger depressed by the index finger. With this arrangement, the cutting device could be operated with either the left hand or the right hand. The tube was clamped to the handle frame at a point behind the main part of the cutting device so that the handle grip could be adjusted for proper balance of the cutting device with no interference to the fingers where they wrapped around the grip.

The new mounting arrangement was designed only for walking operation so that two double rows could be harvested at once. To overcome the problem of stop-and-go travel, the cutting device was suspended from a sliding block that moved along a track on the pivoting boom. Since the cutting device was free to move along the length of the pivoting boom, the harvesting aid could move forward at a steady pace while the cutting device operator stopped to cut the broccoli heads. To maximize the advantage of the sliding support, the boom had to be as long as possible, yet it had to be light enough to pivot easily and strong enough to resist bending. Figure 23 shows the new pivoting boom with the sliding support mounted on the back of the harvesting aid. The boom had a of 2.75 m (9 ft.) track on which the sliding block could move. Self-coiling air hose wrapped around the boom track extended and retracted easily as the cutting device was moved back and forth. A short extension opposite the boom was connected by an elastic cord to the harvesting aid frame so that the boom tended to pull back to its original position when it was released.

The spring-loaded leaf-stripping arms were added to the cutting device in an attempt to substantially improve the leaf-stripping capabilities of the device. The curved arms, which were located approximately 2.5 cm (1 in.) below the cutting blades and pivoted on the same pins, were designed to close around the broccoli stalk just beneath the head and strip the leaves from the stalk as the device was pushed down. When open, the arms formed a ring approximately 18 cm (7 in.) in diameter. The arms were made of 3 mm (1/8 in.) by 14 mm (9/16 in.) steel which was ground into a convex cross-section so that the upper and lower edges would cut the leaf stems without cutting into the stalk.

Coil springs mounted on each pivot pin provided the force to close the leaf-stripping arms. The arms were reopened and reset for the next broccoli head by the movement of the cutting

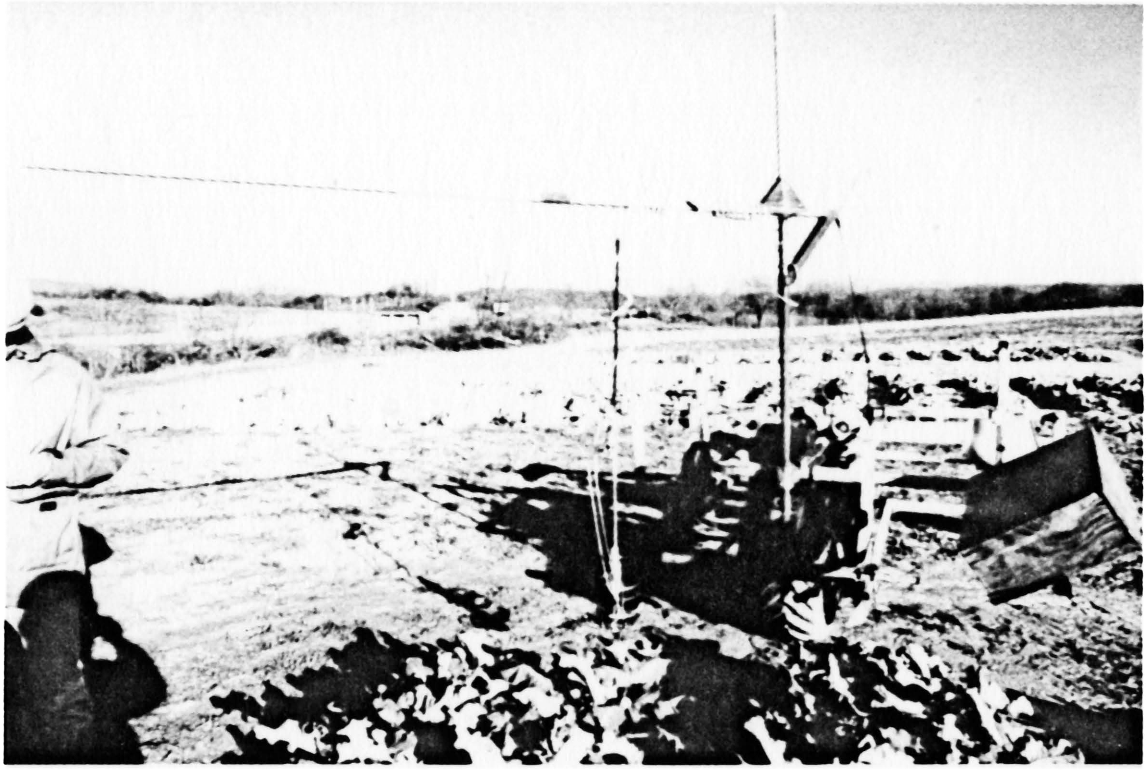


Figure 23. Pivoting boom with sliding support for the cutting device designed for walking operation only.

mechanism as the cylinder was retracted to open the blades. The mechanism for resetting the arms consisted of a small ram added to the short link joining the triangle link and the pivot pin. This ram pushed against the back of a hinge connected to the mounting brackets of both leaf-stripping arms. The arms were forced open as the ram pushed against the hinge, straightening it. The hinge became rigidly set when it was fully straightened and the arms fully opened. Figure 24 shows the leaf-stripping arms and the mechanism for resetting them. The leaf-stripping arms are closed so that the hinge is bent rearward. The cylinder is extended, and the ram is in position to reset the hinge as the cylinder retracts. It should be noted that the ram pivoted freely in the upward direction so that it could slide over the hinge as the cylinder extended. Also, after the arms were open and the hinge set, the ram continued its motion until it cleared the hinge so that there was no obstruction to the hinge when the arms closed again.

The hinge had to be sprung in order to trip the arms to close just beneath the broccoli head. Originally, a small plunger which was depressed when a lever pushed against the top of the broccoli head was used to spring the hinge. The plunger had a small wedge on the bottom that pushed against the front of the hinge. The plunger assembly was able to trip the leaf-stripping arms closed as required, but problems were encountered with the lever that extended into the center of the open ring area to contact the top of the broccoli head. The lever interfered with the broccoli head as the head pushed up into the housing, and eventually the lever broke off. A different mechanism which pushed against the hinge from underneath was then tried. This mechanism had a small lever that was located beneath the leaf-stripping arms. The lever was pushed against the side of the broccoli head or stalk, causing it to pivot and push against the front of the hinge to trip the arms to close. This mechanism worked satisfactorily and was used for the harvest tests with the device. Figure 25 shows the leaf-stripping arms beneath the cutting mechanism and the final version of the mechanism used to trip the arms.

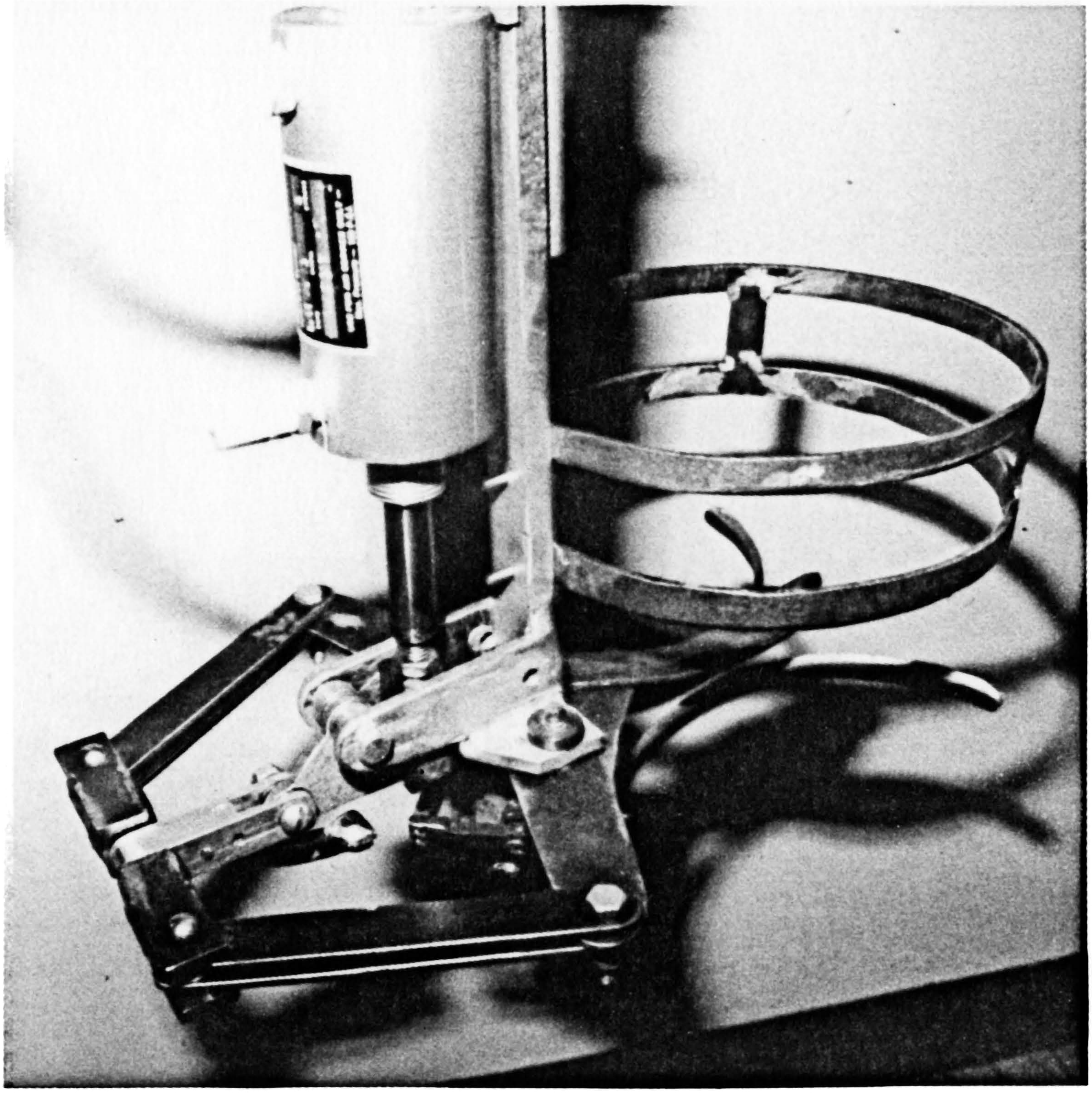


Figure 24. Spring-loaded leaf-stripping arms in the closed position with the ram in position to reset them.

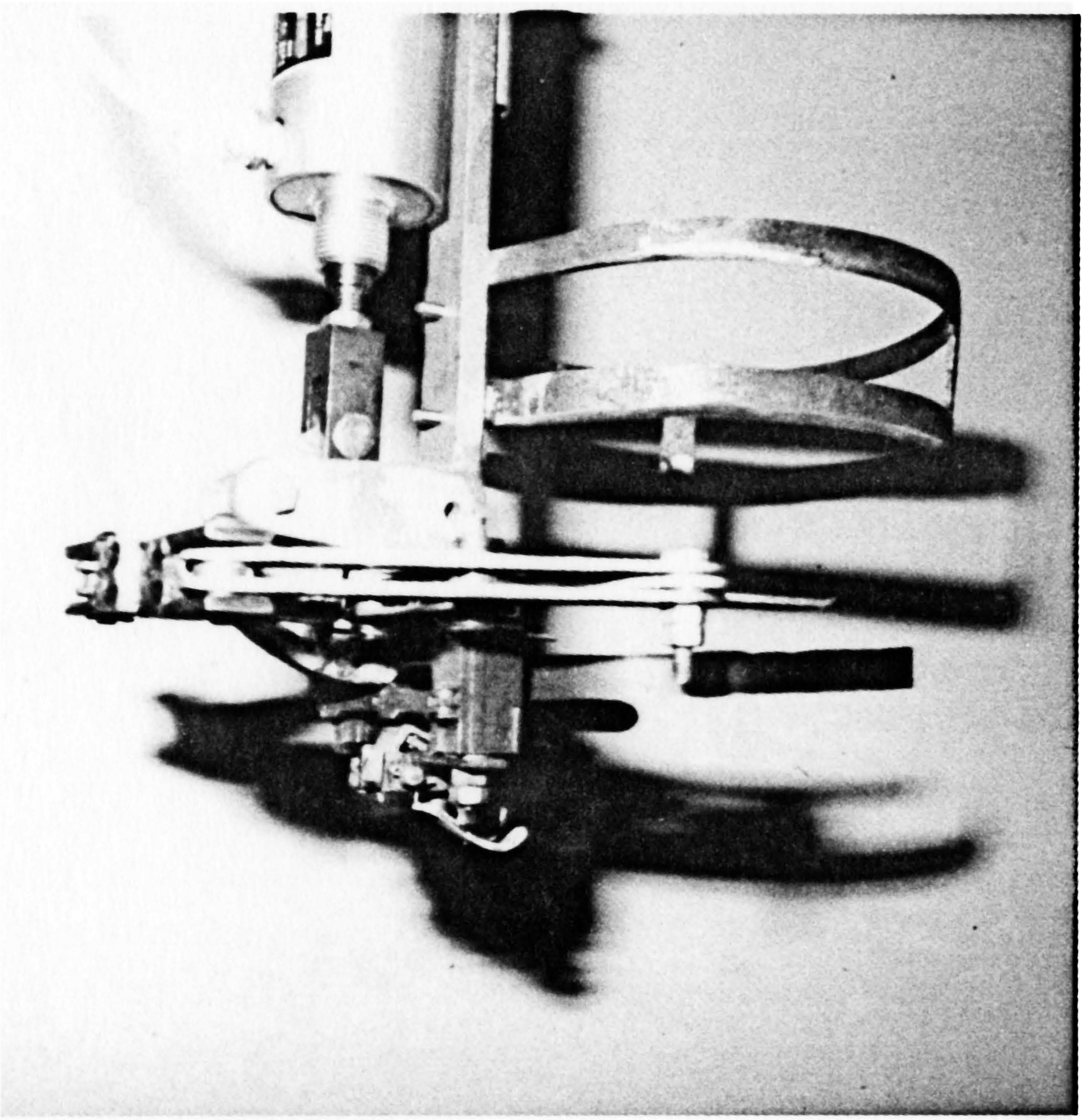


Figure 25. Leaf-stripping arms and the trip mechanism for closing them.

5.3.2 Experimental Procedure

Harvest tests were conducted during the fall of 1988 to evaluate the performance of the new cutting device. Only the walking method was used, and two double rows were harvested at once. A major objective of the tests was to determine if the harvest rate with the cutting device was affected by changes in plant population density. In the 1987 test, different planting patterns had little effect on the performance of the cutting device. However, there was some indication, as evidenced by the significant effect of the number of heads harvested, that different population densities might effect cutting device performance. Of additional interest were effects on performance due to different harvest times and the spacing between double rows. The double-row spacing was considered important because of the reaching to either side required for harvesting two double rows at once.

