Conservation Tillage Machinery for Broccoli Production

by

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(ABSTRACT)

Broccoli is increasingly being grown as an alternate crop in many tobacco producing regions. Many of these regions, especially in Virginia, are quite susceptible to soil erosion losses. In order to reduce erosion and reap the other benefits of conservation tillage, a strip tillage machine named FOR2 was designed, developed and tested. FOR2 prepares the seedbed and places the seed in one pass through the field. This thesis reports the qualitative and quantitative evaluation of FOR2 based on result from two experiments. The first experiment evaluated broccoli emergence under three different tillage treatments, one of which was FOR2. The second experiment assessed the influence of adjustable machine parameters on the prepared soil condition in terms of aggregate size distributions, The parameters that were varied included pre-planting irrigation amount, tiller depth, tiller RPM, and tractor speed.

The analysis revealed that the FOR2 machine produced commercially acceptable stands of broccoli with 77% germination. It was also determined that the percentage of aggregates in the seedbed greater than 0.297 mm was significantly influenced by the irrigation level and the tiller RPM. Tiller depth and tractor speed had no significant effect on the response.

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1.0 Introduction

"No one has ever advanced a scientific reason for plowing" (Faulkner, 1943). This statement pronounced over forty years ago is partially responsible for the revolutionary trend in modern agriculture from conventional tillage to conservation tillage. By the year 2000 over 90% of United States cropland is expected to produce using conservation tillage techniques (Rice, 1983). Conservation tillage has successfully been used for growing corn, soybeans and grains. Conservation tillage has also been used to a lesser extent for growing several horticultural crops, including broccoli.

Conservation tillage is defined as any tillage or planting operation which leaves 20% or more of the ground covered with debris (Dickey et al., 1986). Chemical control of weeds with recently developed herbicides is a major factor which has enabled crop production without primary tillage. Agronomic benefits of conservation tillage crop production include moisture retention, reduced compaction and crop residue buildup. Acceptance of new techniques by farmers must embody economic benefits as well as agronomic benefits that outweigh their associated costs. Conservation tillage provides economic benefits to the properly managed farm which include reduced energy consumption because of fewer field operations, reduced soil loss because less of the soil surface is exposed, and increased yields due to greater timeliness of operations and positive crop response to improved agronomic conditions.

The benefits of conservation tillage will not be fully realized unless there is proper management of a well defined conservation tillage system. This system requires careful selection of crops and their rotations, monitoring of weed and insect populations and, most importantly, making sure that equipment is appropriate for the job and that it is functioning properly.

The research reported herein is based on the design, development and application of conservation tillage planters for production of vegetables and other specialty crops in a desiccated cover

crop such as wheat or rye. One of these machines, called FOR2 was used extensively, and was throughly evaluated in this research. It removes the trash from a narrow strip, prepares a narrow seedbed using discs and a rototiller, and plants the seed, all in one pass through the field. The final outcome is a 7 cm wide seedbed with two small ditches on either side.

FOR2 has two unique design features that enhance its performance. The rototiller housing is much wider than the tiller tines except at the soil surface where it is only slightly wider. This feature prevents clayey soils from caking in the housing and clogging, and allows the soil to flow down the sides of the tiller, behind the tines and back into the narrow strip from where it came. The other unique feature consists of a pivoting mechanism that forces precise tracking of the planter in the prepared strip as the tractor follows a curve.

In order to qualitatively and quantitatively evaluate FOR2, two separate experiments were planned and completed. The first experiment compared broccoli emergence under three different tillage treatments, one of which was FOR2. The second experiment assessed the influence of FOR2's adjustable machine parameters on the prepared soil condition in terms of aggregate size distribution and seedbed geometry. Seedbed aggregate size samples were sieved and the results were statistically analyzed for twelve different machine setup configurations at various irrigation levels. The machine parameters that were adjusted included, tiller depth (3.8, 5.7 cm), tiller RPM (195, 300, 390 r/min), and tractor speed (0.75, 1.12 km/h). Three irrigation levels (low, medium, high) were applied prior to the tests. Rain gauges were used to assess the uniformity of irrigation within one of the plots and moisture content samples were taken throughout all of the plots to determine the uniformity of moisture content. Seedbed width and depth were measured in order to describe the area of tillage and determine the effectiveness of FOR2 for conservation tillage.

2.0 Objectives

The specific objectives of this project were :

1. To evaluate the potential for using a Vegetable Emergence System (VES) machine to direct seed broccoli in a killed cover crop.
2. To develop criteria for an acceptable conservation tillage seedbed for broccoli.
3. To design and construct a conservation tillage planting system that meets the criteria in objective 2.
4. To evaluate quantitatively the performance of the planting system in objective 3 in terms of seedbed aggregate size analysis.
5. To evaluate qualitatively and quantitatively the performance of the planter developed in objective 3 in terms of broccoli stand establishment.

3.0 Literature Review

3.1 Terms and Definitions

Experiments should conform to standards that have been established by various scientific communities. The use of standards allows scientists to compare and contrast each others results in a simple and straightforward manner. An important aspect of standardization is the common use of many terms and their definitions. The terms and definitions that relate to the research reported herein are given in Appendix A.

The term tilth has been widely used to qualitatively describe soil conditions as they relate to the ability of a field to produce a crop. There is no standard definition of tilth, but many researchers described it. Holcomb (1986) implied that good tilth indicates that soils are loose and easily crumbled to provide a good seedbed. Puri and Puri (1939) described soil tilth as the size distribution of aggregate particles as a function of the soils ultimate mechanical analysis. Arya and Blake (1972) showed that the timing of secondary tillage after primary tillage may have significant impact on the tilth or aggregate size distribution of soil particles.

3.2 Erosion

Soil erosion is a continual problem associated with conventional tillage in many parts of the world. The dust bowl experience in the early 1930's brought about a national concern for the care and stewardship of the land. The Associated Press reported that "the entire area from Montana on the west, Texas on the south, and the Ohio Valley on the east was dusted in (sic)" (Rice, 1983). Soil erosion averaged five tons per acre per year nationwide in 1982 and was particularly excessive in the Appalachian States (Rice, 1983).

Wind erosion is especially harmful to exposed soil in many of the Great Plains States (Rice, 1983). Woodruff and Siddoway (1973) reported that 50% of the surface soil should have clods greater than 1 cm in diameter to limit wind erosion. This statement is particularly important since tillage influences clod size. A primary feature of conservation tillage is to render the land less susceptible to erosion from wind and water. Johnson et al. (1984) noted that conservation tillage practices have gained considerable support by merit of their erosion control capability in addition to favorable yields.

3.3 Seedbed Physical Environment

A seedbed can be described either qualitatively, as in tilth, or quantitatively as in aggregate size distribution or some other numerical value. Bowen (1966) summarized the thoughts of many plant growth researchers by writing; "Almost all of the present cultural methods and equipment have been developed for the control of seed and plant environments without the benefit of well explicated and quantitative descriptions of the environments that are to be controlled." He further suggested that adequate descriptions of the plant environment must contain histories of the four edaphic factors: soil temperature, moisture, aeration and impedance. The need for quantitative descriptors of the soil physical environment is extremely important to the designer of field equipment as well as the researcher studying the effects of tillage tools. Lindwall and Erbach (1983) mentioned that improvement of crop emergence requires an improved seedbed which requires quantifying the optimum seedbed. They studied the effects of tillage and planting systems on soil physical properties in relation to emergence and early growth. The physical properties they measured were soil moisture, bulk density, aggregate size distribution and soil temperature. Colvin et al. (1982) suggested using a tillage index that disregards the soil engaging tool and only considers the soil condition. Input to this index would be penetration of tillage, amount of surface residue cover, texture, and height difference perpendicular to the direction of tillage. Many researchers (van Bavel, 1949; Coughlan et al., 1973; DeBoodt et al., 1961; Gardner, 1956; Hagin, 1952; Hammerton, 1961;

Hendrick and Gill, 1974 & 1971; Lindwall and Erbach, 1983; Puri and Puri, 1939; Retzer and Russel, 1941; Stirk, 1958; and Yoder, 1936) have sieved soil samples and calculated numbers characteristic of the sample distributions. The use of quantitative numbers to describe the soil physical condition is difficult because the desired final soil condition is dependent upon the intended use, and researchers are not in agreement about the optimum physical environment for plant growth (Gill and Vanden Berg, 1968; Kepner et al., 1978).

The physical environment that influences plant growth is both above and below the soil surface. The seedbed is the soil portion commonly manipulated to provide optimum germination and emergence. Soil granulation, seed size, crop type and the soil and weather conditions all influence the evaluation of the seedbed (Gupta and Larson, 1982). Hoyle and Yamada (1975) suggested that a desirable seedbed is one having two thirds of the aggregates between 0.5 mm and 11 mm but not over one sixth below 0.5 mm. They also suggested a seedbed classification system based on the percent of undesirable aggregates, their wet stability, and their spatial arrangement.

The root zone includes the seedbed and covers all of the area the roots exploit. Mechanical manipulation of the lower portions of the root zone has proven beneficial to disrupt the hard pans that exist in many southeastern soils, providing less restriction on root growth and allowing roots to obtain water and nutrients from the increased size of the root zone (Khalilian et al., 1986). They also compared the tap root length of six reduced tillage treatments and attempted to correlate this to crop yield. Researchers have successfully measured root penetration as a function of water potential and bulk density (Taylor and Gardner, 1963).

3.4 Soil Aggregation

An aggregate is defined as a group of two or more primary particles which cohere to each other more strongly than to surrounding particles (Kemper and Chepil, 1965). Therefore, aggregate sizes might range from several microns to several centimeters. Many soil physical properties are directly related to the exposed surface areas of soil aggregates, which is a function of aggregate diameter for

spherically shaped aggregates. Retzer and Russell (1941) expressed that soil structure in terms of aggregation influences root penetration, soil aeration, the intake and conservation of soil moisture and soil fertility by influencing biological and chemical reactions. Van Bavel (1949) stated that "only by characterizing the whole size distribution of aggregates in one single representative figure is it possible to test a hypothesis about the difference between the structure of two soils, or to correlate the rate of a certain treatment with aggregate distribution." He also cautioned that the quantitative relation between soil tilth and the results of an aggregate analysis cannot be expected because of the intangible nature of soil tilth (van Bavel, 1953).

There have been many proposals of a set of standardized indices that could be used to characterize aggregate size distributions. All of these indices are based upon a set of data obtained from a mechanical sieve analysis. A sieve analysis yields a set of raw data that contains sieve aperture sizes correlated with the sample weight retained on each sieve. The American Society for Testing and Materials has established guidelines for sieve analysis procedures (ASTM, 1985). These guidelines suggest sample sizes, shaking times, and weighing precision. ASTM (1985) also suggests graphical representation of data using either linear or logarithmic graphs.

The study of aggregates is not a new area of research. As early as 1936, Yoder analyzed erosion losses in terms of aggregates in size classes ranging from 0.005 mm to 2.0 mm. His data was presented as a logarithmic graph of percent weight in a sieve versus the logarithm of the aggregate size defined by the midpoint of the adjacent sieve openings.

Puri and Puri (1939) suggested the use of a weighted mean size, standard deviation or the Schoklitsch number as a characteristic number to describe the size distribution curve of an aggregate analysis. Their numbers are based on a summation curve, which is a graph of percent weight less than the sieve aperture size versus the aperture size. The weighted mean size is the aperture corresponding to 50% of the sample weight less than that size and 50% of the sample weight greater than that size. The standard deviation is defined as the square root of the sum of the square of the deviation of each size from the weighted mean size multiplied by the corresponding percentages. Assuming a maximum diameter of soil particles that bounds the summation curve allows the calculation of the area above and below the curve. The ratio of the area above the curve to the area

below the curve is defined as the Schoklitsch number. They found high correlation between the weighted mean size and the Schoklitsch number and suggested the use of the weighted mean size in addition to standard deviation to describe the results of aggregate sieve analyses.