There were three factors in the harvest test; in-row plant spacing or plant population, double-row spacing, and harvest time. The three in-row plant spacings were 15 cm (6 in.), 23 cm (9 in.) and 30 cm (12 in.). These spacings gave plant population densities of 109,300, 71,300 and 54,600 plants/ha for double rows planted on 122 cm (48 in.) centers. The two double-row spacings were 30 cm (12 in.) and 46 cm (18 in.). There were three harvests. A randomized block design was used for the experiment. There were three blocks with the six planting combinations randomized within each block. Additional broccoli plots were planted for preliminary practice with the cutting device and for the physical properties experiment. The broccoli (cv. Packman), was planted on August 3 at the Virginia Tech Horticulture Farm. Standard recommendations regarding cultural practices such as irrigation, cultivation, and fertilization were followed. Plots were overseeded and thinned to the desired in-row plant spacing approximately three weeks after planting.

The plots were only 9.1 m (30 ft.) long for the 1988 experiment. For the tests, broccoli was harvested from a 6.1 m (20 ft.) section marked within each plot. Because two double rows were harvested at once, the total length of row harvested during each test was the same as in 1987 when a single row 12.2 m (40 ft.) long was harvested. Each of the plots was harvested three times with the cutting device. The first harvest was on October 18, the second was on October 24, and the third was on November 7.

No formal time studies of commercial harvest operations were done during the 1988 harvest season. However, harvest operations were videotaped during two visits to one farm. The videotape was analyzed in order to measure the harvest rate of workers cutting broccoli by hand.

5.3.3 Results and Discussion

The results of the harvest test with the cutting device were analyzed as a 2 x 3 x 3 factorial experiment, with two double-row spacings, three in-row plant spacings, and three harvests. The results for each of the factors are shown in Table 17. The 1988 harvest test data are shown in Appendix E. Overall, the average harvest rate with the cutting device was 11.4 heads/min. The harvest rate was not significantly affected by the double-row spacing, but was significantly affected by the in-row plant spacing, or the plant population. The harvest rate was fastest for the 23 cm spacing, although the difference between the slowest rate (for the 15 cm spacing) and the fastest rate was only 0.5 heads/min. The harvest had a strong effect on the harvest rate, just as it did in 1987. The harvest rate increased significantly with each successive harvest.

The average number of heads harvested in each plot has been included in Table 17 to illustrate the difference between the 1987 and 1988 results. In 1987, the plant population density was constant for all three planting patterns, and the number of heads harvested increased substantially with each harvest (see Table 12). This increase partially accounted for the significant effect of the harvest time on the harvest rate, as evidenced by the fact that the effect of the number of heads harvested was statistically significant. In 1988, the number of heads harvested stayed relatively constant from harvest to harvest, and the effect of the number of heads harvested was not statistically significant. Yet the harvest rate still increased significantly with successive harvests, indicat-

Table 17. Harvest rate with the broccoli cutting device for three different factors during the 1988 season.

Factor		Number of Heads[1]	Harvest Rate (heads/min)
Double-Row Spacing (cm)	30	26.9	11.4 Ns[2]
	46	27.6	11.3
In-Row Plant Spacing (cm)	15	33.2	11.1 a[3]
	23	25.8	11.6 b
	30	22.7	11.4 ab
Harvest	1	28.3	10.3 a
	2	22.6	10.9 b
	3	30.7	13.4 c

[1] Average number of heads harvested in the plots for each factor.

[2] Factor effect nonsignificant at the $\alpha = 0.05$ level.

[3] Values followed by the same letter are not significantly different ($\alpha = 0.05$) by Duncan's Multiple Range Test.

ing the strong influence of other factors, such as the clearing out of the plots, on the increase in harvest rate.

Actually, for the different in-row plant spacing treatments, the number of heads harvested did change with successive harvests, as shown by the physical properties results (see Figure 9). At the 15 cm spacing (with the highest plant population density), the number of heads harvested increased substantially with each successive harvest. At the 30 cm spacing (with the lowest plant population density), this trend was reversed. The combined effect was a lack of uniform increase in the number of heads with successive harvests. Even though the number of mature heads from each plant spacing treatment was changing from harvest to harvest, the number of heads harvested still did not have a significant effect on the harvest rate in 1988. This lack of effect was due to the change to harvesting two double rows at once, which was done specifically for the purpose of minimizing lost time between harvested heads. Lost time is minimized with two double rows because the density of heads available for harvesting for a given length of row is much higher. The total length of row covered in the 1988 harvest tests was the same as in 1987, and the average number of heads harvested per cutting in each plot was about the same (27.3 in 1988, 24.8 in 1987), but the cutting device was operated over a distance of only 6.1 m in 1988 versus 12.2 m in 1987.

The results for the damaged and missed heads are shown in Table 18. None of the factors had any significant effect on damage. As in 1987, the damage criterion was stricter than that used for commercial harvests, and the observed level of damage harvesting with the cutting device appeared to be as low or lower than that of commercial hand harvesting. Overall, the percentage of heads damaged in 1988 (approximately 10%) was higher than in 1987 (approximately 8%). The higher level of damage could have been due to the short lever used to trip the leaf-stripping arms as the cutting device was pushed down over the broccoli head. The cutting device had to be directed so that the lever pushed against the side of the head or the stalk, and it sometimes appeared to cut into the head. However, it is difficult to make comparisons of results from two different years for a subjective parameter such as damage. The damage results were much more consistent in 1988 than in 1987 (see Table 14), indicating a change in subjectivity between the two years.

Table 18. Percentage of heads damaged and missed during the 1988 season.

Factor		Damaged (%)	Missed (%)
Double-Row Spacing (cm)	30	10.7	3.9 Ns[2]
	46	8.9	3.5
In-Row Plant Spacing (cm)	15	9.3 Ns	5.1
	23	9.2	3.4
	30	11.0	2.4
Harvest	1	10.7 Ns	8.5 a[2]
	2	9.7	1.4 b
	3	9.1	1.1 b

[1] Factor effect nonsignificant at the $\alpha = 0.05$ level.

[2] Values followed by the same letter are not significantly different ($\alpha = 0.05$) by Duncan's Multiple Range Test.

The only factor that significantly affected the percentage of heads missed was the harvest, just as in 1987. The percentage of heads missed was much higher for the first harvest than for the second and third harvests. This result reflects both increased visibility due to the clearing out of the plots and the learning curve effect. Although the percentage of heads missed was not significantly affected by the plant spacing, it is interesting to note that the percentage of heads missed decreased as the spacing increased, as would be expected.

Harvesting operations videotaped during two different visits to one farm included leaf-stripping using the leaf-breaking rings, cutting of broccoli heads previously stripped with the leaf-breaking rings, and cutting and stripping of broccoli heads in one operation. Several different workers were timed from the videotape doing the various operations. The average rate for three different measurements of leaf-stripping using the leaf-breaking rings was 25 heads/min. The average rate for four measurements of the time required for cutting previously stripped heads was 13.0 heads/min. The combined harvest rate using the leaf-breaking rings was 8.75 heads/min. The average rate for nine measurements of the time required to cut and strip broccoli heads in one operation was 7.41 heads/min. These results are consistent with the 1987 results, when the average rate at the farm where the leaf-breaking rings were used was 7.62 heads/min, and the average rate at the farm where the leaf-breaking rings were not used was 7.11 heads/min. The average harvest rate with the cutting device in 1988 (11.4 heads/min) was more than 40% faster than the overall average hand harvest rate (approximately 8 heads/min) measured in 1988.

Modifications made to the cutting device based on the 1987 results worked very well. The leaf-stripping arms added to the cutting device in 1988 substantially improved the leaf-stripping capability of the device. Figure 26 shows three sets of broccoli heads. The top set was harvested with the cutting device using the leaf-stripping arms. The middle set was harvested with the cutting device with a stationary ring in place of the leaf-stripping arms to simulate the leaf-stripping action of the 1987 cutting device. The bottom set was cut, stripped and trimmed by hand. The level of leaf-stripping for the top set of broccoli heads appears much improved over that of the middle set. The stationary ring actually seemed to do a better job of leaf-stripping than the arrangement used

Figure 26. Broccoli heads harvested with the cutting device with the spring-loaded leaf-stripping arms (top), with a ring in place of the leafstripping arms (middle), and cut and trimmed by hand (bottom).

in 1987 because the ring was located below the cutting blades instead of above, so the improvement over the 1987 results was probably even greater than shown. A few smaller leaves can be seen broken but still attached to the stalk in the top set of broccoli heads, but these leaves could be easily removed by the operator of the bunching machine. The few small leaves not removed by the leaf-stripping arms can be attributed to poor synchronization of the closing of the leaf-stripping arms as the device was pushed over the head. An improved trip mechanism that reliably closes the leaf-stripping arms right below the edge of the broccoli head every time would improve the level of leaf-stripping even more.

The modifications made to the cutting device itself, as well as to the entire cutting device harvest system, substantially improved the handling of the device. The new handle grip caused no discomfort to the hand, and its longitudinal orientation made it easier to direct as needed. The new design also allowed the device to be operated with either hand. Less force seemed to be required to push the device all the way down over the broccoli head because of the leaf-stripping arms that cut through the leaf stems close to the stalk. The new boom arrangement with the sliding support provided very good freedom of movement for operating the device on two double rows at once (one to each side of the operator), and it eliminated most of the stop-and-go operation required from the harvesting aid. The harvesting aid still had to stop occasionally in order to prevent getting too far ahead of the cutting device operator, but a slower ground speed better matched to the harvesting rate of the cutting device would have eliminated this.

Despite the improved handling of the 1988 cutting device, the average harvest rate in 1988 (11.4 heads/min) was only marginally faster than in 1987 (11.1 heads/min). Actually, a straight comparison is not valid since the tests involved two different broccoli varieties and different plant population densities. Also, the improved level of leaf-stripping achieved in 1988 makes the effective harvest rate better than it appears in comparison to 1987. Still, a more substantial improvement in harvest rate might have been expected considering the new arrangement for harvesting two double rows at once which should have minimized lost time between harvested heads.

The spring-loaded leaf-stripping arms were probably the cause of the lower than expected harvest rate in 1988. While the arms contributed to better handling and an improved level of leaf-stripping, their use required extra manipulation for proper operation. The cutting device had to be tilted slightly as it approached each broccoli head to make sure that the lever for tripping the leaf-stripping arms brushed against the side of the head or stalk. The rate that the cutting device was pushed down had to be synchronized with the tripping of the arms in order to achieve proper leaf-stripping. An improved trip mechanism for closing the leaf-stripping arms is needed. It should be possible to design a trip mechanism that automatically closes the leaf-stripping arms at the correct time without any extra attention by the cutting device operator. Such a mechanism should make the harvesting rate with the device faster and give a better level of leaf-stripping as well.

A look at the 1988 and 1987 results confirms that the base time required for cutting and collecting each head may have been higher in 1988 due to the leaf-stripping arms. Comparing the 1988 results with the 1987 results for one double row (see Table 16), the harvest rate for two double rows was substantially faster for the first harvest (10.3 versus 8.72 heads/min), about the same for the second harvest (10.9 versus 10.6 heads/min), and slightly slower for the third harvest (13.4 versus 13.8 heads/min). For the first harvest, when there were fewer mature heads, harvesting two double rows improved the harvest rate substantially because of the minimization of lost time between harvested heads. By the third harvest, lost time between harvested heads was minimized for either method because of the greater density of heads to be harvested, and the slower harvest rate in 1988 indicates a higher base time for cutting and collecting each head. As discussed, an improved trip mechanism for the leaf-stripping arms should eliminate extra required manipulation and therefore reduce this base time. With a reduced base time, the harvest system as used in 1988, incorporating both the leaf-stripping arms and the two double row operation, should have a substantially faster harvest rate than the 1987 system.

5.4 Summary and Conclusions

A pneumatically powered, manually directed cutting device for selectively harvesting broccoli was designed and built in 1987. The cutting device combined the leaf-stripping and stalk cutting operations into a single operation by having a powered cutting device on the end of an apparatus similar to the leaf-breaking rings. The cutting mechanism for the device used a combination of slider crank mechanisms to transmit power from a vertically mounted air cylinder to a pair of horizontal curved blades that operated in a scissor action. The cutting device was suspended from a pivoting boom mounted on a self-propelled vegetable harvesting aid for conducting field tests to evaluate the performance of the device. The suspension system was designed so that the device could be operated from a seated position over the broccoli or from a standing position walking behind the harvesting aid. Time studies of commercial harvest operations were also conducted in 1987 for use as a basis of comparison for evaluating the performance of the cutting device.

A new cutting device, incorporating modifications suggested by the results of test in 1987, was designed and built in 1988. The handle grip was redesigned and spring-loaded leaf-stripping arms were added below the blades. A new suspension system with a sliding track on a longer pivoting boom was built so that the device could be operated on two double rows at once by the walking method. Field tests were conducted in 1988 to evaluate the performance of the modified cutting device. Informal time studies of commercial harvest operations were also conducted to substantiate the hand harvest rate results measured in 1987.

The following conclusions were reached based on the results of two years of field tests with the broccoli cutting device.

1. The harvest rate with the cutting device was not significantly affected by either the method of operation (walking or seated) or different constant population planting patterns in 1987 when the device was operated on one double or triple row.

2. The harvest rate with the cutting device was not significantly affected by the double-row spacing in 1988 when the device was operated on two double rows at once by the walking method.

3. The harvest rate with the cutting device was significantly affected by the in-row plant spacing, or plant population density, in 1988. The 23 cm spacing, with a population density of 71,300 plants/ha, had the fastest harvest rate.

4. The harvest rate with the cutting device was significantly affected by the number of heads harvested in each plot in 1987, when the device was operated on one double or triple row, but not in 1988 when it was operated on two double rows at once by the walking method.

5. The harvest rate with the cutting device decreased significantly with successive harvests both years.

6. Harvesting two double rows at once was substantially faster than harvesting one double row early in the season when mature broccoli heads were sparse because of the minimization of lost time between harvested heads.

7. The overall average harvest rate with the cutting device was more than 40% faster than the average hand harvest rate measured at commercial farms both years.

The second prototype of the broccoli cutting device worked very well. The leaf-stripping arms added to the device achieved a level of leaf-stripping approaching that of hand stripped broccoli heads. The device could be operated on two double rows at once by the walking method with the new suspension system that allowed the cutting device to move freely along the length of the boom. The harvest rate with the device was more than 40% faster than hand harvesting rates measured at commercial farms, and the potential exists for an even faster harvest rate with a different mechanism for tripping the leaf-stripping arms to close. The broccoli cutting device could be used by broccoli producers to reduce harvest costs by speeding up harvest operations or reducing the size of harvest crews. It has significant advantages over other harvest mechanization strategies because of low cost and ready integration into existing harvest systems. The powered broccoli cutting device represents a significant development in the mechanization of the harvest of broccoli.

Chapter VI

AUTOMATIC MATURE HEAD SELECTION

The development of an automatic selective broccoli harvester is dependent upon the development of some means of automatically selecting the broccoli heads that should be harvested. With broccoli, maturity is primarily a subjective determination based on head size. Marketability is based on other factors as well, such as having a compact head and the head being absent of flowers which indicate overmaturity, but size is the main criterion used by workers cutting the heads by hand. A mature head selection system capable of selecting heads based only on head size should be sufficient for broccoli harvesting applications. The capability of selecting or rejecting heads based on other factors is not very important for two reasons. Poor quality heads that are harvested can be easily sorted out during manual handling required for bunching the broccoli, and heads that are unmarketable based on quality will not become marketable later, so there is no need to leave them in the field for subsequent harvests.

There are two possible ways of selecting mature heads based on size. One way is to size the heads physically. Selective harvesting concepts involving a physical sizing of the fruit or harvested part have been tried for cantaloupes, lettuce, cauliflower and peppers (Harriot et al., 1970; Lenker et al., 1973; Lenker et al., 1978; Fullilove and Futral, 1972). Physical sizing has a possible advantage in that loose heads which may be large enough to be harvested, but are not of marketable quality, may be rejected as too small by the sizing system. However, physical sizing may be difficult with broccoli because the harvested part is so much smaller than with vegetables such as cantaloupe, lettuce, or cauliflower. Also, the widely spreading leaves of broccoli plants may hinder sizing or be damaged in the sizing process.

The other possible way to select mature heads based on size is to use an image processing system to make a visual determination of size. Machine vision systems have been tried for several selective tree fruit harvesting applications (Parrish and Goksel, 1977; Sites and Delwicke, 1985; D'Esnon et al., 1987). Machine vision systems have the potential to determine head size without any physical contact with the plant, but the level of technological sophistication required for such systems could make them prohibitively expensive. Another problem with image processing is that it may be difficult to achieve proper synchronization between image analysis and the harvesting action under field conditions. Most tree fruit harvesting applications have involved a stationary harvester with the picking mechanism operating on fruit that are still in the field of view of the camera of the image processing system. For harvesting broccoli, the heads will be moving in and out of the field of view very quickly, much like inspection applications where the objects are carried on a conveyor past a stationary camera. However, conditions in the field will be much less controlled because the spacing between plants will not be totally uniform and the field speed of the tractor or harvester will be variable.

Despite the problems with size determination methods, the potential increase in harvest efficiency with an automatic selective broccoli harvester makes the development of mature head selection systems desirable. Investigations were conducted during the fall of 1988 to evaluate the potential of two methods for selecting mature broccoli heads based on size; one method involving a physical sizing of the broccoli heads and the other a visual determination of size using digital image processing. The investigations were conducted on the same broccoli grown for harvest tests with the broccoli cutting device.

6.1 Physically Sizing Broccoli Heads Using Spaced Fingers

A simple way of physically sizing broccoli heads is to pass the heads through an opening of a certain size. In the field, this operation can be accomplished by pulling spaced fingers upward through the plant canopy so that plants with mature broccoli heads are obstructed from passing through and are therefore uprooted. With this concept, the head selection and harvesting operations are combined in a single operation. A further advantage of this concept is that a fairly simple mechanism can be used to produce the desired action. The mechanism, which was tried by Fullilove and Futral (1972) and Siow (1979) for selectively harvesting different kinds of peppers, has spaced horizontal fingers mounted on inclined roller chain and sprocket assemblies. The fingers enter the plant canopy near the ground as they come around the lower sprocket, and they rake upward through the plant as they move up the incline. A harvester based on this concept would consist of the inclined raking mechanism plus a cut-off saw for severing the root ball from the plant and conveyors for collecting the plants as they dropped from the fingers at the point where the fingers spread apart going around the upper sprocket.

There are two major factors on which the feasibility of this concept depends. First, the damage to immature plants must not be severe enough to prevent the development of marketable heads for subsequent harvests. The leaves of the broccoli plant as well as the head itself will have to pass through the spaced fingers, and if the leaves are broken or shredded too severely, proper head development may cease. Second, the force required to uproot the plants must be low enough so that plants with mature heads are uprooted before the sides of the head deform from the force of the fingers. If the force required to uproot the plants is too high, even large heads will pull through the spaced fingers, and the sides of the heads will be crushed in the process. Broccoli plants have shallow rooting systems, a condition which should contribute to reduced uprooting force requirements, but the uprooting force may still be high due to compaction or soil surface crusting.

6.1.1 Preliminary Trials

Preliminary trials were conducted to determine if broccoli plants with mature heads could be uprooted by a raking action of spaced fingers. In these trials, special attention was given to leaf and head damage. A simple device with adjustable metal fingers, 1.3 cm in diameter and 28 cm long, was constructed and used to rake broccoli plants with a range of head sizes. The initial trial was conducted on October 20, 1988 with the fingers spaced first at 8.5 cm (3 3/8 in.) and then at 6.4 cm (2 1/2 in.). In both cases, plants with very large heads (over 13 cm in diameter) were uprooted with little or no damage to the heads. Very small heads (more than 1 cm smaller than the opening between the fingers) pulled through the fingers with little damage to the leaves, although a few leaves were broken off or shredded. However, in both cases most of the intermediate size heads (ranging from the size of the opening between the fingers to approximately 4 cm greater in diameter) were not uprooted. These heads experienced damage where the sides of the heads were crushed as the heads pulled through the fingers.

The level of leaf damage sustained by the plants was lower than expected. The fingers were inserted near the ground so that all of the leaves were trapped between two fingers. As the fingers raked upward, the leaves bent upward and they actually seemed to shield the broccoli head from damage, but in most cases they were not broken off or shredded. Damage to intermediate size heads was a problem, however. Ideally, there would be a distinct size boundary above which all the heads would be uprooted and below which all heads would be left undamaged. Instead, a range of intermediate size heads were not uprooted and sustained damage.

The results from the first attempt at uprooting plants indicated that the main limitation to the use of the spaced-finger concept was the high force required to uproot plants, causing a wide range of intermediate size plants not to be uprooted and to sustain damage. Since soil conditions were relatively dry for the first trial on October 20, it was reasoned that wetter soil conditions might lower the required uprooting force, thereby narrowing the range of heads not uprooted and damaged.

To test this hypothesis, the spaced fingers were used to rake broccoli plants again on November 1, after approximately 1.3 cm (1/2 in.) of rain the previous evening. The fingers, spaced first at 6 cm (2 3/8 in.) and then at 7.6 cm (3 in.), were used to rake broccoli plants having a wide range of head sizes, as before. The results were similar to the first attempt, in that several intermediate size plants were not uprooted and sustained damage. However, on this occasion there were also several plants in the intermediate size range that were uprooted by the fingers, indicting that the uprooting force was somewhat reduced due to wetter soil conditions.

Based on the results of the two preliminary trials, an experiment was planned to determine if the force required to uproot broccoli plants was lower under wetter soil conditions and to evaluate the feasibility of selectively harvesting broccoli plants using the spaced-finger concept. There were two parts to the experiment. The objective of the first part was to measure the force required to uproot broccoli plants under wet and dry conditions to determine if the force was reduced due to wetter soil conditions. The objective of the second part was to evaluate the effect of wetting the soil on the harvesting selectivity achieved while raking broccoli plants with the spaced-finger device.

6.1.2 Equipment and Procedure

6.1.2.1 Uprooting Force Measurement Test

Three blocks of mature broccoli plants were identified in the extra plots of broccoli, planted for the cutting device harvest tests, for use in measuring the force to uproot broccoli plants. The blocks were selected so that they had at least ten plants with large heads (over 13 cm in diameter) which were fairly uniform in size. Each of the blocks, which were roughly 1.5 m^2 in area, was divided approximately in half, and a small dike was constructed around one half for containing added water. Approximately 1.3 cm (1/2 in.) of water was applied to the diked area in each block late in the afternoon on November 14, 1988. The next morning, ten broccoli plants from each block (five from the wet half, five from the dry half) were pulled up using a special clamp attached to a spring scale. The force required to uproot each plant was recorded from the spring scale. After all the plants were uprooted, soil samples were taken from the top 5 cm (2 in.) of soil in each block in the area where the plants had been uprooted for determining the moisture content of the upper soil layer. The depth used for the soil samples was the approximate depth of the root ball. Three soil samples were taken from each wet and dry area. The soil samples were not meant to correspond to the soil moisture content around individual uprooted plants.

6.1.2.2 Harvest Selectivity Test

A large number of plants with intermediate size broccoli heads judged to have sound, compact curd structures were identified in the extra plots of broccoli planted for the cutting device harvest tests. The heads were chosen in the size range of approximately 9 to 13 cm (3 1/2 to 5 in.) in diameter so that they were large enough to be marketable but small enough that they would keep until the next harvest if they were missed. The effect of raking with spaced-fingers on these intermediate size heads was considered critical because of possible damage to heads that were not uprooted. From this population of plants, a sample of 40 plants was chosen for the harvest selectivity test. Half of the sample was then randomly selected for constructing dikes around the plants for containing water. Approximately 1.3 to 2.5 cm (1/2 to 1 in.) of water was applied to each of the diked plants late in the morning of November 15, 1988. Four hours later, the diameter of each head was measured and recorded and then the spaced-finger device, with a spacing of 6.4 cm (2 1/2 in.), was used to rake each of the 20 wet and 20 dry plants in an attempt to uproot them. For each plant, a record of whether or not the head sustained appreciable damage was made.

6.1.3 Results and Discussion

6.1.3.1 Uprooting Force Measurement Test

The results for the uprooting force test are shown in Table 19. The average soil moisture content and the average uprooting force are shown for each of the three blocks. An analysis of variance on the force results showed that the force required to uproot the plants was very significantly affected $[P(f) = 0.0001]$ by the wetting of the soil. The mean uprooting force was more than 90N (20 lbf) less for the plants in the wet plots. The mean moisture content in the wet plots was more than 5% greater than in the dry plots. No specific determination was made of the relationship between the required uprooting force and the soil moisture content, and inconsistent results from block to block indicate that other factors had some effect on the uprooting force. However, the magnitude of the differences in uprooting force and soil moisture content between the wet and dry plots indicate that the large reduction in required uprooting force was primarily due to the added water.

6.1.3.2 Harvest Selectivity Test

The results of the harvest selectivity test are shown in Table 20. For the wet soil conditions, 50% of the plants (10 of 20) were uprooted. For the dry soil conditions, only 15% of the plants (3 of 20) were uprooted. In a statistical test for comparing two binomial proportions, this difference in the number of heads uprooted was significant at the $\alpha = 0.01$ level. The distribution of head diameters indicated that head diameter was not a factor in the large difference in the number of heads uprooted. For the 20 heads from the wet soil, the range in head diameter was 8.9 to 12 cm, the mean was 10.7 cm, and the standard deviation was 1.04 cm. For the 20 heads from the dry soil,

Table 19. Soil moisture content and uprooting force results for the broccoli plant uprooting force measurement test.

	Soil Moisture Content (%)		Uprooting Force (N)	
Block	Wet	Dry	Wet	Dry
1	18.9	16.3	199	285
2	22.8	16.4	173	246
3	19.9	13.1	143	284
Mean	20.5	15.3	172	271

Table 20. Results of the harvest selectivity test raking broccoli plants with fingers spaced 6.4 cm apart.

	Number Plants Uprooted	Number Plants Not Uprooted	
Soil Condiiton		Damaged	Not Damaged
Wet	10	3	7
Dry	3	10	7

the range was 9.5 to 12.7 cm, the mean was 11.0 cm, and the standard deviation was 0.986 cm. The heads from the dry soil were slightly larger than those from the wetted soil, which should have contributed to more heads uprooted instead of less.

The results of the uprooting force measurement test showed that the uprooting force was significantly reduced by wetting the soil. The results of the harvest selectivity test show the effect this reduced uprooting force had on the ease with which plants were uprooted. As seen in Table 20, the number of heads that pulled through the spaced-fingers with no appreciable damage was the same under wet and dry conditions. These heads were probably smaller ones that were less likely to be damaged. However, 10 heads pulled through the spaced-fingers and sustained appreciable damage under dry soil conditions while only 3 did under wet soil conditions. These results are exactly the reverse of the results for the number of heads uprooted. The reduced uprooting force due to the wetting of the soil contributed to a substantial proportion of the intermediate size heads being uprooted instead of being pulled through the spaced-fingers and damaged.

Only intermediate sized broccoli heads were used for the harvest selectivity test. Smaller heads are less likely to be damaged by raking with the spaced-fingers, and larger heads are more likely to be uprooted with relatively little damage even when the uprooting force requirements are higher. The intermediate size heads are the most critical to a consideration of the feasibility of the spaced-finger concept because they are most likely to suffer damage from passing through the spaced fingers. Under dry soil conditions with only 3 of 20 intermediate size heads uprooted and 10 of 20 left damaged in the field, the spaced-finger concept probably would not be feasible for a selective broccoli harvester. However, under wet soil conditions, 10 of 20 intermediate size heads were uprooted and only 3 of 20 were left damaged in the field. Since uprooted plants represent heads successfully harvested, selective harvesting with the spaced-finger concept may be practical under wetted soil conditions. Wetted soil conditions could be achieved with a light application of irrigation water the evening before a harvest. While such a practice is not standard currently, it would be possible if irrigation pipe could be left in the field throughout the season, and the added water might contribute to higher yields later in the harvest season.

6.1.4 Summary and Conclusions

An investigation was conducted to evaluate the feasibility of selectively harvesting broccoli using a concept of spaced-fingers raking upward through the plant canopy to uproot the plants with mature heads. Preliminary trials were conducted using a simple device with adjustable metal fingers to rake broccoli plants with a wide range of head sizes. Very large heads were generally uprooted by the spaced-fingers with little or no damage to the head, and small heads generally pulled through the spaced-fingers with little or no damage to the plant leaves. Intermediate size heads mostly pulled through the fingers and sustained damage during a trial when soil conditions were dry. When soil conditions were wet, several intermediate size heads were uprooted, indicating that the uprooting force was reduced by the wetting of the soil. A test was conducted measuring the force required to uproot broccoli plants under wet and dry soil conditions to verify that the uprooting force was reduced by the wetting of the soil. Another test was conducted to determine how the reduced uprooting force requirement under wet soil conditions affected the harvest selectivity achieved while raking with the spaced-fingers. The following conclusions were reached based on the results of these tests:

1. The average force required for uprooting broccoli plants with mature heads was significantly reduced due to wetting of the soil.