Retzer and Russell (1941) used the coefficient of aggregation to characterize aggregate size distributions. The coefficient of aggregation is based on the assumptions that aggregates of all sizes have the same average density, aggregates of all sizes have the same average configuration, and the diameters of the aggregates on any given screen are linearly distributed between the diameter of the openings of that screen and the opening on the next larger screen. They calculated the coefficient of aggregation as 10^6 times the reciprocal of the sum of the ratio of the weight to the average diameter for each size group, which is proportional to the reciprocal of the total surface area per unit weight of soil, hence its practical significance.

Mazurak (1950) used a different summation curve than Puri and Puri (1939). He used a graph of percent weight less than the sieve aperture versus the aggregate diameter on a decreasing logarithmic scale. The area under the curve and to the right of the geometric mean is equal to the area above the curve and to the left of the geometric mean. Therefore he stated:

$$GM = \frac{D}{2^{\frac{\sum P - 50}{100}}} \qquad [1]$$

where, GM = geometric mean

D = diameter of openings in largest sieve

P = cumulative percent retained in each sieve

Van Bavel (1949, 1953) suggested the use of a mean weight diameter (MWD) to characterize aggregate size distributions. He used a similar graph to the one of Puri and Puri (1939) but used the upper limit diameter of the sieve section instead of the midpoint diameter. The MWD was defined as the area above the aggregate size distribution curve bounded by upper limits of 0% and 8 cm. The area can then be calculated assuming a continuous function with the aid of a planimeter. Although he defined this area in terms of integrals, no attempt was made to numerically integrate for obtaining the MWD.

Youker and McGuinness (1957) suggested a method to calculate the MWD using numerical integration. They used the midpoint of the sieve section diameter rather than the upper limit as suggested by van Bavel (1949, 1953) and summed the product of the midpoint diameter and the percent retained in each sieve section to obtain a value that was correlated using linear regression with MWD. Stirk (1958) showed that the MWD calculation by Youker and McGuinness (1957) was actually a weighted arithmetic mean size (AMS) analogous to the weighted mean proposed by Puri and Puri (1939).

Gardner (1956) found that a majority of over 200 aggregate size distributions fit a log-normal distribution. Therefore, a complete characterization of this distribution requires only the specification of the geometric mean diameter (GMD) and the standard deviation.

Many researchers have compared the various aggregate size distribution descriptors shown above. Browning et al. (1943) examined the relation between the coefficient of aggregation and the percentages of aggregates greater then 0.10 mm, 0.25 mm, and 0.50 mm. They found a positive curvilinear relationship with these size separates. They also noted a linear relation between the percentages of aggregates greater than 0.1 mm and 0.25 mm. Strickling (1950) showed that the use of aggregate size distributions was unnecessary due to a high linear relation between large (> 1.0 mm) and small (< 0.25 mm) aggregates. In his further analyses, he used the percent of water stable aggregates greater than 0.25 mm. Van Bavel (1949) noted many faults with the coefficient of aggregation by Retzer and Russell (1941). Van Bavel noted that the soil surface area responsible for the soil physical environment includes the aggregate interior surfaces in addition to the aggregate exterior surfaces. He also noted that the coefficient of aggregation is a function of the sample size. DeBoodt et al. (1961) stated that fines (0.0 mm - 2.0 mm) may not be omitted in the geometric mean diameter (GMD) determination by Gardner (1956) because the distribution then fails to be log-normal.

The MWD proposed by van Bavel (1949) seems to be used most commonly. Ahmad and Paul (1978) used the MWD as part of a study on the effects of subsoiling on soil physical conditions. Hagin (1952) also used MWD to assess the relation between plant growth and the soil

structure found by aggregate analysis. Lindwall and Erbach (1983) used MWD to analyze planter effects on soil properties and crop emergence.

Gupta and Larson (1982) used the GMD to assess the relation between drop height of aggregates in a drop-shatter test and the resultant sieve distribution. Allmaras et al. (1965) showed that various tillage treatments greatly affected the GMD as calculated from a log-normal distribution assumption.

One of the most comprehensive comparisons of methods for expressing aggregation data is provided by Schaller and Stockinger (1953). They compared sieve results using potential characteristic numbers that were percent greater than 2.0 mm, 1.0 mm, and 0.25 mm, GMD, and MWD. They concluded that a single size separate such as > 2 mm or > 1 mm can be used to adequately describe an aggregate sieve analysis. They showed that more samples are necessary with the percent greater than analysis to obtain the same degree of accuracy as that provided by the GMD and MWD. They acknowledged the fact that the characteristic number of an aggregate size analysis is only beneficial if it can be correlated with crop response.

The degree of aggregation has been reported to affect yields to a great extent. Very fine soil aggregation causes crusting and poor capillary action, whereas very coarse soil aggregation causes poor seed-soil contact and also poor capillary action. There is a desired soil physical condition that will provide optimum plant growth. Hammerton (1961) found that more beet seedlings were produced and that emergence was faster when planted in a fine soil (particle size < 1 mm) than in a medium (particle size between 3 mm and 6 mm) or a coarse (particle size between 6 mm and 9 mm) soil. This result was attributed to better moisture conditions and lower mechanical impedance in the fine soil as compared to the medium or the coarse soil.

Johnson and Taylor (1960) found that the highest rate of corn emergence occurred when at least 30% of the soil at seed level was able to pass through a 2.54 mm screen. They also reported that, as a crop becomes established, coarser seedbeds provide better crop response. This concept promotes the idea of strip tillage to produce finer aggregates in the small seedbed and leave the remainder of the root zone in its natural coarse state. Larson (1964) suggested a GMD of 5.0 mm for corn growth in the western corn belt. Hagin (1952) studied the influence of three aggregate size

classes on wheat growth. His findings showed definitely better plant growth and yield in coarse aggregates (MWD = 1.70 mm) than in fine aggregates (MWD = 0.33 mm). This result was attributed to poor oxygen supply to the roots on a finely aggregated soil.

Pollock and Manalo (1969) showed an increase in bean seedling epicotyl fresh weight when grown in coarse sand (approximate MWD = 0.351 mm) versus fine sand (approximate MWD = 0.175 mm).

Hoyle and Yamada (1975) suggested that optimum crop yields depend upon a uniform seedbed of proper aggregate size, the right spatial distribution, and stability of aggregates. They showed an increase in seedling emergence, an increase in uniformity of emergence, and a decrease in time untill emergence for different vegetable seeds in beds that have been aggresized (rototilled when wet) to provide uniform aggregates of a medium size (0.5 mm - 11.0 mm). Hoyle and Yamada also noted Russell's (1958) statement that soils with crumbs between about 0.5 mm and 3 mm are ideal.

Taylor and Johnson (1956) found that both early and late stands of corn were significantly correlated to the weight of aggregates less than 2 mm. Hoyle et al. (1972) stated that, in the San Joaquin Valley of California, the presence of primary particles (< 0.5mm) in the seedbed significantly retarded emergence, adversely affected nutrient uptake and formed serious clods.

As can be seen from the above summaries, many researchers have found aggregate size distributions that were favorable to various crops. Many reasons why favorable crop responses are observed remain hypotheses and are still being researched by many scientists.

3.5 Soil Crusting

A problem in many finely prepared soils is the formation of a surface crust, which is a compacted layer that inhibits hypocotyl emergence. The primary cause of crusting is the destruction of soil aggregates by excessive mechanical manipulation, rainfall, or irrigation, resulting in reduced aeration, increased density, and cohesion among soil particles (Hemphill, 1982). Bilbro and

Wanjura (1982) stated that rain formed soil crusts annually necessitate replanting thousands of hectares of cotton, resulting in large economic loss.

The strength of soil crusts can be measured quantitatively by a variety of machines. Bowen (1966) used a rubber balloon placed at seed level and measured the pressure required to inflate this balloon sufficiently to rupture the soil surface. Hemphill (1982) used a pentrometer with a 2 mm diameter plunger to measure the degree of soil crusting, whereas Bilbro and Wanjura (1982) used a 3.97 mm diameter pentrometer. Bowen and Coble (1967) proposed a backward driven rotary hoe wheel with curved tines that gave a lifting rather than a pressing force on the soil surface. The torque was then measured and correlated with seedling emergence.

Numerous researchers have studied ways in which crusting can be reduced using chemicals. Wilcox and Johnson (1971) reported using vermiculite, nurseryman compost (sawdust), petroleum coke and perlite at a rate of 0.16 L/m of row to reduce the potential for crusting. They found that the use of all of the above except perlite consistently increased emergence of tomatoes. Ells (1965) studied the effects of asphalt emulsion, sand, and perlite additions to the seed furrow. All of the additions proved to reduce crusting and permit emergence of tomatoes. Hemphill (1982) also studied the benefits of using vermiculite in addition to phosphoric acid (H_3PO_4), Nalco 2190, neutral ammonium phosphate solution ($NH_4H_2PO_4$), and sulfuric acid to reduce crusting. Vermiculite was found to be the most effective, applied at a rate of 1.3 m^3/ha and then covered with approximately 5 mm of soil.

3.6 Conservation Tillage

In his 1943 book, Plowman's Folly, Edward Faulkner showed that the moldboard plow is the least satisfactory implement for the preparation of land for the production of crops. He also predicted that when the devastation caused by the plow becomes recognized, American agriculture will undergo drastic revision. This author believes that the use and increase in conservation tillage is just one of the revisions Faulkner was predicting. In 1983, 20% of all U.S. farmers who planted crops

used conservation tillage, representing 33% of all cropland (Padgett, 1985). USDA has predicted that by the year 2010 farmers will use conservation tillage on 90% of the land they plant (Padgett, 1985). Virginia, West Virginia and Kentucky claimed to have 30-50% of their cropland in no-tillage production in 1983, while many states claimed that at least 25% of their cropland was in conservation tillage (Rice, 1983).

When compared with conventional tillage, conservation tillage has many advantages and some disadvantages and limitations. The three main advantages of conservation tillage are soil and water retention, lower production costs, and greater production efficiency (Bartok and Ashley, 1986; Kepner et al., 1978; and Rice, 1983). Another advantage is the greater timeliness of field operations because of better trafficability of the soil (Russell, 1978).

Limitations of conservation tillage have also been reported. Lindwall and Erbach (1983) reported that cooler soil temperature and poorer seed placement have been blamed, and rightly so, for depressed crop growth in no-till fields. Bartok and Ashley (1986) reported that crop management of no-till may be more time consuming due to more stringent monitoring requirements for weeds, pests, fertilizer application, and planting equipment.

Because of the many vegetables grown and the variety of physical environments they require, conservation tillage production of vegetables is not as widespread as it is in corn, soybeans and grains. Tompkins et al. (1976) studied minimum tillage snap beans and found that pod yields from reduced tillage plots were not significantly different from pod yields of conventional tillage plots. Smith and Younts (1986) found that reduced emergence occurred for dry edible beans and beets in conservation tillage when compared with conventional tillage. Booster et al. (1983) reported that the use of strip tillage in snap bean production reduced the yield about 32%. Tessore (1981) reported that for asparagus, watermelon, sweet corn, cabbage, cucumbers, lima beans, peppers, tomatoes, muskmelon, snap beans, and irish potatoes, plant stands were higher, fruit yield was greater and production was greater for no-tillage practices versus conventional.

3.7 Conservation Tillage Equipment

There are many different pieces of equipment used for conservation tillage, and many of these have potential to be used successfully for vegetable production. A few of these pieces of equipment will be reviewed here. Townsend and Bethge (1984) developed a furrow opener for seed and fertilizer placement in no-tillage production. Their system was designed to 1) penetrate hard soil without large vertical forces, 2) cut through crop residue on the surface, and 3) place the fertilizer, a layer of soil, the seed, and a second layer of soil sequentially from the bottom of the furrow to the top. Rhine and Wilcox (1985) described the VES (Vegetable Emergence System) machine as a complete machine for secondary tillage and seeding. The VES was designed to operate on previously tilled seedbeds with a rototiller operating at a 2.5 cm depth which provides the secondary tillage. Following the tiller is the seeding unit in combination with starter fertilizer and anticrustant delivery tubes. The Ro-Till machine developed by Bush Hog Inc. contains a subsoiler, waffle coulters and a rolling basket to form a seedbed. This machine has shown a 10 to 15 bushel corn yield advantage over the chisel plow and no-tillage equipment (Zahradnik, 1986). In order to evaluate tillage systems, Parka and Meeker (1983) and Colvin et al. (1984) have suggested identification systems. Parka and Meeker proposed a generic description of combination tillage equipment that characterizes each soil working tool rather than using one name to characterize the whole piece of equipment. Colvin et al. proposed a tillage index based on the soil physical conditions of height difference of row versus inter-row, amount of soil surface covered by plant residue, roughness of soil surface, and depth of tillage, rather than the tillage tool itself.