2. The percentage of intermediate size heads uprooted under wet soil conditions (50%) was more than three times the percentage uprooted under dry conditions (15%).

3. The reduced uprooting force required under wet soil conditions resulted in many intermediate size broccoli heads being uprooted instead of being pulled through the spaced-fingers and damaged.

4. Selectively harvesting broccoli using the spaced-finger concept does not appear feasible under dry soil conditions because of the high force required for uprooting plants.

5. Selectively harvesting broccoli using the spaced-finger concept does appear feasible under wet soil conditions.

The feasibility of using this concept under wet soil conditions is dependent upon the practicality of a broccoli producer applying irrigation water prior to a harvest. An application of approximately 1.3 cm (1/2 in.) the night before a harvest should be sufficient to significantly reduce the force required to uproot the plants without making the field too muddy for harvest operations. A selective harvester based on this concept would be especially useful for harvesting large-headed broccoli using a schedule of only two or three widely spaced harvests. A closer finger spacing could be used for the last harvest to more thoroughly glean the field. More work needs to be done to evaluate the effect of different finger spacings. Various finger spacings were tried in the preliminary trials, but only one spacing was used in the harvest selectivity experiment. Work is also needed to more thoroughly evaluate the effect of raking on leaf damage to the plants. Damage to immature plants is critical to a consideration of the feasibility of a selective harvesting concept. The low level of leaf damage noted in this investigation was promising, but the actual raking mechanism is needed to fully evaluate this factor because of the probable effect of the raking rate.

One limitation to this concept is the fact that the entire plant (minus the roots) will be harvested, necessitating an additional operation for leaf removal. However, it should be possible to develop mechanisms to aid in the leaf stripping operation. Pinch rollers have been used for leaf removal in other vegetable harvesting applications, and a flail device for knocking the leaves off is a possibility as well. Such a device could be manually-fed, similar to the bunching machines, with an opening into which the stalk-end of the broccoli head could be inserted.

6.2 Digital Image Processing for Sizing Broccoli Heads

Advances in computer technology and the development of specialized software have substantially reduced the cost of high quality digital image processing systems. While such a system may still be prohibitively expensive for broccoli harvesting applications, computer technology trends toward reduced costs, increased capabilities and simpler operation indicate that vision systems will become more practical for this type of application in the future. For this reason, an investigation was conducted to determine whether a digital image processing system could be used for selecting mature broccoli heads based on a determination of head size. A major objective of the study was to find a method of distinguishing broccoli heads from a background of foliage using textural information. Textural information was used because the broccoli head and leaves are the same color, green. A further objective of the study was to determine how accurately the image processing algorithm developed to use textural information could measure the size of broccoli heads. The time required for image processing was also of interest because of the requirement for high speed processing for real-time automatic broccoli harvesting in the field.

6.2.1. Gray Level Run Length

Although broccoli heads and leaves are the same color, they have different textures. The leaves have a smooth surface, while the heads have a surface with a uniform roughness due to the structure of the small curds that make up the head. In a digitized image, leaves and spaces between leaves are characterized by large areas of nearly constant gray levels, while head areas reveal a fine grainy structure due to rapidly changing gray levels.

Textural information can be analyzed by using a gray level run length algorithm. A gray level run is a set of consecutive, collinear pixels having the same gray level value. As described by

Galloway (1975), gray level run length matrices can be computed for runs along the horizontal, vertical, +45, and -45 degrees axes. Matrix elements (i, j) specify how many times a picture contains a run of length j with gray level i in a given direction. The following example shows a 5 x 4 picture with three gray levels (0, 1, 2) and the resulting gray level run length matrices for the four principle directions.

Picture: $$\begin{matrix} 0 & 0 & 2 & 1 & 1 \\ 1 & 2 & 2 & 0 & 1 \\ 2 & 0 & 0 & 0 & 0 \\ 1 & 0 & 2 & 1 & 2 \end{matrix}$$

Run length matrices:

		run length j				
	0°	1	2	3	4	5
gray	0	2	1	0	1	0
level	1	4	1	0	0	0
i	2	4	1	0	0	0

		run length j				
	45°	1	2	3	4	5
gray	0	5	0	1	0	0
level	1	6	0	0	0	0
i	2	3	0	1	0	0

		run length j				
	90°	1	2	3	4	5
gray	0	4	2	0	0	0
level	1	4	1	0	0	0
i	2	4	1	0	0	0

		run length j				
	-45°	1	2	3	4	5
gray	0	0	1	0	0	0
level	1	4	1	0	0	0
i	2	6	0	0	0	0

These four matrices are added to form a specific run length matrix for that picture. The number of computations is directly proportional to the number of pixels and gray levels in the picture. A 244 x 256 pixel image would require a considerable number of computations, so the number of gray levels should be minimized as long as textural information is not lost. Different functions emphasizing short runs, long runs, gray level nonuniformity, or run length nonuniformity can be calculated to obtain various numerical texture measures from the matrices (Galloway, 1975).

The long run function has the following form:

$$RF = \sum_{i=1}^{N_g} \sum_{j=1}^{N_r} \frac{j^2 p(i,j)}{\sum_{i=1}^{N_g} \sum_{j=1}^{N_r} p(i,j)} \tag{1}$$

where $p(i,j)$ = i, j th the entry into a run length matrix

N_g = number of gray levels

N_r = number of different run lengths.

This function emphasizes long runs by multiplying each run length by the length of the run squared. The denominator is the total number of run lengths in the picture and serves as a normalizing factor.

6.2.2 Equipment

The vision system used for the experiment consisted of a video camera (Panasonic CCTV) with a 16 mm television lens and a video display, an digitizer/transmitter board (ImageWise) connected to the video camera, and a microcomputer (Jameco JE1019) (CPU 28086, 16 mHz). The digitizer/transmitter board, or frame grabber, captures a picture in 1/60 th of a second and stores it as 244 lines of 256 pixels with 64 gray levels (Ciarcia, 1987). The frame grabber converted the stored video image to RS-232 serial data and transmitted it at 28800 bits per second to the microcomputer. Control and utility software supplied with the frame grabber were written in Turbo Pascal (Ciarcia, 1987). Additional software, developed specifically for this investigation for implementing different image processing steps, was also written in Turbo Pascal.

6.2.3 Experimental Procedure

Images of 50 broccoli plants with a wide range of head sizes were taken with the video camera under artificial light conditions on November 18, 1988. The plants, which were dug from the extra broccoli plots for the cutting device harvest tests, were kept watered and handled gently so that the foliage remained intact to better simulate field conditions. A stand was designed to hold three plants upright in a row with a distance of 23 cm (9 in.) between plants. The image of the center plant held in the stand was taken so that each head had a full background of leaves similar to that found in the field. The camera was mounted in a field of ten 15 W fluorescent light tubes and adjusted so that the distance from the lens to the top of the broccoli heads was 32 cm (12.5 in.). The F-stop and depth of field of the camera were adjusted for the first broccoli plant and left at the same settings for the rest of the plants. The frame grabber captured the image of each broccoli head, and the digitized image was stored on disk for processing purposes.

Head diameter measurements were made with calipers on each broccoli head. The measurements were made in the directions perpendicular and parallel to the camera stand. The equation for the area of an ellipse was used to calculate the broccoli head area as an independent measurement of head size. The measured head area was considered to have an uncertainty of approximately $\pm 4\ \text{cm}^2$ due to the uncertainty of the head diameter measurements and the irregular shape of the head.

Seven randomly chosen digitized images of broccoli heads were used to evaluate the different gray level run length functions that can be used as numerical texture measures. The relationship between head size and the long run function was good, so the long run function was used for image analysis.

Computation time for this run function, as seen in Eq. 1, is proportional to the size of the run length matrix. Therefore, both the number of run lengths and the number of gray levels had to be minimized to minimize computation time. A Fourier Power Spectrum analysis of several pictures of broccoli heads showed that the frequency of runs under ten pixels long was much different for head and leaf areas. To enhance the discriminating capability of the run function, all of the runs ten or more pixels in length were therefore grouped together. A total of ten run length categories were used, with the first nine categories for runs of from one to nine pixels in length, and the tenth category for the longer runs.

Two different procedures were tried for reducing the number of gray levels. In the first procedure, the gray level values, which were concentrated near the dark end of the gray scale in the original images, were spread evenly over the entire gray scale in a normalization process. Then the 64 gray levels of the scale were divided into eight gray level groups. In the second procedure, the number of gray levels was reduced to just two through manipulation of the image using some standard image processing algorithms. The original image (Figure 27) was first filtered with an algorithm that averages the values of the eight nearest neighbors of a pixel and replaces the current pixel value with that number (Ciarcia, 1987). Figure 28 shows the filtered image of the broccoli head shown in Figure 27. The pixel values from the original image were then subtracted from the filtered image, and the resulting image was put in binary form by setting all pixel values less than two equal to zero (black) and all those equal or greater than two equal to 63 (white). Figure 29 shows the final result of the processing steps.

The run function and actual head area were calculated for all fifty broccoli plant images. Two of the images were out of focus due to smaller distances from the camera to the head, and these

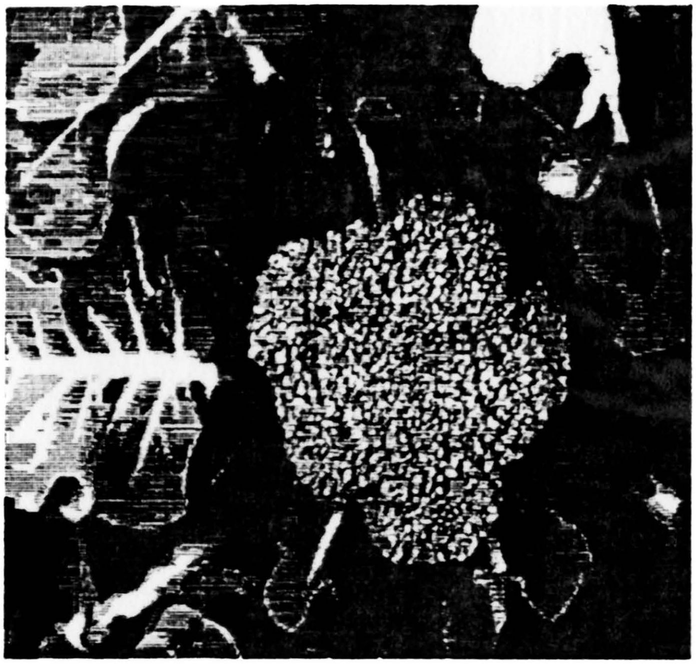


Figure 27. Digital image of a broccoli head and background foliage.

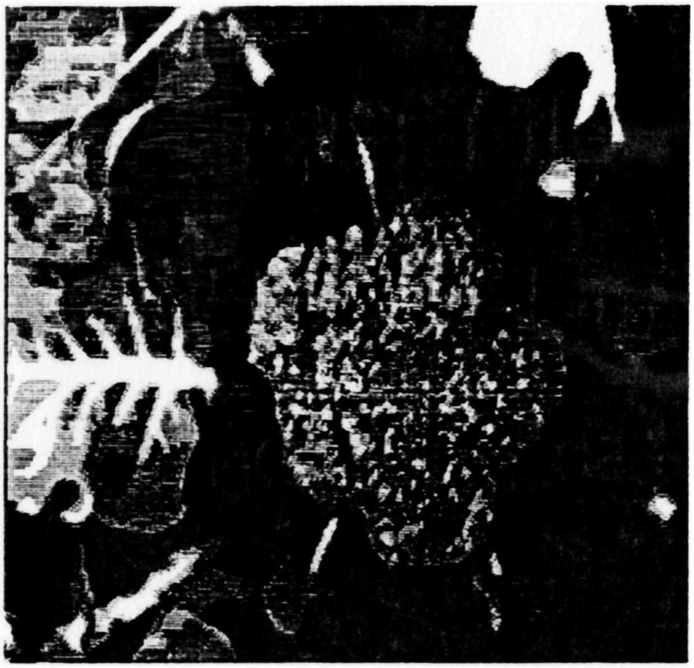


Figure 28. Filtered image of the broccoli head in Figure 27.

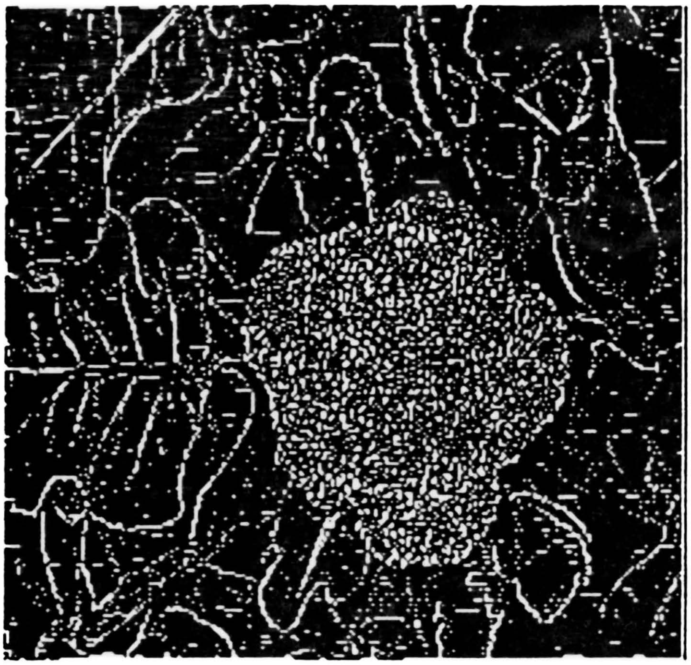


Figure 29. Black and white image of the broccoli head in Figure 27 after the original image was subtracted from the filtered image.

images were discarded. The remaining 48 images were divided into two groups of 24 images each. The division was based on measured head area and done so that each group contained the full range of head sizes. One group was used to find a suitable model to predict head area. The other group was used to verify the model. This approach prevents curve over-fit in a certain data set and is known as cross validation (Myers, 1986).

6.2.4 Results and Discussion

Prior to using the data sets for model development and verification, the long run function was calculated for thirteen randomly chosen broccoli head images using both the eight gray level and two gray levels reduction procedures. Data for the thirteen images suggested an exponential relationship between the run function and the measured head area. An exponential curve, fitted to the data using Margaret's iterative method (SAS, 1983), had an equation of the following form:

$$Y = Ae^{BX} \tag{2}$$

where Y = predicted area (cm^2)

X = run function [RF in Eq. (1)]

A, B = iteratively determined coefficients.

For the two gray level reduction procedure, the standard error of head area prediction using an equation of this form was ± 8 cm^2. For the eight gray level reduction procedure, the standard error was slightly higher at ± 11 cm^2. Since the two gray level reduction procedure also required less computation time because of the smaller matrix, it was used for all run function calculations.

The measured head areas and the run function values for the 24 images in the model development data set are shown in Table 21. From the data, coefficients were determined for a model with the form of Eq. (2).

Table 21. Run function values and measured and predicted head areas for the model development set of broccoli head images.

Picture[1] Number	Run Function	Measured Head Area(cm)	Predicted Head Area(cm)
49	106.6	19	32
38	99.0	39	40
48	92.9	42	48
50	87.5	47	57
30	86.1	53	60
5	95.3	59	45
37	80.7	65	70
31	78.5	71	75
4	81.2	77	69
19	73.6	82	87
6	76.9	91	79
40	67.5	92	105
45	68.1	97	103
8	77.7	100	77
17	70.2	108	97
42	66.7	110	108
22	60.5	127	130
3	58.8	134	137
35	53.2	141	163
27	55.0	146	154
32	52.9	162	164
11	56.1	174	149
1	49.6	189	181
2	45.5	207	206

[1] Broccoli plant pictures were numbered in the order that they were taken.

$$Y = 824e^{-0.031X} \tag{3}$$

Figure 30 shows a plot of Eq. (3) and the data used to develop it. The equation had a standard error of head area prediction of ± 12 cm^2. This error corresponds to a ± 0.8 cm error in head diameter estimation for a 10 cm diameter head.

The head area model was used to predict the head areas for the 24 pictures in the model verification data set. The measured and predicted head areas as well as the run function values are shown in Table 22. Figure 31 shows the model verification data set plotted on the same graph with the model development data set and the head area prediction curve. For the verification data set, the standard error of head area prediction using Eq. (3) was ± 16 cm^2. While this standard error was larger than that for the model development data set, it is in the same range and shows that head size can be predicted with the run function. This standard error corresponds to a ± 1.0 cm error in head diameter estimation for a 10 cm diameter head. It should be noted that a substantial portion of the standard error of head area prediction is due to the uncertainty of the measured head area, estimated at ± 4 cm^2, so the accuracy of the model may be even better than indicated.

The data set used in this experiment had a range of head sizes from 4.7 to 17.0 cm in diameter, with a median between 10 and 11 cm. The cut-off point between immature and harvestable size heads is typically given as 7.5 cm (3 in.). Only six out of 48 observations in this data set were below that cut-off point, so a new data set with more observations below 7.5 cm would be needed to accurately model head selection based on that criterion. However, a look at a higher cut-off point, more toward the middle of the data set, gives an indication of the head classification capability of this method. For a selection criterion of 10 cm (4 in.) in diameter, the head area would be 78.54 cm^2. For the model verification data set in Table 22, only head #14 would be incorrectly classified (as immature instead of harvestable) using this criterion. For the model development data set in Table 21, only head #8 would be incorrectly classified. These results indicate good head classification accuracy. For broccoli harvesting applications, exact classification is not even required since

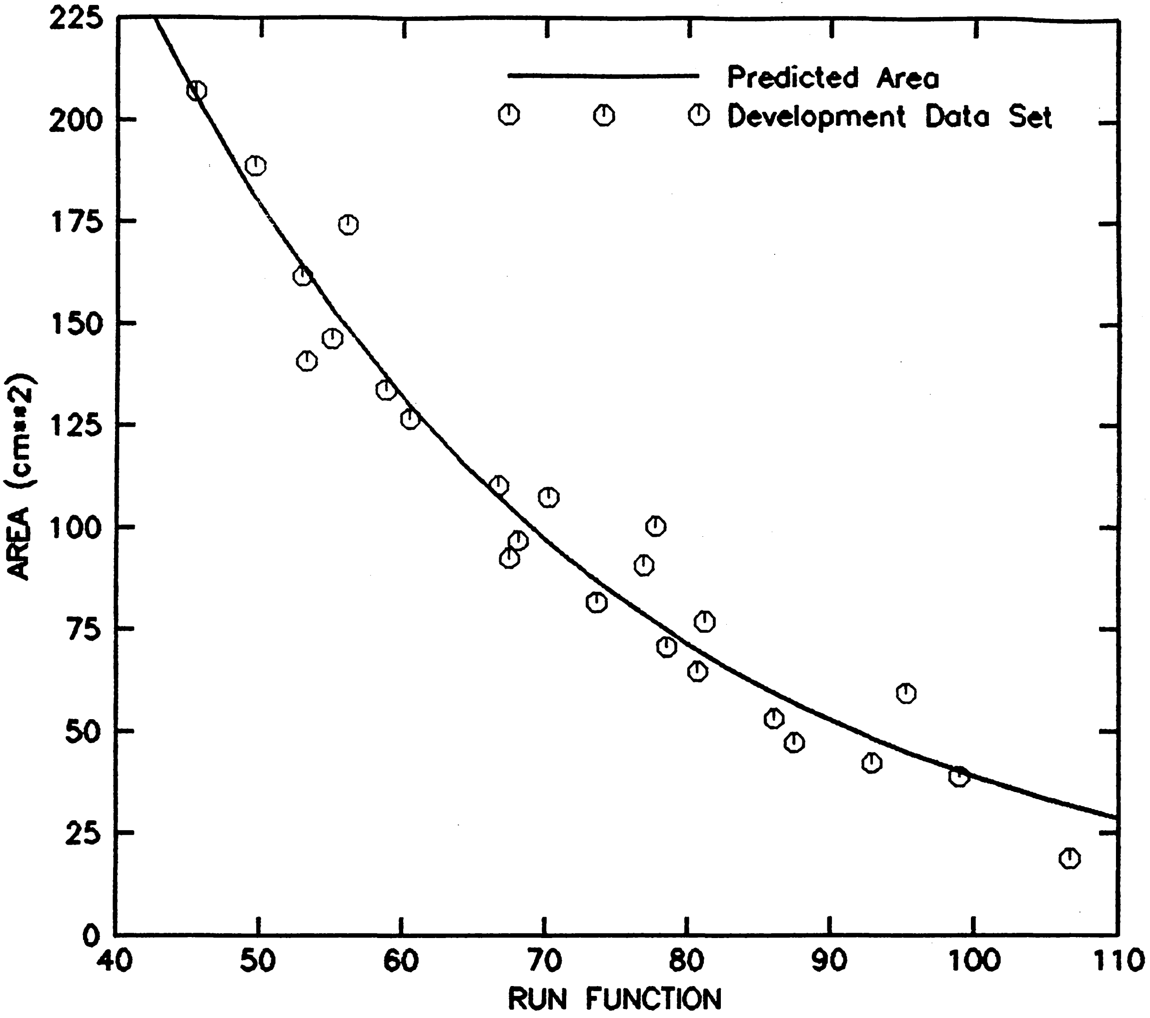


Figure 30. Exponential curve for predicting broccoli head area from the run function and the data used to fit the curve.

Table 22. Run function values and measured and predicted head areas for the model verification set of broccoli head images.

Picture[1] Number	Run Function	Predicted Head Area(cm)	Measured Head Area(cm)
23	95.6	27	44
47	92.0	40	50
7	93.2	47	48
39	87.0	53	58
15	86.2	55	59
34	88.7	63	55
29	82.6	69	66
46	79.9	71	72
14	79.5	82	73
41	76.7	83	79
28	71.7	89	92
25	72.9	92	89
26	71.7	93	92
24	74.8	97	84
9	73.1	101	88
16	69.6	109	98
43	64.5	120	115
18	60.6	131	130
12	73.4	137	88
20	60.5	145	130
44	63.4	155	119
21	55.0	173	154
33	55.1	177	153
36	49.5	199	182

[1] Broccoli plant pictures were numbered in the order that they were taken.

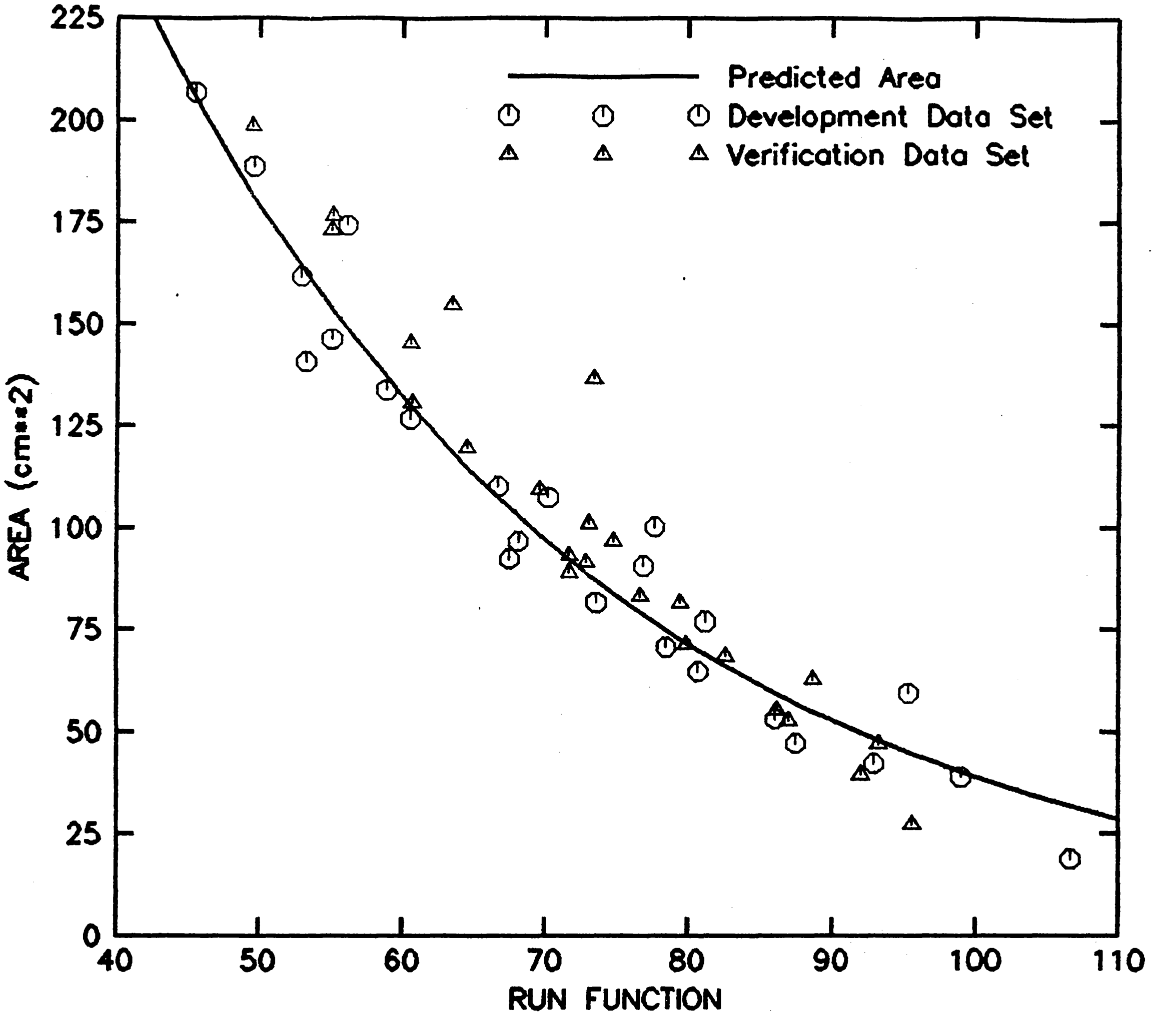


Figure 31. Head area prediction model with both the model development and model verification data sets.

undersized heads which are harvested are still marketable, and oversized heads which are not harvested may still be marketable by the next harvest.

The results of this experiment show that the gray level run length method of textural analysis can be used to accurately predict broccoli head size. This result is an important step in progress toward the development of an automatic selective broccoli harvester because it demonstrates the feasibility of using image processing for mature head selection. This experiment, however, was only a preliminary step, and further investigations are needed before a field operable system can be developed.

There are several important areas where more work is needed. Pictures should be taken of broccoli plants under different light conditions in order to study the effect of light on the run length parameter. In conjunction with this study, the effects of the camera F-stop setting and the distance from the camera to the broccoli should be investigated as well. The distance is particularly important because of the variable height of broccoli heads in the field. The greater the distance, the greater the depth of field. With a greater depth of field, the focus and head size estimation should be less affected by the variations of up to 13 cm (5 in.) in head height shown in the results of physical properties measurements reported in Chapter 4.

As attention is turned to images covering a larger area (due to greater distance), segmentation techniques for locating broccoli heads and the frequency of image sampling will have to be considered. Larger images are likely to contain two or more broccoli heads at once, so segmentation techniques will be required so that only those rows and columns of pixels that contain head areas are processed. Such techniques reduce computation time and can be used to locate mature heads for harvesting. Image sampling rate is also important for minimizing computation time. Images should be sampled far enough apart so that the images of individual heads are processed only once and so that sufficient computation time is available before the next image is sampled. However, there should be enough overlap so that image edges are not a factor.

The time required for image processing is an important consideration because of the need for sufficient field speed to make automated harvesting practical. In this experiment, 2.2 s were required to transmit the 62 kbyte needed for one picture, and another 0.5 to 1.0 s was required for computation. Computation time can be substantially reduced through changes in hardware and improved processing techniques; thus, data transmission time is the real limiting factor. A setting on the digitizer/transmitter board that was used could have been changed to double the transmission rate. Substantial further reductions should be possible with equipment that employs parallel rather than serial data transfer. The equipment used for this experiment was inexpensive. With more sophisticated equipment, which should become increasingly affordable in the future, image processing at rates fast enough for practical automated harvesting should be achievable.

6.2.5 Summary and Conclusions

An investigation was conducted to evaluate the feasibility of using a digital image processing system for selecting mature broccoli heads based on size. A texture analysis method based on gray level run length was developed for predicting head area. Images of 50 broccoli plants with a wide range of head sizes taken under controlled lighting conditions were analyzed to determine how accurately the gray level run length algorithm predicted head area. Two different methods for reducing the original 64 gray levels of the digital images were tried. Head areas and run function values were calculated for each of the images. The set of broccoli head image was divided into two data sets, and one set was used to develop a head area prediction model while the other set was used to verify the model.

The following conclusions were reached based on the results of this investigation:

1. The two gray level reduction procedure required less computation time to calculate the run function than the eight gray level reduction procedure. Results also indicated that the two gray

level reduction procedure may have had a better correlation between head area and the run function.

2. A head area prediction model with an exponential relationship between head area and the long run function was determined from the model development data set.