3.8 Direct Seeding

To obtain a uniform crop it is important that seed be placed at uniform depth regardless of soil or residue conditions (Powell, 1982). Bowen (1966) reported differently than Powell and re-

commended that planting depth should be a function of soil moisture content and be controlled to ± 3.2 mm. Lindwall and Erbach (1983) found that planting depths of corn varied widely but that emergence was not affected due to adequate moisture conditions throughout the seedbed.

Proper planting on the contour with combination tillage tools and seeding equipment requires that seeds be placed in the prepared strip. This requirement is not always met with rigidly mounted planters (Powell, 1982). Kepner et al. (1978) described the trailing characteristics of a three-point hitch mounted implement without sway bars when operated around a curve. For ideal trailing of an implement (no corner cutting), they suggested that the horizontal hitch point should be halfway between the rear axle center line and the center of resistance on the implement. Hunt and Garver (1973) displayed various tractor steering configurations and showed how the axles project to the turning center.

3.9 Rotary Tillage

Rotary tillage is an old practice dating back to the early 1900's. The rotary hoe was invented in 1890 and was used successfully for cultivation of corn, soybeans and other crops (Shawl, 1927). In 1910 Von Meyenburg of Switzerland obtained a patent on what has become known as the rototiller (Kelsey, 1946). In 1946 Greene asked questions about rotary tilled soil dealing with moisture content, germination, yield and aeration. Some of these questions are still not answered today.

A rotary tiller or rototiller, as used in this thesis, is a soil manipulating piece of equipment that consists of a powered horizontal shaft perpendicular to the direction of travel on which soil cutting tools (tines) are attached and revolved through the soil at high speed. Kelsey (1946) set high standards for the requirements of a rototiller. He stated that it must go into a field of standing corn and chop it up completely in one pass and bury every particle of cornstalk while leaving a clean seedbed ready for planting.

The performance of rotary tillage is a function of soil conditions, blade kinematics, and soil flow dynamics (Kinzel et al., 1981). The soil conditions include moisture, texture, and previous tillage and cropping histories (Smith, 1983). Blade kinematics include rotor speed, forward speed, and the shape and arrangement of the tines (Cooper, 1971). The soil flow dynamics are not well defined, but are a function of soil conditions and blade kinematics.

There are many rototiller design parameters that have been described by Hendrick and Gill (1971,1974,1978) in a series of papers. These parameters are direction of rotation, depth of operation, ratio of rotor peripheral to machine forward speed, blade clearance angle and the equations of motion used to characterize the trochoidal path of a point on a tine. Hendrick (1971) also suggested a recommended nomenclature for rotary tillage tools. Since most of Hendrick's, and Hendrick and Gill's research is very detailed and mathematically involved, it will not be reported here.

The performance of rototilling has been reported by a number of researchers. Hendrick (1979, 1980) noted the advantages of rotary chiseling versus rigid chiseling. Tillage performance was characterized by power consumption and by the resulting clod size distribution. Smith (1983) reported that two limitations of rotary tillage are high fuel consumption and excessive tillage action. He also reported that tail gate adjustment affects the amount of soil recirculation therefore affecting clod size. Gill and Hendrick (1976) reported that rotary tillage tools cause an irregular furrow bottom due to the geometry of the rototiller.

Hendrick and Gill (1971) reported that the blade clearance angle must be greater than zero to prevent the back face of the blade from compressing uncut soil. They also stated that the maximum clod size is limited by the cutting geometry. The depth of tillage did not seem to affect clod size at low peripheral velocities for some blade configurations. Adams and Furlong (1959) found that as rotor peripheral speed increased from 122 m/min to 305 m/min, average lump diameter decreased even though the increment of cut remained constant. They also found that decreasing the depth of cut from 5 cm to 6 cm decreased the average lump diameter from approximately 5 cm to approximately 3 cm even though the rotor speed was held constant. Davies et al. (1982) wrote that the extent of rototiller pulverization can be reduced by reducing rotor speed, increasing forward

speed, using less blades, raising the tail gate or by shallower working depths. Cooper (1971) noted that the degree of soil pulverization can be varied by controlling the length of cut, adjusting the soil shield, controlling the depth of cut, and changing the rotor speed.

4.0 Machine System Development

4.1 Acceptable System Criteria

In order to objectively analyze various pieces of conservation tillage equipment for broccoli, certain criteria are needed to express the views of this author as to what comprises an acceptable seedbed in a conservation tillage system. These criteria are stated below along with goals to be either met or exceeded in the development of the author's machines.

1. Planting equipment must operate in a killed cover crop such as wheat or rye standing as tall as 10 cm.
2. The trash (dessicated cover crop) must be either removed from the seedbed area or finely chopped so that it does not interfere with proper seed placement.
3. The soil in the seedbed must be granulated so that it flows smoothly around the furrow opener to enable proper coverage of the seed and good seed-soil contact.
4. The final seedbed level should be at or above the original soil level to prevent water accumulation and soil erosion during high intensity rainfall.
5. The prepared seedbed should have uniform depth and width.
6. The prepared seedbed must enable uniform depth of seed placement with proper direct seeding planters.
7. The direct seeding planters and the seedbed preparation unit must be coupled on the same implement so that tillage and planting can be accomplished in one tractor pass.
8. The implement must be three-point hitch mounted and be capable of operating from a 40 kW tractor for a two row machine.
9. The implement must be capable of operating on a curve which implies that the planter must track in the prepared soil strip.
10. Power requirements should be minimized.
11. Tillage action should be minimized.

4.2 Vegetable Emergence System

A VES (Vegetable Emergence System) machine was obtained from K-C Tool Inc., Rushville, Indiana in the spring of 1985. VES machines are used for direct seeding tomatoes in Ohio and Indiana in conventionally prepared soils (Rhine and Wilcox, 1985). This two row VES machine was modified to be used in a stubble mulch field. Its functional components are shown in Figure 1. The only soil engaging tool is the hydraulically driven rototiller. The tiller has four equally spaced L-shaped tines symmetrically arranged to achieve a 20 cm tip diameter, with tips pointing away from the center toward the shield. The width of cut is approximately 9 cm and the tiller housing is approximately 3 mm away from the tines on the sides and 10 cm away from the tines in the radial direction. The complete tiller unit floats via a linkage and spring mechanism that is mounted on the front tool bar. Tiller depth adjustment is obtained by lowering the tiller horizontal shaft in relation to the housing. Following the rototiller and mounted on a second toolbar are two Dahlman precision seeders. Each Dahlman seeder (Figure 2) consists of a rolling disc furrow opener and trash cutter, and a seed meter driven by a split rubber press wheel. Attached behind the seed metering unit but in front of the press wheel are spouts for liquid starter fertilizer (10-34-0) and vermiculite anticrustant.

During the summer of 1985 several shortcomings were discovered when the VES machine was operated in a desiccated mulch stubble at the Virginia Tech Horticulture Research Farm. In heavy trash, the tiller left too many large wheat stems unchopped and the large amounts of trash caused poor functioning of the seeder. When operated in slightly moist soils with high clay content, the tiller housing would pack with soil causing depressed seedbed surface levels and high power consumption. The soil packing also caused lodging of rocks and sticks between the tines and the packed soil, which caused the tiller rotation to be stopped several times. Because the Dahlman seeders have one wheel floatation, nonuniform seed placement resulted when operated on an uneven soil surface. The seeders were mounted rigidly to the frame and not allowed to pivot. This

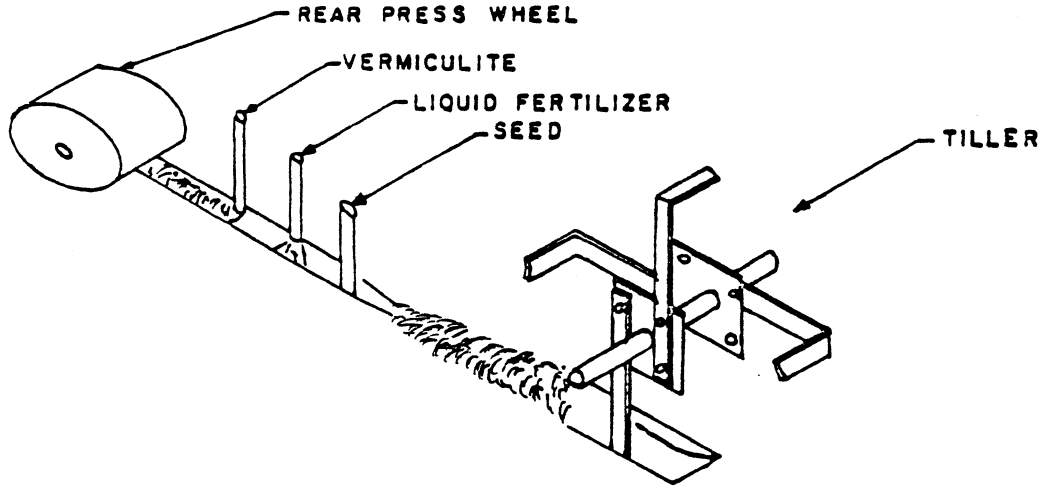

Figure 1. Functional components of VES machine.

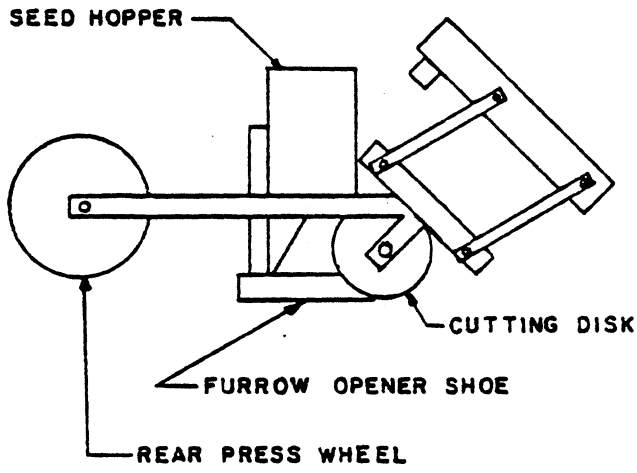

Figure 2. Dahlman precision seeder.

feature restricted machine operation to straight rows because the planter could not follow the prepared strip when operated on a curve.

Several good features of the VES machine were also observed. Floatation of the rototillers was achieved and a uniform depth seedbed was obtained. The starter fertilizer and vermiculite systems worked well and were capable of variable flow control and precise placement.

To overcome the shortcomings while retaining the good features of the VES machine, modifications were made to improve the seedbed environment and overall machine performance. The functional components of the modified VES machine are shown in Figure 3. Trash clearing discs were added in front of each rototiller to remove the killed mulch stubble from the seedbed surface. Notched 30 cm diameter discs were used with two discs per row. Stanhay precision seeders (Figure 4) were used in place of the Dahlmans seeders to take advantage of two wheel floatation of the Stanhay seeders. Additional modifications included adding a granular fertilizer system and a granular insecticide system with distribution tubes immediately preceding the rototillers.

The modified VES machine was tested by planting broccoli in the summer of 1985 in Halifax County, Virginia. The trash clearing discs worked well, but because they were mounted rigidly they did not consistently engage the soil when the soil surface was uneven. It was hoped that the trash clearing discs would help prevent clogging of the rototiller, but clogging still persisted. Since the trash clearing discs removed about 1.5 cm of soil in addition to the trash, the rototiller had less soil to granulate, which caused a seedbed surface below the original soil surface. A large amount of rain fell in a short time from hurricane Danny a few weeks after planting. The depressed seedbed surface permitted surface runoff to flow from the untilled areas between the rows to the softer and more erodible rows, which caused the soil in many of the rows to be washed out.

Although several problems existed, experiments were performed to analyze the effects of starter fertilizer and vermiculite on broccoli emergence. Four treatments were applied in a randomized complete block experiment with two replications. The four treatments were 1) starter fertilizer at a rate of 0.3 L/100 m, 2) vermiculite at a rate of 15.5 L/100 m, 3) starter fertilizer and vermiculite at the rates in 1 and 2, and 4) no starter fertilizer or vermiculite.

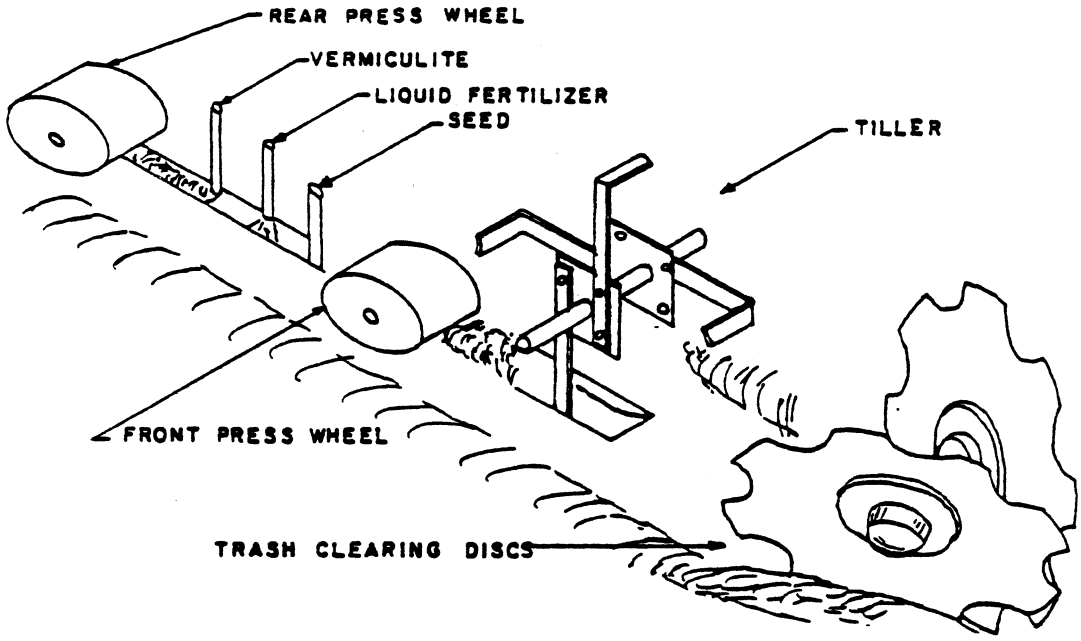

Figure 3. Functional components of modified VES machine.

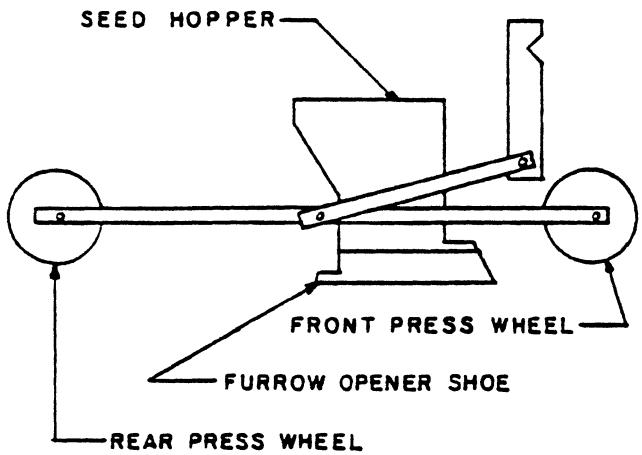

Figure 4. Stanhay direct seeder.

The results from these experiments are shown in Table 1. The greatest number of plants occurred when no starter fertilizer or vermiculite was placed in the row, but this treatment was statistically the same as the treatment with both pop-up and vermiculite together and as the treatment with vermiculite only. The low emergence with the treatment having only starter fertilizer might have been caused by a toxic effect of the fertilizer on the seed, but this toxicity might have been reduced when the fertilizer was absorbed by the vermiculite in the combination treatment.

4.3 FOR1 Machine

Tests with the VES machine provided valuable qualitative and quantitative data on the design requirements for a conservation tillage machine for soil conditions such as those found in Virginia. For simplicity, the chemical additive components were thought to be unnecessary at this stage of development, and design emphasis was placed on seedbed preparation. FOR1 (For Optimum Returns) was the machine which resulted. Figure 5 shows the functional components of this machine. The FOR1 machine has three main sections, 1) the soil preparation unit, 2) the floating mechanism for the soil preparation unit, and 3) the frame and hitch. The seeding units and their frame members were not included in this machine since the main objective was to obtain a suitable seedbed.

The soil preparation unit consists of three separate soil tools. The first soil engaging tool is a trash clearing disc. Each row unit employs one 30 cm diameter disc, angled 30° away from the row. A shank supports the trash clearing disc and is mounted such that working depth is adjustable.

Following the trash clearing disc are the hiller discs, which funnel soil into the tiller. There are two concave 30 cm diameter discs for each row unit, arranged such that lines passing through their axes lie in the same horizontal plane. The discs have adjustable depths and angles as measured between the direction of movement and the perpendicular line through the disc axis. They can also be adjusted along a horizontal direction perpendicular to the direction of travel. They are fixed in that they must be vertical and one disc must lead the other by 6 cm.

Table 1. Results from modified VES experiment.

Treatment	Mean number Plants/ row
Starter fertilizer	38 a
Vermiculite	46 a b
Starter fertilizer and vermiculite	51 a b
No starter fertilizer or vermiculite	65 b

Means followed by the same letter imply statistical equivalence according to Duncan's Multiple Range Test at a 0.01 alpha level.

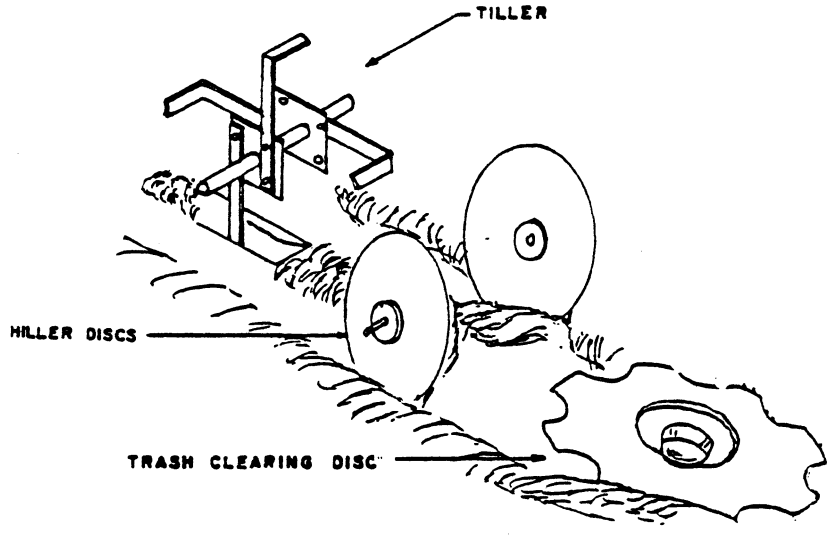

Figure 5. Functional components of FOR1.

Immediately following the hiller discs is the rototiller. There is one tiller for each row unit. The tiller consists of four tines, a housing, a shaft and a hydraulic motor. The four L-shaped tines are suitably mounted to the shaft such that they are 6.4 cm apart and point toward each other, thus providing a width of cut of only 7.6 cm. The housing is made of thin sheet metal and is shaped such that the clearance between the sides and the tines is 6 mm and the clearance between the top and the tines in the radial direction is 15 cm. The housing opening in the front is about 5 cm above the soil level to allow soil clumps generated by the hiller discs to enter. In contrast, the rear opening is only 3 cm above the original soil surface to provide a smooth seedbed. The housing is mounted such that it can be raised or lowered to provide tiller depths from 1 cm to 7 cm. A hydraulic motor is mounted to the support frame on the side of the housing and is directly coupled to the shaft. The motor is driven from hydraulic power obtained through the remote ports on the tractor and motor speed control is obtained through a flow divider valve. Two motors were needed for the two row machine; therefore, to maintain high RPM's, the motors were coupled in series and case drains were used.

Another major section of FOR1 is the floating mechanism. All of the soil tools for each row are mounted on the same structural member. Also attached to this member is a 41 cm diameter ground wheel placed between the trash clearing disc and the hiller discs. The entire soil preparation unit floats via a parallel linkage that is attached between the fore part of the soil preparation unit and the tool bar. Each row unit has its own parallel linkage, providing the much needed independent row floatation. The weight of the tools and their mountings is sufficient to provide soil penetration.

The frame and hitch section consists of a 10 cm square tool bar onto which a category II three-point hitch was mounted. Height adjustment of the soil preparation unit was obtained by adjusting the ground wheels. Therefore, a wide range of toolbar heights is acceptable as long as the parallel linkages are nearly horizontal.

Tests with the FOR1 machine in the summer of 1986 revealed two inadequacies in the machine parts related to seedbed preparation. These were rototiller clogging and failure of the row unit to float properly. It was hoped that since the tiller housing was made of thin steel and that it

was allowed to shake, the soil would not stick to the inside. Soil did adhere to the inside and continually built up until there was no clearance between the sides and the tines. Clogging of the tiller resulted in a disastrous seedbed. The row units floated well as long as the forces on the trash disc were small. When the trash disc engaged hard soil, enough force on the disc occured to twist the parallel links and cause extremely poor performance. The whole row unit would cant to the side, causing soil tools to be lifted out of the soil.

4.4 FOR2 machine

Based on the results from experimentation with the FOR1 machine, it was determined that several modifications needed to be made. Thus, FOR2 was designed, built, and tested. FOR2 is a one row machine with a soil preparation unit and a planter (Figure 6). It prepares the soil and seeds in one tractor pass through the field, and has the ability to operate on a curve. The soil preparation unit is similar to that used in FOR1 except it is mounted rigidly to the tool bar and the tiller housing has been changed. The hiller discs remain as they were on the FOR1 machine. The trash clearing section employed two 30 cm diameter discs, arranged so that they meet in the front and are spaced about 37 cm apart in the rear, thus providing a 76° wedge shape. they are also tilted 15° from the vertical which provides minimal soil lifting and more soil scraping.

A major objective in the design of FOR2 was to prevent tiller clogging. This objective was accomplished through the design of a spacious tiller housing. A sectional view of this housing is shown in Figure 7. It has 15 cm of clearance from the tines in the radial direction and about 9 cm of clearance between the sides of the tines and the sides of the housing, except at the soil surface where the clearance is only about 1 cm. This design allows soil to enter the front of the tiller, become mixed and be thrown throughout the tiller housing, then flow down the sides of the tiller housing and to the rear of the tines where it can flow back into the strip cut out by the tines. Clogging is eliminated by this design because the soil in its trajectory from the rear of the tines to the top of the housing has room to fall down the sides instead of being forced to fall into the path

Figure 6. FOR2 Machine.