3. When the head area prediction model was used on the model verification data set, the standard error of head area prediction (± 16 cm^2) was somewhat larger than that for the model development set (± 12 cm^2), but in the same range. These errors correspond to errors of less than ± 1.0 cm in head diameter estimation for a 10 cm diameter head.

4. The model predicted head area with good accuracy, and has the capability for successful classification of heads into immature and harvestable sizes.

5. The image processing rate in this experiment was too slow for real-time automatic harvesting, but indications are that computation and data transmission times can be reduced enough to make automatic mature head selection practical.

This investigation was only a preliminary study, or "proof of concept," to determine if digital image processing methods based on textural analysis could be used for automatic mature head selection. The results clearly show that the concept is feasible, and they indicate that a field operable digital image processing system for automatically selecting mature broccoli heads can be developed.

Chapter VII

SUMMARY OF HARVEST MECHANIZATION PROSPECTS

7.1 Introduction

Previously, once-over harvesting was considered the only practical approach to mechanizing the harvest of broccoli. Mechanisms for cutting and collecting broccoli in a single harvest were built and tried, and widespread adoption seemed likely as soon as uniformly maturing broccoli varieties could be developed. The development of varieties with once-over harvest yields comparable to selective harvest yields, however, has proved to be very difficult. In addition to the reduction in yield, another disadvantage of once-over harvesting is the probable requirement for additional manual handling of the head for leaf-stripping, trimming, and sorting. For these and other reasons, once-over mechanical harvesting of broccoli has not been adopted and most likely will not be in the near future.

Mechanization of the selective harvest of broccoli has the potential to improve harvesting efficiency without the problems associated with once-over harvesting. There are, however, two main constraints to mechanization of the selective harvest of any vegetable. The first constraint is the requirement for some means of selecting which fruit or plant to harvest. The second constraint is the difficulty in harvesting the fruit or plant without excessive damage to remaining plants which would reduce subsequent yields. Overcoming these constraints can require advanced technology and complex mechanisms, and little success has been achieved with selective mechanical harvesting of any commercial vegetables. Up to now, little attempt has been made to mechanize the selective harvest of broccoli because of the difficulty in overcoming these constraints. The results of the investigation reported herein, however, prove that creative approaches utilizing both old and new technology make the mechanization of the selective harvest of broccoli a realistic possibility.

In this investigation, two different approaches to the mechanization of the selective harvest of broccoli were studied. One approach involved the use of a harvest aid, a manually-directed powered cutting device, which can fit readily into existing harvest systems. The use of this device mechanizes the cutting process and eliminates the stooping involved with manual harvesting but retains the human factor for selecting mature heads and controlling the motion of the device, thereby minimizing damage to remaining plants. This investigation included the design and development of the cutting device and the accompanying support system for operating it in the field. Extensive testing of the system was also done to optimize performance.

The other approach investigated involved complete mechanization of the selective harvest of broccoli through the automation of the mature head selection process and the development of mechanisms to cut, lift and collect heads without damaging neighboring plants. Broccoli maturity is based primarily on head size, and automation of the head sizing process in the field must be accomplished before an automatic selective harvester can be developed. This investigation included experiments to evaluate the feasibility of two different concepts for selecting mature heads based on size. One concept used spaced fingers raking upward through the plant canopy to uproot plants with mature heads. This concept combines the head selection and harvesting operations in a single operation, so a consideration of the mechanism used to produce the desired action was inherent in the evaluation of the head sizing concept. The other concept used a digital image processing system to make a visual determination of head size based on textural information. Such a system may be prohibitively expensive for broccoli harvesting applications presently, but computer technology trends toward decreased costs and increased capabilities indicate that vision systems will become more practical for this type of application in the future. Consideration was not given to accompanying harvesting mechanisms in evaluating this concept.

Both of these approaches have merits, and one method may fit into certain production situations better than the other. The results of this investigation do not favor one approach over the other. These results are meant, instead, to extend the base of background information for future developments in both mechanization areas and to give direction to those developments, enhancing the chances for the success of selective broccoli harvest systems. The following is an analysis, based on the results of this investigation and the experiences of the author, of the prospects for broccoli harvest mechanization using two different approaches: partial mechanization using a powered cutting device and complete mechanization using an automatic selective broccoli harvester.

7.2 Powered Broccoli Cutting Device

The cutting device functioned very well. With the modifications made after the 1987 season, the cutting device could be used with good freedom of movement, and a high level of leaf-stripping could be achieved. The harvest rate with the cutting device averaged between 11 and 12 heads/min both years, substantially faster than the average harvest rates measured in commercial fields (between 7 and 8 heads/min). The device has the potential to fit readily into existing harvest systems for the following reasons: 1) it is used by workers moving through the field in the same manner as for conventional manual harvesting, 2) no additional manual handling is required for trimming or sorting, and 3) pneumatic power already in place for bunching machines is used as the power source. The device is better suited to smaller production situations because of problems with operating a large number of cutting devices off of a single field pack machine. However, smaller operations should benefit the most from this type of technology because large operations already enjoy the advantages of the economics of scale. Low-cost technology to increase harvest efficiency can help smaller producers reduce production costs and possibly expand production, thereby allowing them to compete better with large-scale operations.

As promising as the cutting device seems, a further increase in harvest rate with the cutting device may be required to make it a viable alternative to conventional manual harvesting. The current labor savings potential may not be enough because leaf-stripping and cutting labor only account for about half of the total labor required for the harvest. If the harvest rate with the cutting device could be increased to approximately twice the hand harvest rate, or about 15 heads/min, then total harvest labor requirements could be reduced by 25% or more. In Virginia, a labor savings of 29% could be achieved if a seven-person harvest crew, with four people for leaf-stripping and cutting, could be reduced to a five-person crew. Such a reduction in labor requirements could result in a savings of $500/ha over a harvest season based on harvest labor estimates of 350 h/ha in Virginia and a wage of $5/h.

The potential for increasing the harvest rate with the cutting device is good, especially through improved activation of the leaf-stripping mechanism, as discussed in Chapter 5. The present trip mechanism might be modified to improve the synchronization between the closing of the leaf-stripping arms and the lowering of the cutting device, but careful consideration will have to be given to the lever for contacting the head. The lever must reliably contact the head as the device is lowered, yet not interfere with the head as it enters the device or the blades when the cut is made. The lever must have sufficient stiffness to perform the tripping function, yet it should be soft enough not to damage the head. A new type of trip mechanism, or even a new type of leaf-stripping mechanism, is also a possibility. Electronic sensing may be the answer to completely reliable activation of the leaf-stripping mechanism, but added complexity and possibly weight will have to be considered. Other alternatives include manual activation of the trip mechanism through a button or trigger in the handle and a leaf-stripping mechanism utilizing wire pulled taut around the broccoli stalk instead of leaf-stripping arms.

A smaller increase in harvest rate with the cutting device may be possible through weight reduction which would make the device easier to handle. Some weight savings should be possible through the more detailed design, stricter machining specifications, and better component matching that would accompany commercial production of the device. A more detailed force analysis can be done to optimize the linkage design so that force transmission is maximized. Sharper blades, such as can be made from surgical steel, should also contribute to lower cylinder force requirements, allowing the use of a smaller, lighter cylinder.

Improved activation of the leaf-stripping mechanism and weight savings through better design and fabrication should combine to increase the harvest rate with the cutting device substantially, perhaps as high as the desired 15 heads/min. If these improvements were made, the cutting device would be a viable alternative to conventional manual harvesting. Whether or not producers would adopt the cutting device in its present form is another question, however. The suspension system required to support the device may be a deterrent to acceptance by the producers, both because of added complexity and expense and for unfounded reasons such as awkward appearance. Substantial weight savings would have to be achieved to make unsupported operation of the cutting device practical. Weight savings of the magnitude required are probably not possible with the cutting device in its present form; radical design changes may be needed. Before much effort is put into the development of a new form of cutting device, further investigations should be made regarding producer acceptance of the device in its present form. The device should be mounted on commercial field pack machines, and trials should be conducted directly comparing cutting device and conventional manual harvesting. An investigation should also be conducted to determine the maximum cutting device weight that would make unsupported operation practical in a commercial production situation.

7.3 Automatic Mature Head Selection

The powered cutting device has strong potential to benefit small broccoli producers, but it is less likely to help in situations where very large harvest crews are used. Harvest efficiencies will already be high in those situations, and the expense and complexity of operating a large number of cutting devices may be prohibitive. Most of the broccoli in this country is produced in California, where production is on a very large scale; thus, widespread adoption of selective harvest mechanization technology will only occur through complete mechanization of the harvest. The results of this investigation demonstrate the feasibility of automatic mature head selection, a prerequisite for the development of an automatic selective harvester. Head selection based on size can be accomplished either by a physical sizing of the head or through the use of a machine vision system. A consideration of the harvesting mechanisms that can be coupled with the different selection systems is important to an evaluation of the prospects for complete mechanization of the selective harvest of broccoli.

7.3.1 Physically Sizing Broccoli Heads Using Spaced Fingers

The concept for physically sizing broccoli heads combines the head selection and harvesting operations in a single operation. A major advantage of this concept is that a mechanism capable of performing this operation is fairly simple in design and has been tried before. The mechanism, which has spaced horizontal fingers mounted on inclined roller chain and sprocket assemblies, has only mechanical components and should, therefore, be relatively inexpensive. A major limitation to this concept is that all of the broccoli plants, including those with immature heads, must come in contact with the harvesting mechanism, so the chances for damage that would reduce subsequent yields are increased. However, the results of the experimentation with this concept indicated that plant foliage was not excessively damaged by raking fingers and that head damage could be minimized if the force to uproot plants were reduced through a wetting of the soil. The feasibility of this selective harvesting concept depends to a large extent on the practicality of incorporating late season irrigations in a broccoli harvest system.

There are other limitations to this concept. Since the broccoli heads will be harvested with the leaves still attached to the stalk, an additional operation, manual or otherwise, will be required for leaf-stripping. Rows may have to be spaced far apart to accommodate the inclined roller chain and sprocket assemblies so that plants in adjacent rows are not damaged by the horizontal fingers as they move down the incline. The inclination angle of the chain will have to be low in order to attain both a ground speed fast enough to make mechanical harvesting practical and a vertical raking rate with the fingers slow enough to minimize damage. With a low inclination angle, the roller chain and sprocket assembly may have to be excessively long to get sufficient lift to uproot the plants and clear the row.

The requirement for an additional operation for leaf-stripping is a big disadvantage to this concept. Manual leaf-stripping would be very slow, negating most of the labor savings obtained through harvest mechanization. Flail devices for removing the leaves could probably be developed which would be manually-fed, similar to the bunching machines, with an opening into which the stalk-end of the broccoli head could be inserted. Leaf-stripping could be accomplished much faster with such a device, but each head would still require manual handling, an operation that would add to the complexity and labor requirements of the system. Physically sizing broccoli heads using spaced fingers may only be practical if leaf-stripping can be accomplished automatically. Pinch rollers have been used to remove leaves from other vegetables as they were conveyed from the harvesting mechanism to the collection bin (Esch and Marshall, 1987). Pinch rollers should be able to strip the leaves from broccoli stalks as well, but it may be difficult to cause the broccoli heads to rotate so that the leaves are removed from all sides. This problem must be overcome before a system for automatically removing leaves can be developed.

7.3.2 Digital Image Processing for Sizing Broccoli Heads

Machine vision systems have great potential for application in selective harvest mechanization. Because selection is based on a visual determination of size or maturity, without physical contact between the fruit or vegetable and the selection system, plant damage that can reduce subsequent yield is avoided. For tree fruit harvesting applications, vision systems use the differences in color between the mature fruit and the immature fruit and foliage as the distinguishing factor for locating and selecting mature fruit. Broccoli heads and leaves are both green, so a vision system cannot use color as the distinguishing factor. In this study, the use of textural information for distinguishing between broccoli heads and leaves was investigated, and the results show that broccoli heads can be accurately sized with a vision system using the gray level run length method of textural analysis.

This result demonstrates the feasibility of using machine vision for automatic selective harvesting of broccoli, but much work remains to be done before a field-operable mature head selection system can be developed. Because lighting conditions in the field will be much different from laboratory lighting conditions, both the effects of lighting conditions and possible methods for field illumination of broccoli plants must be investigated. A careful selection of image processing system components must be done so that mature head selection can be performed in real time. For this experiment, an inexpensive image processing system that was already available was used to test the feasibility of the concept. For the development of a field-operable prototype system, components must be matched to the function with less concern about costs. Costs will decrease in the future with continued advances in computer technology.

Further work is also crucial in the development and refinement of algorithms for sizing, selecting, and locating mature broccoli heads. These algorithms will direct the action of a harvesting mechanism, so their development is dependent on the type of harvesting mechanism used. Different types of harvesting mechanisms will be required depending on the method used to selectively cut, lift, and collect heads with minimal damage to neighboring plants. Two main approaches are possible: the action of the harvesting mechanism can come from the side of the plant row, or it can come from above the plant row.

If the action of the harvesting mechanism comes from the side of the row, the image processing algorithms can be somewhat simpler because the location of the broccoli heads to be harvested will only have to be determined in one direction, parallel to the row. The harvesting mechanism can also be fairly simple, such as a knife with a cutting action perpendicular to the row and a ram or deflector with a similar motion for pushing the cut head out of the row onto a conveyor located between the rows. There are some major disadvantages to this approach, however. Single rows with enough space between them for conveyors or other means of head collection will be required. Widely spaced single rows will reduce the yield potential, and it may be difficult to achieve a harvest rate high enough to make mechanical harvesting practical if only one row can be harvested at a time. Also, broccoli heads harvested by this approach would still have the leaves attached to the stem, presenting the same problem as with the concept for physically sizing broccoli heads using spaced fingers.

If the action of the harvesting mechanism comes from above, the cut head can be lifted from the plant row from above, eliminating the requirement for single rows. If multiple rows are used, the harvest rate achieved with a single image processing system and harvesting mechanism can be much higher, although image processing algorithms will have to be somewhat more complex because the location of the broccoli heads to be harvested will have to be determined in directions both parallel and perpendicular to the row. However, if the required algorithms can be developed, it should be much more cost effective to increase the harvest rate through the use of advanced software than with the additional hardware that would be required if only one row could be harvested at a time. Triple rows of broccoli planted 30 cm (12 in.) apart would present an image processing system with a solid, continuous block of broccoli plants. In order to get the entire block in the field of view of the camera, the camera would need to be somewhat distant from the broccoli, but this greater distance would help overcome the problem of variable broccoli head height.