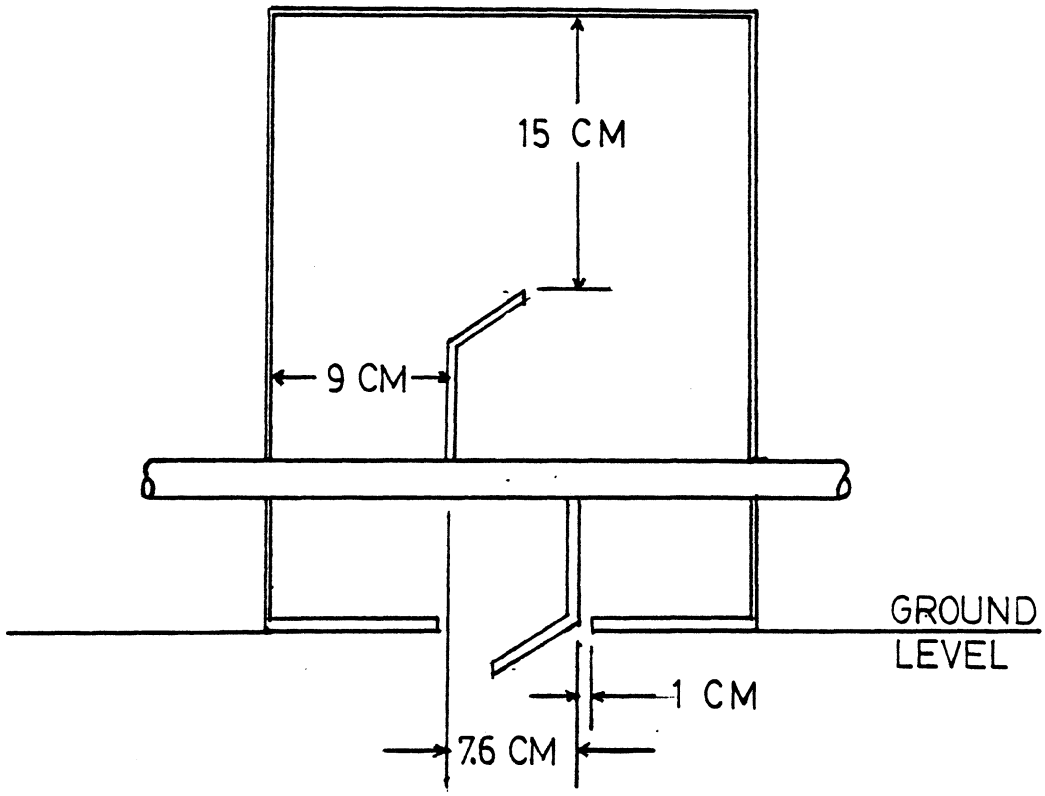

Figure 7. Sectional view of FOR2 tiller housing.

of oncoming soil particles as was the case in the previously discussed tiller designs with small clearances. The small clearance between the tines and the sides at the soil surface is needed so that the tilled soil is not spread over a larger area than from where it came, which would result in seedbed depression.

The complete soil preparation unit is mounted rigidly to a tool bar. Floatation is maintained by only using a one-row machine where the ground wheel follows the ground contour and the whole machine moves up and down via the three-point linkage. If a two-row machine was used and each row unit was mounted rigidly to the frame, uneven soil surfaces would cause one of the rows to be out of the soil.

Steel tubing from the front tool bar extends to the rear of the tiller to support a second tool bar on which the planting unit and drive mechanisms are attached. A Stanhay S780 precision seeder is used to produce a specific seeding density. The planter unit is driven via universal joint telescoping drive shafts from ground driven wheels. Modifications to the Stanhay were necessary in order to allow the seedbox and metering unit to pivot in a horizontal plane which allows precise tracking of the tilled strip as long as the conditions established in Section 4.5 are met. These modifications included support frames for the metering unit and for the ground wheels in addition to telescoping universal joint drive shafts that connect the ground wheels to the metering unit. The telescoping shafts limit the pivot angle of the seeding unit to pivot to 30° from the direction of travel by interference between the outer telescoping portion and the universal joint. Eight bearing supports are necessary to support the two outer shafts and the one center shaft that drives the seeding unit. The metering unit contains a seed belt with punched holes that travels in a loop while entrapping the seed in the punched holes and ejecting it in the furrow. Variable seed spacing is obtained by using various hole spacings on the belt and by adjusting the pulley drive speed ratios.

4.5 Planter Tracking

Concern about seed placement in the middle of the tilled strip arises from the geometrical conditions that exist when a tractor travels in an arc instead of a straight line. A conventional three point hitch on a tractor is designed so that it can be operated in two ways, rigid and free.

With the rigid configuration, the two lower links are stabilized to eliminate horizontal implement movement in relation to the tractor while maintaining vertical implement freedom. Rigid configurations are most commonly used for planting and cultivating equipment where straight rows are desired. The rigidity is necessary in some instances so that when an implement is operated on a hillside, gravity does not pull it down the hill, causing the direction of implement travel to be unparallel to its intended direction of travel. For a planter, this misdirection can cause poor seed placement and poor soil coverage. For a cultivator, this misdirection can mean interference between the cultivator tools and the existing plants. When a tractor on which an implement is rigidly mounted travels on a curve of a set radius, the implement center swings outward and travels on a curve with a larger radius.

A free configuration of the three-point hitch is necessary for some field operations so that outward swinging of an implement is possible. Some tillage and mowing operations require free configurations where the lower links are free to travel in the horizontal plane. High draft operations such as plowing require free horizontal movement so that the ground engaging tool is not pushed sideways against untilled soil. Mowing operations require free movement so that the width of cut remains relatively constant on the corners as well as the straight portions. When the lower links are free, the implement will cut to the inside on a curve as shown in Figure 8. This is due to the forces on the implement that tend to move the implement along the line of pull which is tangent to the arc of travel of the implement at the center of resistance of the tool. The amount of corner cutting is the distance from the center of resistance of the tool to the arc of travel of the tractor center. The horizontal direction of the line of pull can be found by summation of the linkage forces in the horizontal plane. The free hitch is such that it is the same as a trailed implement pulled from

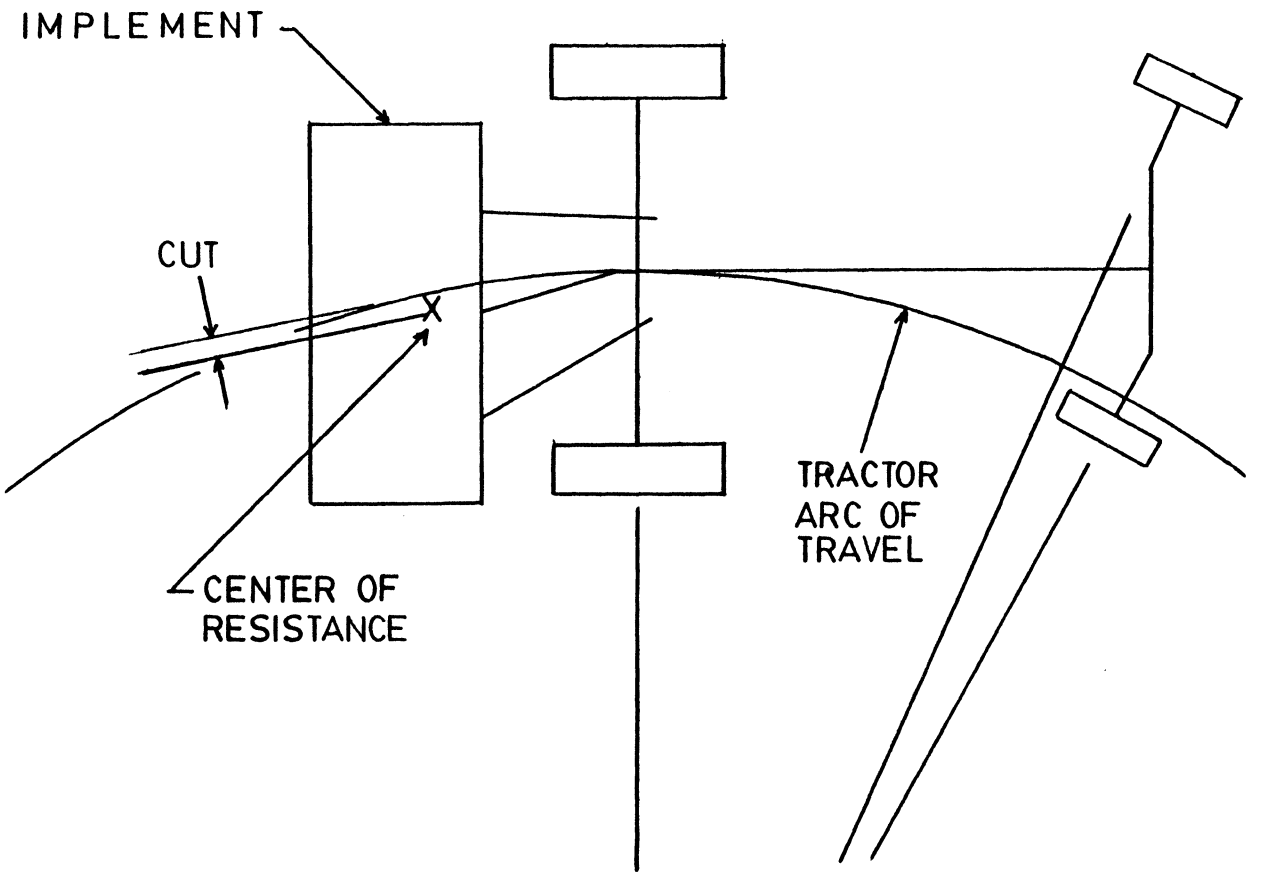

Figure 8. Diagram of tractor and free 3-point hitch implement turning geometry.

the point defined as the intersection of the line of pull and the tractor centerline. For implement trailing with no corner cutting, the hitch point should be halfway between the center of pull on the tractor and the center of resistance of the tool (Kepner et al., 1978).

Calculation of the actual amount of corner cutting is desired as a function of tractor and implement geometries. Figure 9 is a diagram of a conventional front steering, rear-wheel-drive tractor pulling a single- axle trailer from the drawbar around a curve of a set radius. The horizontal center of pull of the tractor is at point C on the tractor axle and equidistant between the wheels. The true hitch point is located at point B on the tractor centerline at the drawbar pin. Point A defines the center of resistance of the trailer. The center of the radius of curvature of the tractor and the trailer is at point D. By using similar triangles and noting that the amount of corner cutting equals $\overline{CD} - \overline{AD}$, the amount of cut (CUT1) can be calculated from:

$$CUT1 = \overline{CD} - \sqrt{\overline{BC}^2 + \overline{CD}^2 - \overline{AB}^2} \qquad [2]$$

Therefore, the amount of cut is a function of the radius of curvature, the distance from the tractor axle to the drawbar pin and the distance from the drawbar pin to the trailer axle. It should be noted that when the hitch point is equidistant from the tractor axle and the trailer axle, $\overline{BC}$ equals $\overline{AB}$ and the amount of cut equals zero (Figure 10), which is the same result stated earlier from Kepner et al. (1978). It should also be noted that when the radius of curvature is large compared to the hitch dimension, $\overline{CD}^2$ dominates under the radical sign and the amount of cut approaches zero.

The theory developed for a trailed implement above can be expanded upon to represent a rigid three point hitch mounted implement with a pivoting planter. Figure 11 is a diagram of such an implement. Point E is the center of resistance of the implement. Point F is the hitch point of the implement which is rigid to the tractor frame. Point G is the center of the final strip seedbed preparation area. With FOR2, point G is the center of the tiller, point H is the center of pull of the tractor and point I is the center of the radius of curvature of the tractor and implement.