With multiple rows viewed by one camera, image processing algorithms must be capable of sizing multiple broccoli heads in one image. It may be possible to use segmentation techniques coupled with the gray level run length textural analysis method to significantly reduce the complexity of the computations required for sizing and locating multiple heads in an image. Instead of calculating a run function value for an entire image to determine head area, columns and lines can be analyzed individually to block out areas that contain head. With everything in rectangular blocks, it will be very easy to determine the length of the sides of the blocks, instead of calculating area, and center point coordinates of blocks larger than a certain size can be quickly determined for directing the action of a cutting mechanism. A further advantage of this type of segmentation technique is that it may be possible to determine the size of partially obstructed heads based on head diameter (measured as the length of the side of a block) instead of head area.

Harvesting the broccoli head from above will be more complicated than harvesting from the side, but the results of the work with the powered cutting device indicate that it can work very well. In two years of field tests with the device, broccoli heads were found to stand straight enough for a mechanically-directed harvesting action from above to be effective. Also, the heads were nearly always retained in the cutting device after they were cut; thus, they can be lifted from the plant row from above. The same type of mechanism used for the cutting device could be used for an automated harvester if actuators for moving the device up and down and from side to side were developed. Also necessary in adapting the harvesting mechanism for an automated harvesting system would be a means of transferring the head from the cutting device to a conveyor after lifting it from the plant row.

Harvesting broccoli heads from above with a mechanical cutting device has significant advantages over other concepts for automated selective mechanical harvesting. With the leaf-stripping mechanism on the bottom of the cutting device, the leaves can be stripped from the stalk automatically during the harvesting action, eliminating the need for any additional manual handling of the head. Accurate synchronization will be required for a high level of leaf-stripping, but for automated harvesting it should be practical to use electronic sensing to reliably activate the leaf-stripping mechanism. The cutting device will be mechanically directed, so weight will not be a concern, and electronics will already be in place on the harvester for the vision system. The use of electronic sensing also has other potential advantages. If the top of the head is sensed to activate the leaf-stripping mechanism, it may be possible to automatically control the length of the cut broccoli head. If broccoli can be harvested automatically with a uniform stalk length, the use of bunching machines could be eliminated if consumer acceptance of broccoli marketed by weight (instead of in bunches) could be obtained.

The necessity of stripping the leaves from the stalk, which is unique to broccoli, may be the most critical factor in determining which type of system would be best for automated selective mechanical harvesting. Based on this factor alone, an automated harvester using machine vision and a cutting device harvesting mechanism would be the best choice among the systems that have been discussed. Other advantages strongly favor this system as well. The harvest rate potential is higher, and the possibility exists for harvesting heads with a uniform stalk length. Most importantly, the cutting device has already been developed and tested extensively. Clearly, further work will be needed before such a system can be developed. The visual accessibility results from 1987 and 1988 concerning the use of machine vision were promising, but different varieties should be investigated to identify which have heads less obstructed from view by leaves. The control aspects of moving the cutting device both laterally and vertically at the required speeds must be studied before designing an actuator. If a satisfactory actuator can be developed, prospects for the development of an automated selective broccoli harvester incorporating machine vision and a cutting device harvesting mechanism should be good.

Chapter VIII

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APPENDIX A: 1987 Physical Properties Data

Block/Harvest	Planting Pattern	Height (cm)	Head Diameter (cm)	Stalk Diameter (cm)	Visual Accessibility
Block 2,	A	43	11.8	3.73	0.5
	A	36	8.8	3.43	0.0
1st Harvest	A	38	99.5	3.20	1.0
	A	38	95.8	3.40	0.5
	A	36	82.3	3.50	0.5
	A	38	11.0	3.45	0.5
	A	38	10.8	3.23	1.0
	A	38	10.8	3.20	0.5
	A	41	8.3	2.63	0.0
	A	38	11.0	3.42	0.5
	B	36	8.7	3.45	0.5
	B	36	12.4	3.65	1.0
	B	36	11.6	3.23	0.5
	B	36	11.5	3.28	1.0
	B	38	9.4	3.55	1.0
	B	33	8.7	3.25	0.5
	B	33	7.3	2.80	1.0
	B	31	8.2	3.03	1.0
	B	38	9.5	3.30	0.0
	B	38	12.3	3.15	0.5
	C	38	9.0	3.33	0.0
	C	38	10.2	2.95	1.0
	C	38	8.9	2.85	1.0
	C	38	11.0	2.90	0.0
	C	36	8.6	2.83	0.5
	C	38	11.7	3.35	1.0
	C	36	11.4	3.35	0.5
	C	36	10.4	3.35	0.5

	C	36	9.9	3.63	1.0
	C	36	10.1	3.40	0.5
Block 3	A	43	10.4	2.88	1.0
3rd Harvest	A	41	11.8	3.05	1.0
	A	41	9.0	2.80	0.5
	A	46	11.8	2.83	1.0
	A	41	9.2	2.68	0.5
	A	38	8.8	2.93	1.0
	A	41	10.8	2.78	1.0
	A	41	12.2	2.95	0.5
	A	36	8.2	2.28	1.0
	A	41	11.4	3.00	1.0
	B	38	10.4	3.00	0.5
	B	33	8.2	3.00	1.0
	B	41	13.0	3.33	0.0
	B	36	8.4	2.73	1.0
	B	33	6.5	2.80	0.5
	B	41	9.8	2.65	1.0
	B	41	9.6	2.65	1.0
	B	41	11.3	3.30	1.0
	B	38	12.6	3.30	0.5
	B	33	9.1	2.93	1.0
	C	41	9.3	2.70	1.0
	C	38	10.6	3.13	0.5
	C	36	12.5	3.48	1.0
	C	43	11.0	3.10	1.0
	C	36	9.0	2.85	1.0
	C	43	10.7	3.13	1.0
	C	43	11.3	2.95	1.0
	C	38	11.1	3.03	1.0
	C	33	9.0	2.88	0.5
	C	43	10.1	3.23	1.0

APPENDIX B: 1988 Physical Properties Data

Harvest	Row Spacing (cm)	Plant Spacing (cm)	Height (cm)	Head Diameter (cm)	Stalk Diameter (cm)	Weight (g)	Visual Accessibility
1	30	23	32	9.52	3.56	191	0.0
1	30	23	28	8.76	3.30	150	0.0
1	30	23	30	8.89	3.43	159	0.5
1	30	23	36	9.14	3.68	195	0.5
1	30	23	29	12.70	3.05	204	1.0
1	30	23	32	12.19	3.30	204	1.0
1	30	23	33	12.70	4.06	268	0.0
1	30	23	34	11.56	3.56	236	0.5
1	30	23	33	10.29	3.05	136	0.5
1	30	23	33	12.45	3.30	213	0.5
1	30	23	25	9.27	3.30	154	0.5
1	30	23	36	11.43	2.92	154	0.0
1	46	30	32	8.89	3.56	177	0.5
1	46	30	28	10.41	3.30	186	1.0
1	46	30	30	10.67	3.30	182	1.0
1	46	30	32	9.40	3.30	168	1.0
1	46	30	33	9.14	3.43	182	1.0
1	46	30	32	8.89	3.56	177	0.5
1	46	30	28	10.41	3.30	186	1.0
1	46	30	30	10.67	3.30	182	1.0
1	46	30	32	9.40	3.30	168	1.0
1	46	30	28	11.56	3.05	186	0.0
1	46	30	33	12.57	3.68	227	1.0
1	46	30	29	10.16	3.94	213	0.5
1	46	30	29	9.40	2.92	127	1.0
1	46	30	28	9.40	3.17	154	0.0
1	46	15	32	9.78	3.94	200	1.0

1	46	15	29	10.79	3.05	163	0.5
1	46	15	32	9.27	3.05	136	0.5
1	46	15	34	11.94	3.43	218	1.0
1	46	15	32	8.51	3.30	159	0.5
1	46	15	37	9.27	3.17	145	1.0
1	46	15	29	10.29	3.17	154	1.0
1	46	15	32	8.51	2.92	118	1.0
1	46	15	33	8.51	3.43	150	1.0
1	30	15	33	13.72	3.56	259	0.0
1	30	15	29	9.65	3.05	141	1.0
1	46	23	30	9.78	3.56	186	0.5
1	46	23	33	8.51	3.68	182	1.0
1	46	23	30	11.05	3.30	204	1.0
1	46	23	28	10.41	3.68	218	0.5
1	46	23	30	9.78	3.56	182	1.0
1	46	23	.	9.40	3.56	163	.
1	46	23	29	11.30	3.43	200	0.0
1	46	23	30	12.06	3.17	204	1.0
1	46	23	28	10.67	3.56	195	1.0
1	46	23	29	8.64	3.17	191	1.0
1	30	30	29	9.27	3.56	191	0.0
1	30	30	28	8.76	3.94	200	1.0
1	30	30	32	9.14	3.68	186	1.0
1	30	30	30	9.14	3.43	177	1.0
1	30	30	27	10.16	3.43	213	0.5
1	30	30	27	9.91	3.68	177	1.0
1	30	30	28	12.70	3.30	218	1.0
1	30	30	30	8.25	3.43	177	0.0
1	30	30	30	10.03	3.43	159	0.5
2	30	23	36	12.70	2.92	209	0.5
2	30	23	33	10.67	3.30	173	1.0
2	30	23	33	11.94	2.79	195	0.5
2	30	23	39	10.67	3.05	191	1.0
2	30	23	37	10.92	3.17	168	0.0
2	30	23	36	9.14	2.67	173	0.5
2	30	23	39	10.41	2.92	173	0.5
2	30	23	34	8.38	2.79	123	1.0
2	30	23	33	13.21	2.79	241	0.5
2	30	23	32	12.95	2.54	222	1.0
2	30	23	36	10.16	3.05	173	1.0
2	30	23	38	11.43	2.92	245	1.0
2	30	23	37	13.46	3.05	222	1.0
2	30	23	30	9.14	2.92	177	1.0
2	30	23	36	9.65	2.54	114	1.0
2	30	23	39	9.91	2.54	136	1.0
2	30	23	33	9.65	3.05	159	1.0
2	30	23	37	10.92	3.05	177	1.0
2	30	23	32	9.14	2.54	123	1.0
2	30	23	34	14.22	2.79	268	0.5
2	46	15	36	10.92	2.79	182	0.5
2	46	15	38	11.43	2.54	159	1.0
2	46	15	39	11.18	2.79	145	0.0
2	46	15	36	10.92	2.54	168	0.5
2	46	15	37	9.14	2.92	177	1.0
2	46	15	36	11.18	3.30	213	0.5
2	46	15	38	9.65	2.79	141	0.0

2	46	15	32	11.43	2.92	213	1.0
2	46	15	36	9.65	2.92	222	0.5
2	46	15	33	9.40	2.54	141	1.0
2	46	15	37	9.14	2.67	145	1.0
2	46	15	39	12.70	2.54	159	1.0
2	46	15	37	11.18	3.17	173	0.5
2	46	15	37	9.91	3.05	163	0.5
2	46	15	37	8.64	2.67	127	1.0
2	46	15	36	9.40	2.67	127	1.0
2	46	15	36	11.94	2.92	163	1.0
2	46	15	34	.	3.05	250	0.5
2	46	30	33	9.91	3.30	232	1.0
2	46	30	34	11.43	3.17	250	1.0
2	46	30	33	12.95	2.92	163	0.0
2	46	30	32	10.67	2.79	163	1.0
2	46	30	32	9.14	2.79	145	1.0
2	46	30	32	9.65	2.92	173	0.5
2	46	30	29	.	.	.	1.0
2	46	30	30	.	.	.	1.0
2	46	30	32	8.83	3.05	136	1.0
2	46	30	34	10.16	2.67	136	1.0
2	46	30	34	10.67	3.43	209	1.0
2	46	30	32	9.65	3.43	218	0.0
2	46	30	34	10.41	3.05	195	0.5
2	46	30	36	11.68	3.05	213	0.5
2	46	30	33	12.95	3.30	268	1.0
2	46	30	33	11.18	3.05	191	1.0
2	46	30	32	.	.	.	1.0
2	46	30	33	.	.	.	1.0
2	46	30	32	.	.	.	1.0
2	30	15	37	10.92	2.92	195	0.5
2	30	15	38	9.91	2.41	136	1.0
2	30	15	36	11.43	2.92	191	0.5
2	30	15	36	9.91	2.54	127	0.5
2	30	15	39	9.14	2.67	136	0.0
2	30	15	41	11.94	2.67	186	0.5
2	30	15	38	9.40	2.54	150	1.0
2	30	15	37	10.92	2.79	195	0.0
2	30	15	37	9.40	2.79	150	0.0
2	30	15	42	8.89	2.67	132	1.0
2	30	15	38	10.67	2.54	145	1.0
2	30	15	39	8.64	2.54	118	1.0
2	30	15	38	10.16	2.79	154	0.5
2	30	15	38	11.68	3.30	200	1.0
2	30	15	37	10.92	2.54	150	1.0
2	30	15	36	9.91	2.92	159	0.5
2	30	15	34	10.41	2.79	150	0.5
2	30	15	34	8.89	3.05	141	0.0
2	30	15	38	9.40	2.92	141	0.5
2	30	15	36	10.16	2.79	154	0.5
2	30	15	39	9.14	2.29	114	0.5
2	30	15	32	10.92	2.67	173	0.0
2	30	15	34	11.68	2.92	204	1.0
2	30	30	33	11.43	3.05	209	1.0
2	30	30	33	10.67	2.92	173	0.5
2	30	30	28	9.40	2.67	145	1.0

2	30	30	33	9.65	2.79	127	1.0
2	30	30	37	9.14	2.79	150	0.5
2	30	30	33	11.18	3.56	268	1.0
2	30	30	29	12.45	3.05	218	1.0
2	30	30	28	10.92	2.67	177	1.0
2	30	30	30	10.92	3.05	195	1.0
2	30	30	28	11.43	3.68	259	1.0
2	30	30	33	11.18	2.92	200	1.0
2	30	30	32	9.91	3.17	186	0.5
2	30	30	30	10.92	2.67	173	0.5
2	30	30	34	11.43	2.79	177	1.0
2	30	30	33	10.41	3.68	222	1.0
2	30	30	33	8.89	3.30	168	0.0
2	30	30	29	9.14	2.92	136	0.5
2	30	30	32	8.89	2.79	132	1.0
2	30	30	.	.	.	.	1.0
2	46	23	34	9.40	3.17	163	0.0
2	46	23	33	9.40	2.79	177	0.5
2	46	23	32	10.92	3.30	222	1.0
2	46	23	36	10.92	2.92	154	1.0
2	46	23	34	12.70	2.41	141	1.0
2	46	23	38	10.16	3.34	281	1.0
2	46	23	32	9.65	3.17	173	1.0
2	46	23	30	10.92	3.30	218	0.5
2	46	23	33	11.43	2.79	154	1.0
2	46	23	34	9.91	2.92	200	0.5
2	46	23	28	8.38	2.79	182	1.0
2	46	23	33	11.68	3.05	141	1.0
2	46	23	30	10.92	3.05	159	0.5
2	46	23	34	9.40	2.79	163	0.0
2	46	23	34	10.67	2.92	200	1.0
2	46	23	34	10.67	2.92	186	0.0
2	46	23	33	11.18	3.17	200	0.5
2	46	23	32	12.45	3.05	227	0.5
3	30	23	36	10.92	2.54	177	1.0
3	30	23	37	8.89	2.92	209	1.0
3	30	23	43	11.81	2.67	204	1.0
3	30	23	38	11.81	2.67	195	1.0
3	30	23	36	12.32	2.03	100	1.0
3	30	23	36	9.02	2.79	168	1.0
3	30	23	37	11.05	2.41	150	1.0
3	30	23	36	10.92	2.54	145	1.0
3	46	15	38	10.54	2.29	150	0.0
3	46	15	39	10.67	2.41	168	1.0
3	46	15	41	10.79	2.92	191	1.0
3	46	15	37	9.14	2.41	127	1.0
3	46	15	41	9.91	2.41	150	1.0
3	46	15	39	10.41	2.67	145	1.0
3	46	15	33	11.30	2.54	114	1.0
3	46	15	38	11.18	2.67	173	0.5
3	46	15	36	10.16	2.29	132	0.5
3	46	15	38	10.79	2.67	154	0.0
3	46	15	36	9.27	2.67	195	1.0
3	46	15	36	10.03	2.16	109	1.0
3	46	15	36	9.02	2.92	182	1.0
3	46	15	36	9.02	2.67	173	1.0

3	46	15	34	11.56	2.16	86	1.0
3	46	15	37	8.25	2.41	95	1.0
3	46	15	36	9.52	2.79	145	0.5
3	46	15	39	9.91	2.54	132	0.5
3	46	15	36	9.65	2.41	109	0.5
3	46	15	38	11.43	2.54	109	0.5
3	46	15	37	12.32	2.67	123	0.0
3	46	30	34	9.91	2.67	132	1.0
3	46	30	25	9.78	2.29	136	1.0
3	30	15	34	8.51	2.41	123	1.0
3	30	15	38	12.19	2.41	118	1.0
3	30	15	41	9.91	2.54	145	1.0
3	30	15	41	11.05	2.16	100	0.5
3	30	15	41	9.40	2.54	100	1.0
3	30	15	37	10.16	3.17	145	1.0
3	30	15	39	10.54	2.54	204	0.0
3	30	15	38	8.64	2.67	132	1.0
3	30	15	38	8.51	2.67	191	1.0
3	30	15	36	8.51	2.67	109	0.5
3	30	15	30	9.91	2.16	136	1.0
3	30	15	36	8.89	2.92	186	1.0
3	30	15	37	8.89	2.29	91	1.0
3	30	15	32	10.41	2.67	136	0.0
3	30	15	33	8.64	2.16	163	1.0
3	30	15	38	10.41	2.54	82	1.0
3	30	15	38	9.78	3.17	127	1.0
3	30	15	38	9.02	2.41	177	1.0
3	30	15	36	11.68	2.16	95	0.5
3	30	15	36	9.27	2.92	100	1.0
3	30	30	34	10.54	1.90	104	1.0
3	30	30	36	10.67	3.30	250	1.0
3	30	30	32	11.05	2.92	168	1.0
3	30	30	33	10.54	2.92	195	1.0
3	30	30	34	11.81	2.67	163	1.0
3	46	23	29	10.41	2.79	145	1.0
3	46	23	33	11.43	2.29	109	1.0
3	46	23	34	11.30	2.79	168	0.5
3	46	23	29	9.40	2.67	177	1.0
3	46	23	33	10.03	2.54	145	1.0
3	46	23	34	10.79	2.54	136	0.5
3	46	23	38	10.03	2.54	136	0.5
3	46	23	33	11.05	3.05	150	1.0
3	46	23	36	10.29	2.79	168	1.0
3	46	23	34	10.03	2.54	154	0.5
3	46	23	36	10.92	2.29	141	1.0
3	46	23	36	9.91	2.54	136	1.0
3	46	23	33	10.03	2.67	132	1.0

APPENDIX C: 1988 Correlation Data

Harvest	Height (cm)	Head Diameter (cm)	Stalk Diameter (cm)	Weight (g)	Visual Accessibility
1	34	12.32	3.17	218	0.5
1	29	9.40	3.30	159	1.0
1	36	10.03	2.79	145	0.0
1	34	9.40	3.17	150	0.5
1	33	8.89	3.17	163	0.5
1	28	8.76	2.67	132	0.5
1	34	12.19	2.92	213	0.0
1	32	10.16	3.05	182	0.5
1	34	10.29	2.79	145	0.0
1	30	10.54	3.05	177	1.0
1	33	12.95	3.30	250	1.0
1	32	10.16	2.79	159	0.0
1	34	12.57	3.56	250	1.0
1	36	9.02	2.79	114	0.5
1	32	9.27	2.92	141	1.0
1	33	11.18	2.79	186	0.5
1	34	8.25	2.29	104	1.0
1	36	11.56	2.41	168	0.5
1	28	8.51	3.43	182	1.0
1	36	11.18	3.05	191	0.0
1	34	13.08	3.17	245	1.0
1	30	9.52	3.30	177	0.0
1	34	9.78	2.79	132	1.0
1	34	9.52	2.67	127	0.0
1	29	9.02	3.05	150	1.0
1	34	9.91	2.67	132	0.5
1	34	14.35	2.92	254	1.0
1	36	12.57	3.05	222	0.5

1	34	10.79	2.79	168	1.0
1	32	9.78	2.92	150	0.5
1	34	10.16	2.79	141	1.0
1	33	9.78	2.79	132	0.5
1	33	12.70	3.05	218	0.5
1	33	10.16	3.17	186	1.0
1	34	11.18	3.30	195	0.0
1	36	11.43	2.67	177	1.0
1	36	11.43	2.92	177	0.5
1	33	11.68	2.67	159	1.0
1	32	8.89	3.43	168	1.0
1	32	7.87	2.41	95	0.0
2	32	10.16	3.30	182	0.5
2	34	8.89	2.41	109	0.0
2	30	9.40	3.05	163	1.0
2	34	10.16	2.92	159	0.0
2	34	9.91	2.54	127	1.0
2	34	8.64	2.41	104	1.0
2	36	9.65	2.67	136	1.0
2	33	8.64	2.79	136	1.0
2	32	10.16	3.17	182	1.0
2	38	8.38	2.41	118	1.0
2	37	9.65	2.16	104	1.0
2	34	9.65	2.79	145	1.0
2	32	8.38	2.79	141	0.5
2	30	10.67	2.92	173	0.0
2	37	10.16	2.79	159	1.0
2	29	8.64	2.92	141	0.0
2	39	8.38	2.54	118	0.5
2	30	8.38	2.54	104	1.0
2	36	9.40	2.92	136	1.0
2	34	8.64	2.41	104	1.0
2	37	8.89	3.05	150	1.0
2	39	9.91	2.67	141	0.5
2	37	9.65	2.54	132	0.0
2	39	8.64	2.54	109	0.5
2	36	9.65	3.05	173	1.0
2	37	9.65	2.92	154	1.0
2	34	8.89	2.67	118	1.0
2	38	10.67	2.79	173	0.5
2	33	9.40	3.05	154	0.5
2	32	9.40	3.05	154	1.0
2	36	8.89	2.54	114	1.0
2	37	10.92	2.79	159	1.0
2	37	9.65	2.67	141	1.0
2	37	8.38	2.41	104	0.5
3	34	9.40	2.29	95	0.5
3	37	9.02	2.41	114	0.5
3	32	8.25	2.41	100	1.0
3	39	10.67	2.16	118	1.0
3	37	9.91	2.54	132	1.0
3	36	9.14	2.92	136	1.0
3	33	10.16	2.16	123	1.0
3	36	9.52	2.67	127	0.5
3	37	10.03	2.54	141	0.5
3	38	10.92	2.54	168	1.0

3	33	9.52	2.67	127	1.0
3	36	10.03	2.54	127	0.0
3	38	9.40	2.41	132	1.0
3	39	13.08	3.05	241	0.5
3	39	10.79	2.41	154	1.0
3	32	9.91	2.67	127	1.0
3	37	9.14	2.41	109	1.0
3	34	9.27	2.16	95	1.0
3	41	8.64	1.90	82	1.0
3	34	9.27	2.41	118	1.0
3	34	8.38	2.54	104	1.0
3	30	9.40	2.41	123	1.0
3	30	9.40	2.41	118	1.0
3	39	10.54	2.67	154	1.0
3	36	9.14	2.16	86	1.0
3	36	9.78	2.41	114	0.5
3	34	10.16	2.54	127	1.0
3	39	10.16	2.29	118	1.0
3	30	9.91	2.41	132	1.0
3	36	9.40	2.67	123	0.5
3	34	8.89	2.41	114	1.0
3	29	10.41	3.05	173	1.0
3	38	10.29	2.67	150	1.0
3	39	9.91	2.54	132	1.0
3	36	9.27	2.67	127	0.5
3	33	9.40	2.29	123	1.0
3	33	9.02	2.54	109	1.0
3	36	8.89	2.67	109	1.0
3	39	9.91	2.41	145	0.5
3	43	9.78	2.29	118	0.5
3	42	8.89	2.16	100	1.0
3	38	9.02	2.41	114	0.5
3	39	9.65	2.16	114	1.0
3	41	10.03	2.29	114	1.0
3	43	9.27	2.16	104	1.0
3	38	9.91	2.41	123	1.0
3	37	10.03	2.79	141	1.0
3	38	9.52	2.67	136	1.0
3	39	10.54	2.79	150	1.0
3	39	10.67	2.41	136	0.5
3	38	10.79	2.79	154	0.5
3	42	10.03	2.29	145	1.0
3	36	9.78	2.92	150	0.5
3	42	9.65	2.41	132	1.0
3	46	10.79	2.29	145	1.0
3	39	11.94	2.92	186	0.5

APPENDIX D: 1987 Cutting Device Harvest Test Data

Block	Method	Planting Pattern	Harvest	#Harvested	#Missed	#Damaged	Time (S)
1	W	A	1	24	2	5	124
1	W	B	1	28	1	5	159
1	W	C	1	10	2	0	91
1	S	A	1	15	3	1	104
1	S	B	1	9	5	0	65
1	S	C	1	8	2	1	73
1	W	A	2	22	1	3	145
1	W	B	2	19	3	0	115
1	W	C	2	20	2	3	118
1	S	A	2	15	0	1	114
1	S	B	2	25	2	3	132
1	S	C	2	17	3	2	93
1	W	A	3	29	0	4	140
1	W	B	3	17	0	0	117
1	W	C	3	46	1	5	218
1	S	A	3	23	1	1	106
1	S	B	3	36	2	2	139
1	S	C	3	37	0	7	179
2	W	A	1	14	3	2	106
2	W	B	1	18	0	0	117
2	W	C	1	27	0	3	147
2	S	A	1	29	3	3	166
2	S	B	1	15	0	1	102
2	S	C	1	22	2	1	103

2	W	A	2	25	1	3	126
2	W	B	2	33	0	7	167
2	W	C	2	43	0	1	187
2	S	A	2	27	2	5	130
2	S	B	2	27	0	3	115
2	S	C	2	37	1	8	175
2	W	A	3	27	1	1	97
2	W	B	3	18	0	1	75
2	W	C	3	20	1	0	68
2	S	A	3	16	0	2	70
2	S	B	3	25	1	1	89
2	S	C	3	34	0	2	115
3	W	A	1	11	0	0	99
3	W	B	1	4	0	0	98
3	W	C	1	23	0	3	173
3	S	A	1	6	1	1	94
3	S	B	1	11	0	0	67
3	S	C	1	9	0	0	63
3	W	A	2	18	0	2	90
3	W	B	2	19	1	2	110
3	W	C	2	33	0	3	180
3	S	A	2	21	1	2	102
3	S	B	2	32	0	2	144
3	S	C	2	36	0	2	170
3	W	A	3	32	0	3	145
3	W	B	3	42	0	1	159
3	W	C	3	37	2	2	138
3	S	A	3	26	0	1	110
3	S	B	3	33	0	1	133
3	S	C	3	49	0	1	190

APPENDIX E: 1987 Cutting Device Harvest Test Data

Block	Row Spacing (cm)	Plant Spacing (cm)	Harvest	#Harvested	#Missed	#Damaged	Time (S)
1	30	15	1	25	4	5	152
1	30	23	1	11	0	1	59
1	30	30	1	18	0	2	111
1	46	15	1	14	4	0	80
1	46	23	1	20	1	2	120
1	46	30	1	22	2	2	127
1	30	15	2	28	0	5	153
1	30	23	2	13	0	0	74
1	30	30	2	20	0	4	109
1	46	15	2	20	0	4	109
1	46	23	2	23	0	4	129
1	46	30	2	19	0	2	107
1	30	15	3	49	0	6	222
1	30	23	3	27	0	0	130
1	30	30	3	20	1	2	83
1	46	15	3	43	1	1	197
1	46	23	3	32	1	2	141
1	46	30	3	24	0	4	110
2	30	15	1	11	2	2	74
2	30	23	1	45	1	5	246
2	30	30	1	19	2	2	107
2	46	15	1	31	2	2	171
2	46	23	1	45	3	6	271

2	46	30	1	34	3	4	202
2	30	15	2	39	1	4	222
2	30	23	2	13	1	1	67
2	30	30	2	21	0	2	115
2	46	15	2	19	0	1	114
2	46	23	2	24	0	2	131
2	46	30	2	27	0	2	135
2	30	15	3	42	0	5	193
2	30	23	3	35	0	3	141
2	30	30	3	23	0	4	108
2	46	15	3	47	1	3	219
2	46	23	3	20	1	2	83
2	46	30	3	15	0	0	66
3	30	15	1	41	4	2	233
3	30	23	1	31	2	4	181
3	30	30	1	38	5	3	216
3	46	15	1	41	4	2	245
3	46	23	1	28	4	2	151
3	46	30	1	35	2	4	215
3	30	15	2	25	0	1	153
3	30	23	2	27	1	3	149
3	30	30	2	17	1	2	90
3	46	15	2	33	0	1	187
3	46	23	2	23	0	3	129
3	46	30	2	17	0	1	91
3	30	15	3	35	0	2	158
3	30	23	3	25	0	2	105
3	30	30	3	27	1	5	116
3	46	15	3	51	0	5	215
3	46	23	3	26	1	3	124
3	46	30	3	12	0	1	61

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