Any combination seedbed preparation and tillage machine needs to place the seed in the center of the tilled strip which is not the line of travel of the tractor when the tractor follows a curve. As

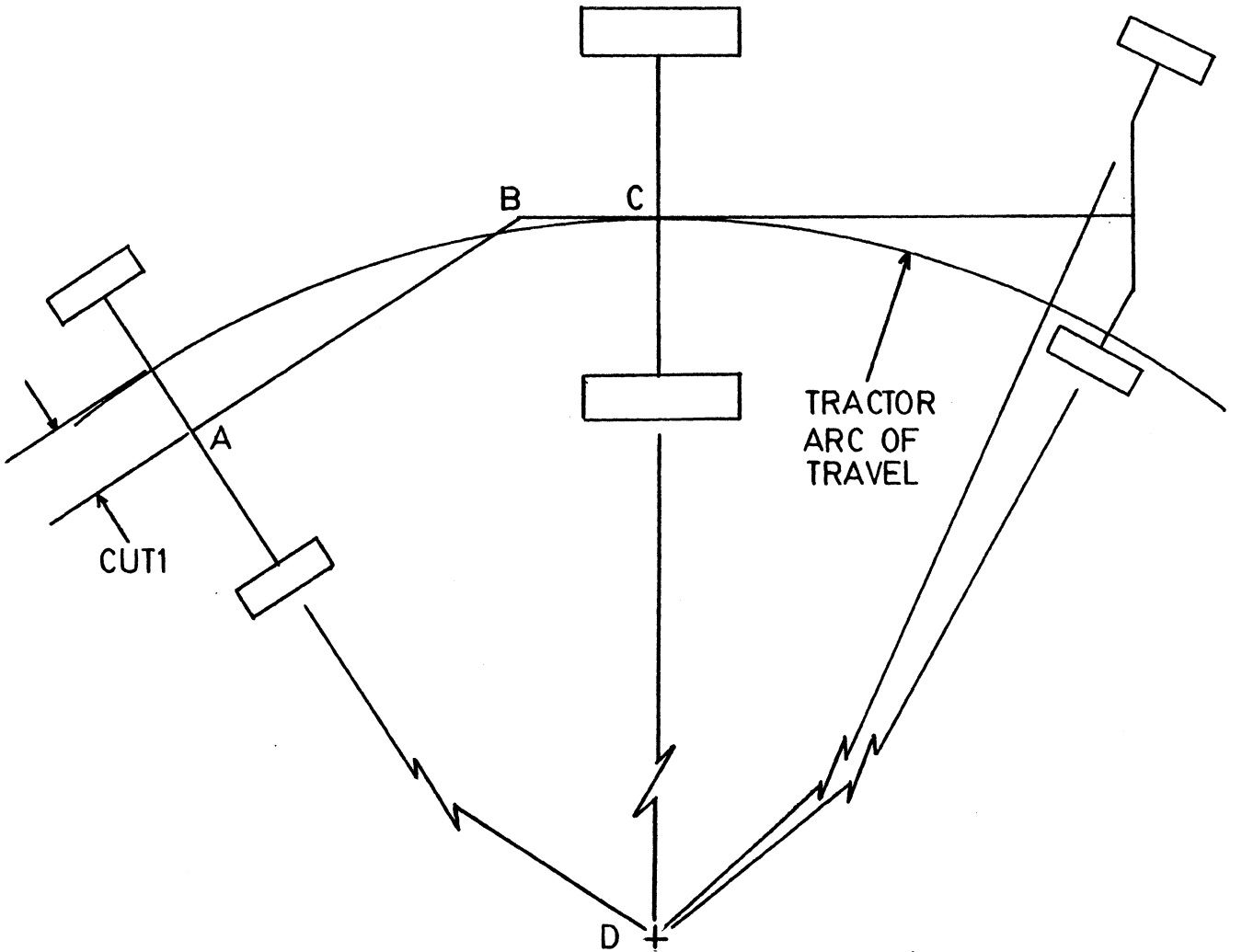

Figure 9. Diagram of tractor and trailer turning geometry.

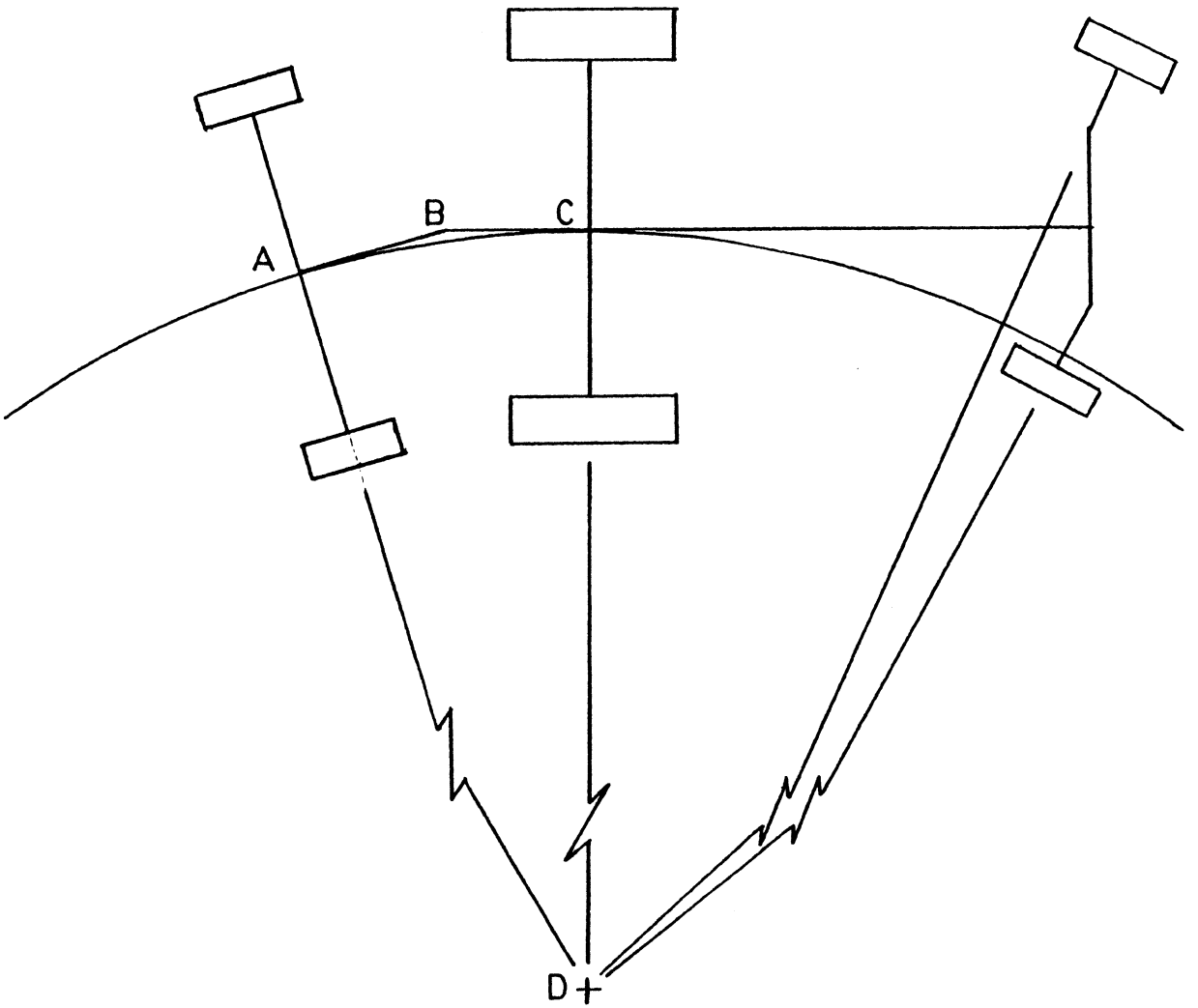

Figure 10. Diagram of tractor and trailer ideal geometry.

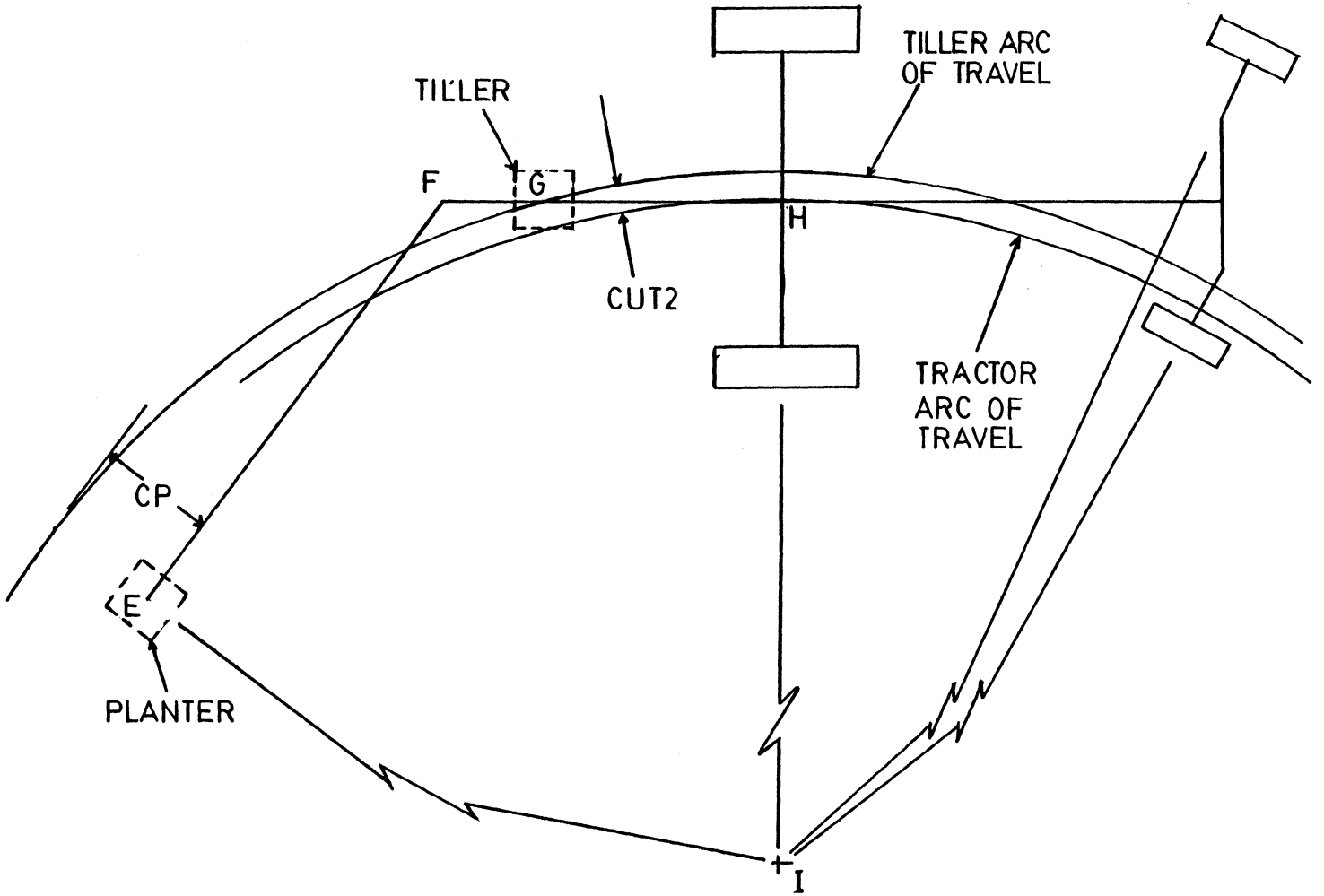

Figure 11. Diagram of tractor and rigid 3-point hitch implement geometry.

can be seen from Figure 11, Point G swings away from the tractor line of travel. The critical geometric dimensions are:

$\overline{EF}$ = length of planter from seed drop point to planter pivot point

$\overline{FG}$ = distance from planter pivot to center of tiller

$\overline{GH}$ = distance from center of tiller to center of tractor rear axle

$\overline{HI}$ = radius of curvature on which the tractor is driven

$\overline{FH}$ = distance from planter pivot point to center of tractor rear axle

The amount of outside cut of the tiller, defined as CUT2, is calculated from:

$$CUT2 = \sqrt{\overline{GH}^2 + \overline{HI}^2} - \overline{HI} \quad [3]$$

As in the previous example with the trailer, but using different notation, the amount of inside cut of the planter from the tractor travel line is calculated from:

$$\overline{EI} = \sqrt{\overline{FH}^2 + \overline{HI}^2 - \overline{EF}^2} \quad [4]$$

Therefore, the cut distance from the planter to the tiller, defined as CP, is calculated as:

$$CP = \overline{GI} - \overline{EI} \quad [5]$$

The equation that defines the distance from the center of the tiller to the center of radius is:

$$\overline{GI} = \sqrt{\overline{GH}^2 + \overline{HI}^2} \quad [6]$$

By substituting equations 4 and 6 into 5, the calculation of the cut of the planter (CP) is made as a function of fixed geometry and radius of curvature. Therefore:

$$CP = \sqrt{\overline{GH}^2 + \overline{HI}^2} - \sqrt{\overline{FH}^2 + \overline{HI}^2 - \overline{EF}^2} \quad [7]$$

For perfect planter tracking CP must equal zero. Solving Equation 7 for $\overline{GH}^2$ when CP equals zero yields:

$$\overline{GH}^2 = \overline{FH}^2 - \overline{EF}^2 \quad [8]$$

Equation 8 is the design equation that defines certain geometrical constraints to control in order to obtain perfect planter tracking. Equation 8 is not a function of radius of curvature; therefore, it is valid for all curves of any radius. Equation 8 states that to obtain perfect planter tracking, the distance from the center of the tiller to the center of the tractor rear axle squared must equal the distance from the planter pivot point to the center of the rear axle squared minus the distance from the seed drop point to the planter pivot point squared. Figure 12 shows one of the many possible geometries that satisfies Equation 8.

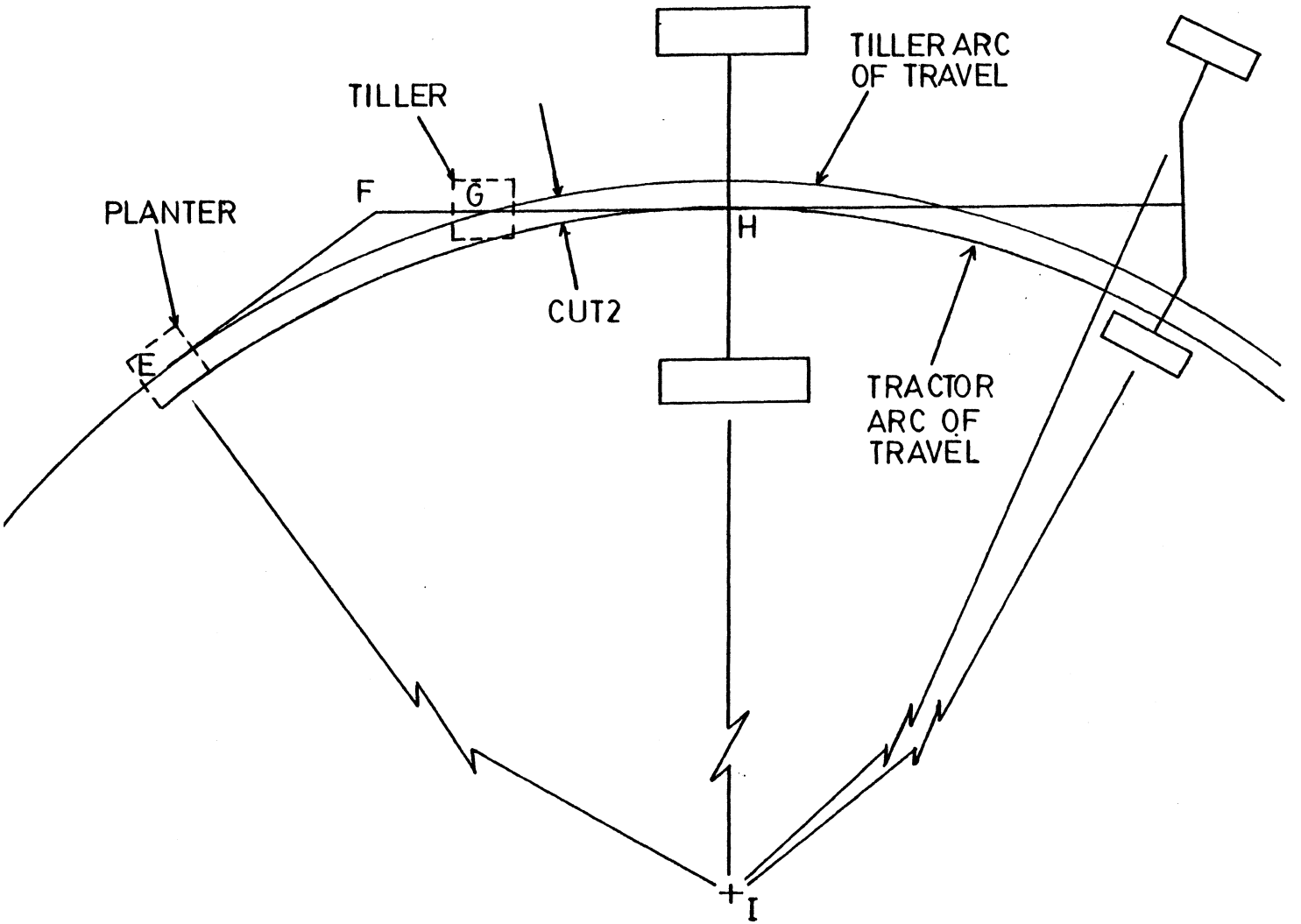

Figure 12. Diagram of tractor and rigid 3-point hitch implement ideal geometry.

5.0 Experimental Methods

Preliminary experimentation with the FOR2 machine showed that a good seedbed could be prepared and that the machine functioned as expected. Therefore, the machine and its performance warranted qualitative and quantitative evaluation. Two separate experiments were planned and conducted 1) to measure broccoli emergence with FOR2 versus other promising conservation tillage equipment, and 2) to measure the aggregate size distributions as a function of machine setup configurations and moisture treatments.

5.1 Broccoli Emergence

Experimental plots were established in Halifax County, Virginia at the Waller farm in the summer of 1986 in order to compare broccoli emergence under three different treatments. These treatments were A) FOR2, B) Ro-Till without secondary tillage, and C) Ro-Till with secondary tillage. The plot was planted in a wheat cover crop in the Fall of 1985 and was desiccated with paraquat in late July, 1986. On July 31, 1986 the plot was mowed with a rotary mower to approximately 15 cm and the experiments were planted the next day. A randomized block experiment was used with four replications. Irrigation was applied at regular intervals throughout this experiment. The soil was moist most of the time, but the upper 1 cm dried on one or two occasions for short intervals of time.

In treatment A the FOR2 machine was used as previously described to plant broccoli in single rows 91 cm apart with a theoretical seed spacing of 95 mm within the row. The rototiller was ad-

justed to operate at about a 3.8 cm depth at 300 RPM. The trash clearing discs were set to operate at a 1.5 cm depth and the hiller discs were set to cut 2 cm of soil at a 30° angle from the direction of travel. Seed depth was set at 6 mm.

Treatment B consisted of preparing a strip of soil with the Ro-Till machine described in section 3.7. The Ro-Till machine was equipped with trash clearing discs in front of the ripper chisel and employed 46 cm wide cultipackers as a final seedbed conditioner prior to planting. Stanhay seeders were operated as a separate piece of equipment in this treatment and were used to seed one row in each strip prepared by the Ro-Till machine.

Treatment C consisted of preparing a strip of soil as in treatment B, but instead of using the Stanhay seeder as the implement to seed in the prepared strip, the FOR2 machine was used without the trash clearing discs. This treatment was used to determine if the seedbed after using the Ro-Till was sufficient to provide good emergence or if the additional soil granulation provided by the FOR2 machine was needed.

Stand counts were made five days after planting to determine the effect of treatment on emergence. The plants that were visible above the soil surface were counted from the middle 6 m of each 18 m long row. If the row had skips over 50 cm in length, the skipped length was measured and subtracted from the total 6 m length to determine the average number of plants per meter, which was then multiplied by six to obtain the number of plants per 6 m. These measurements were then statistically analyzed using analysis of variance (ANOVA) procedures to compare the three treatments.

5.2 Aggregate Size Analysis

Experimental plots were prepared at the Virginia Tech Horticulture Farm to test the quality of the seedbed prepared by the FOR2 seedbed preparation unit under a variety of machine configurations and irrigation levels. The FOR2 machine was operated without the seeding unit so that soil from an undisturbed seedbed could be sampled. A randomized split-plot design was used with

three replications. Each replication was divided into three irrigation levels (low, medium, high) which were split into two tiller depth levels (3.8, 5.7 cm). Each split section contained a 2-way factorial with three levels of tiller RPM (195, 300, 390 r/min) and two levels of tractor speed (0.75, 1.12 km/h). A treatment is therefore defined as a single combination of irrigation level, tiller depth, tiller RPM and tractor speed. In total 36 treatments existed and from each of these treatments three samples for aggregate size analyses and three other samples for moisture content analyses were collected. In addition to the soil samples, two seedbed measurement combinations were taken from each of the treatments in the first replication. The combination included measurements characteristic of the strip of prepared soil.

5.2.1 Statistical Design

The field layout for the experiment is shown in Figure 13. This field layout lends itself to a statistical analysis that enables comparisons of all treatments and also allows inspection of any interactions that exist. The randomized split-plot design was blocked on irrigation level because of the constraints imposed by irrigation equipment and then further split on tiller depth because of limited space. The irrigation levels, tiller depth, and the six factorial treatments within each split-plot were completely randomized to ensure that variations in the measured response were due to set parameters. Therefore, a statistical model can be written that is suitable for this analysis. It is:

$$r_{ijklm} = \mu + R_i + I_j + D_k + P_l + S_m + INT + e_{ijklm} \qquad [9]$$

where r_{ijklm} = response

R_i = an effect due to replication level i

I_j = an effect due to irrigation level j

D_k = an effect due to tiller depth level k

P_l = an effect due to tiller RPM level l

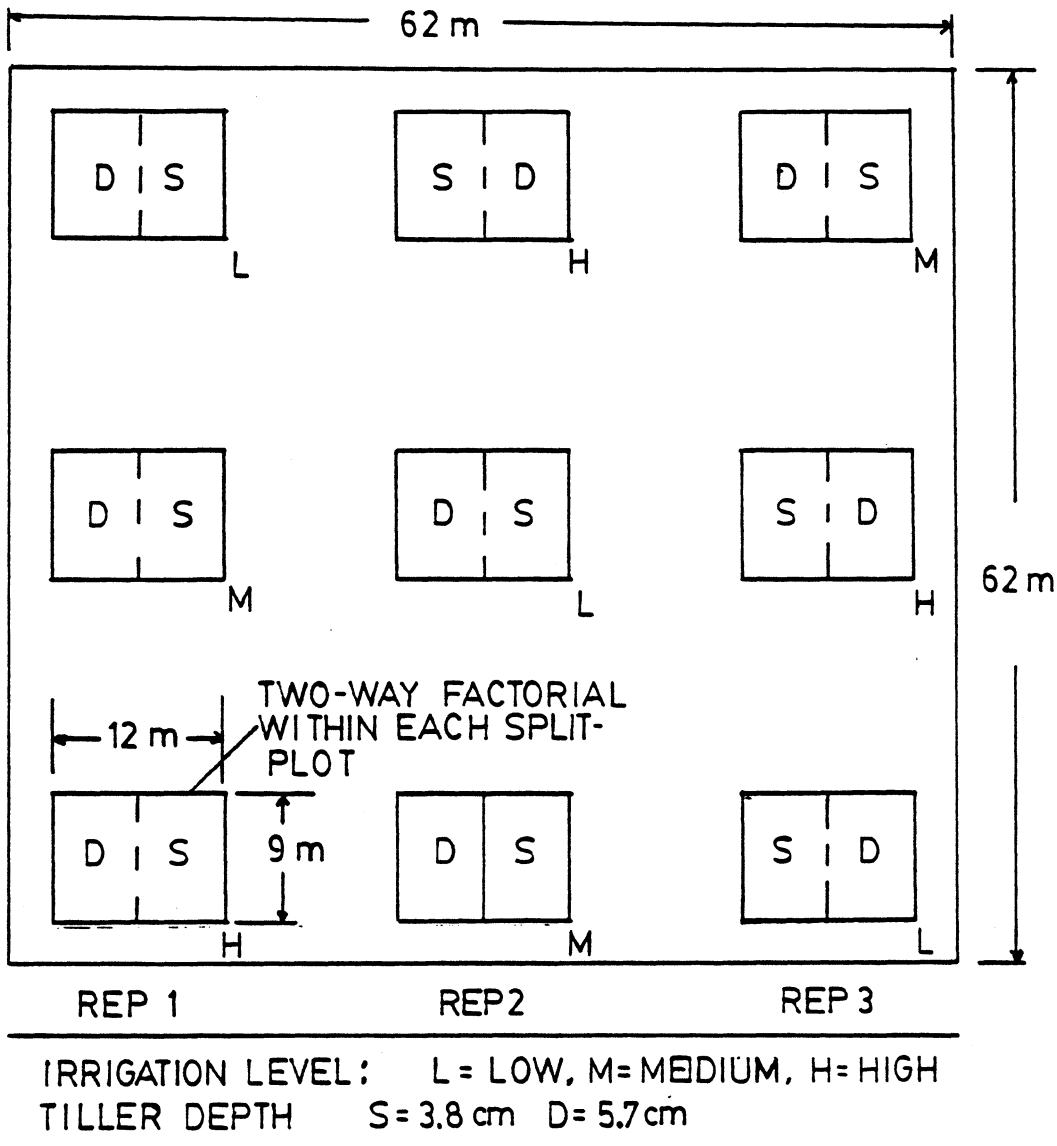

Figure 13. **Field layout for aggregate size experiment.**

S_m = an effect due to tractor speed level m

INT = all of the interactions between the five single factors above

e_{ijklm} = a random error associated with the ijklm response

The response e_{ijklm} is a measured output from the treatment that is thought to be characteristic of the treatment. The factors on the right side of the equation represent sources of variability in the response. Several responses were examined to determine how they were influenced by the effects or sources of variability.

5.2.2 Field Processes

Irrigation was applied to the experimental plots during the evening of September 25, 1986. Figure 14 shows the diagram of the irrigation lines and the sprinkler heads in the high irrigation level plot of the first replication. The other plots that received water had similar arrangements. Plots with high irrigation levels were irrigated first for 110 minutes. Then, plots of medium level were irrigated for one half of that time. Plots of low irrigation level received no water. In the high irrigation level plot of the first replication, 42 rain gauges were set up so that a coefficient of uniformity could be determined according to the equation defined by Christiansen (1942):

$$C_u = 100\left(1.0 - \frac{\sum_{i=1}^{n} x_i}{mn}\right) \qquad [10]$$

where, C_u = coefficient of uniformity

x = deviation of individual observation from the mean

m = mean

n = total number of observations

The determination of this coefficient was important so that it would be known if uniform irrigation occurred throughout the plot. Visual inspection during the following morning dictated that a higher level of moisture was needed in the irrigated plots; therefore, more irrigation was applied.

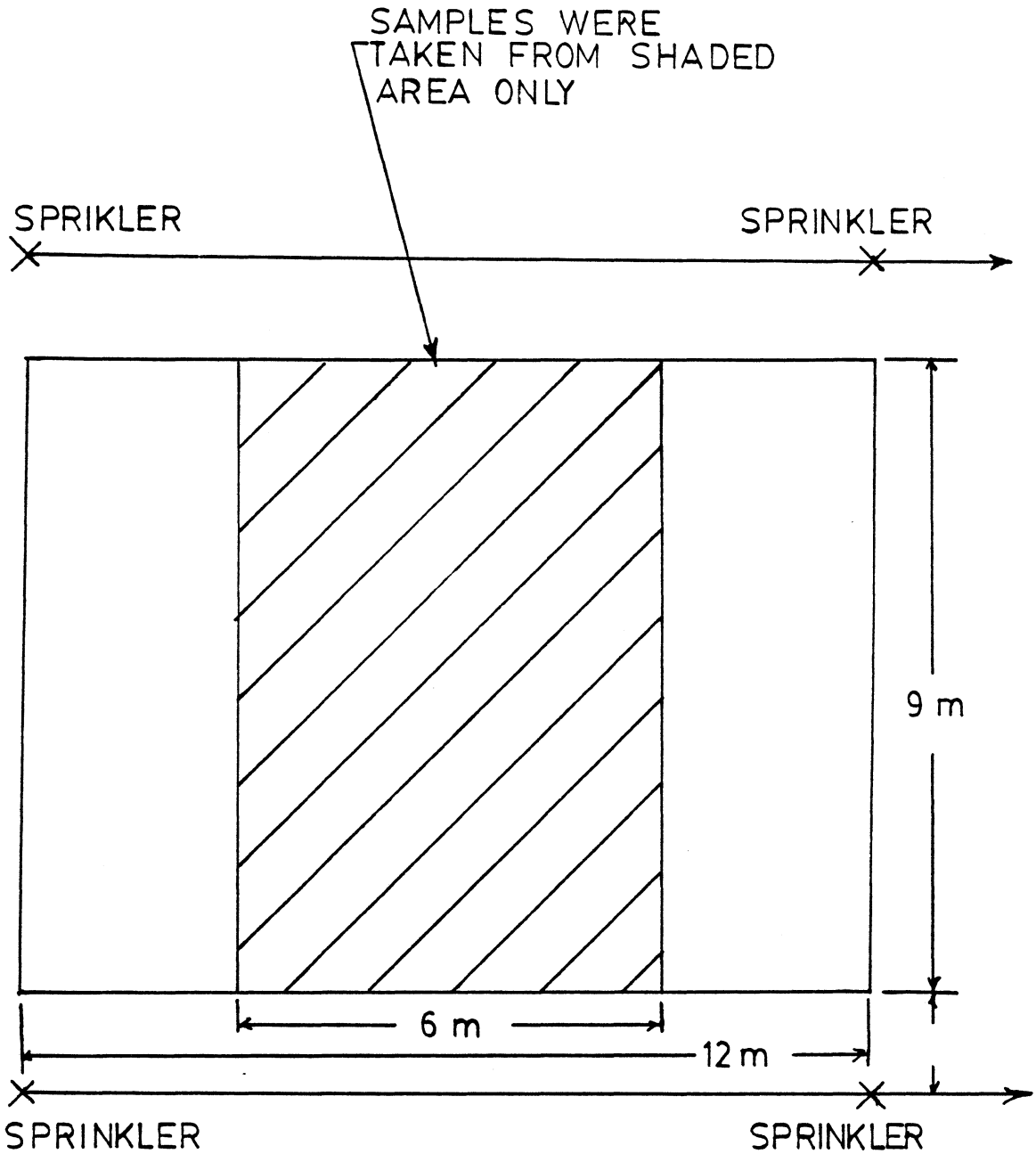

Figure 14. Diagram of irrigation lines and sprinklers.

The high level plots were irrigated for an additional 60 minutes, and the medium level plots were irrigated for an additional 30 minutes.

The irrigation pipes were removed from the field and the FOR2 machine was prepared to operate by mid-morning. Two treatments in one plot were prepared by FOR2 and soil samples were collected from those treatments before proceeding. After all of the shallow treatments were completed, the process was repeated for the deep tiller depth treatments. Soil moisture content samples were placed in 170 ml plastic bags and transported along with the aggregate size samples to the Agricultural Engineering Plant Environment Laboratory for analysis.

The geometry of the seedbed was measured immediately preceding the collection of soil samples for each treatment in the first replication. The geometrical data collected included measurements of seedbed width, seedbed height above initial ground level, and seedbed depth. From each treatment in each plot within each replication, three sets of geometrical data were taken.

5.2.3 Moisture Content Analysis

All of the moisture content soil samples were weighed to the nearest 0.01 g. The bags were then opened and the soil was allowed to air dry for three weeks so that the soil would not adhere to the sides of the plastic bag when dumped. The soil samples where then dumped into metal trays and dried at 105°C for 24 hours (Gardner, 1965). The soil samples were then reweighed and the moisture content was calculated as:

$$MC = \frac{I - F}{I} \times 100 \qquad [11]$$

where, MC = percent moisture content wet basis

I = initial sample weight

F = final sample weight

A total of 324 sample moisture contents were determined with each one corresponding to a soil sample for aggregate size evaluation.

5.2.4 Sieving Procedure

The soil samples for sieving were allowed to air dry for at least one month before being sieved. A Cenco-Meinzer sieve shaker with adjustable vibrational frequency was used with seven sieves and a pan. Sieve sizes used are shown in Table 2. This selection of sizes was in close accordance with ASTM (1985) guidelines for choosing sieves in such a way that successively smaller sieves have openings that are one half the size of the next larger size. This selection facilitates easy plotting on logarithmic paper. A beam-type balance, accurate to 1 g was used to obtain tare weights for each sieve. In accordance with ASTM guidelines, the approximate total soil amount to be sieved was determined to be 1400 cm^3 or 1050 g.

The frequency of the oscillatory shaker was set at index level 2. A higher level was observed to impose excessive forces on the soil aggregates and cause breakdown of the aggregates into primary particles. A lower frequency was observed to be insufficient and failed to provide every soil aggregate the chance to fall through an opening in the sieve in which it was contained.

The shaking time for each soil sample was determined according to ASTM guidelines, which state that shaking time should be long enough so that an additional 1 minute does not change the weight on any one sieve by more than one percent. Table 3 shows experimental data for one of the soil samples that were used to determine shaking times. These samples were shaken for 1, 2, and 3 minutes and the sieve sections with soil were weighed after each minute. From this data and the calculations of percent change as shown in the table, a two minute shaking time was determined to be sufficient for all 324 samples.

Each soil sample was dumped into a flat tray with one open side and a portion approximately equal to the calculated sample size was scraped into a pan and dumped into the nest of sieves. The nest of sieves was then shaken at the prescribed level for two minutes and then each sieve was weighed to an accuracy of 1 g. The weights for each sieving were recorded and then stored in the Virginia Tech mainframe computer for further processing.

Table 2. Sieve sizes and designations.

Sieve Designation	Sieve Opening (mm)
3/4	19.000
3/8	9.500
No. 4	4.760
No. 8	2.362
No. 18	1.000
No. 30	0.589
No. 50	0.297
Pan	0.000

Table 3. Sieve shaking time results.

WEIGHT (g) IN EACH SIEVE (% CHANGE FROM PREVIOUS MINUTE)			
	SHAKING TIME (min)		
SIEVE DESIGNATION	1	2	3
3/4	4.5	0 (100)	0 (0)
3/8	148.5	149 (0)	147 (1)
No. 4	140	132 (6)	131 (1)
No. 8	199	189 (5)	187 (1)
No. 18	284.5	256.5 (10)	257 (0)
No. 30	106	127.5 (20)	129 (1)
No. 50	115.5	123 (6)	123 (0)
Pan	142	164 (15)	166 (1)

6.0 Results and Discussion

6.1 Broccoli Emergence

Experiments were performed to compare broccoli emergence after five days under three different tillage and planting systems in Halifax County, Virginia according to the experimental methods previously described. These systems were A) FOR2, B) Ro-Till without secondary tillage, and C) Ro-Till with secondary tillage using the FOR2 machine without trash clearing discs. Table 4 shows the ANalysis Of VAriance (ANOVA) results for this experiment. This analysis compares the number of plants that have germinated and emerged through the soil after five days for each of the three different treatments above.

It is evident from the statistical analysis that significant interaction exists. Therefore, the interaction must be examined before proceeding to test the main effects, otherwise the interaction may mask these main effects and tests on main effects might be misleading. Figure 15 shows that the differences in mean response between the three levels of treatment does not change dramatically across levels of replication. Likewise, in Figure 16, the difference in mean response between the four levels of replication does not change dramatically over the levels of treatment. Although these graphs imply significant interaction, it is still informative to report the main effect results even though they may be masked by the interaction. Mean results are shown in Table 5 for all replications and treatments.

The significance of the replication effect implies that differences occurred in the number of plants that emerged in the replications. A Duncan's multiple range test comparing the mean emergence for each replication shows that replications 2, 3, and 4 produced the same emergence

Table 4. ANOVA results for broccoli emergence experiments.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	11	876.75	79.70	8.00(S)
ERROR	36	358.50	9.96	PR > F 0.0001
CORRECTED TOTAL	47	1235.25		

R-SQUARE	C.V.	ROOT MSE	EMERGENCE MEAN
0.71	8.12	3.16	38.88

SOURCE	DF	ANOVA SS	F VALUE	PR > F	S/N
TRMT	2	208.63	10.47	0.0003	S
REP	3	222.41	7.44	0.0005	S
REP*TRMT	6	445.71	7.46	0.0001	S

S=Significant, N=Nonsignificant

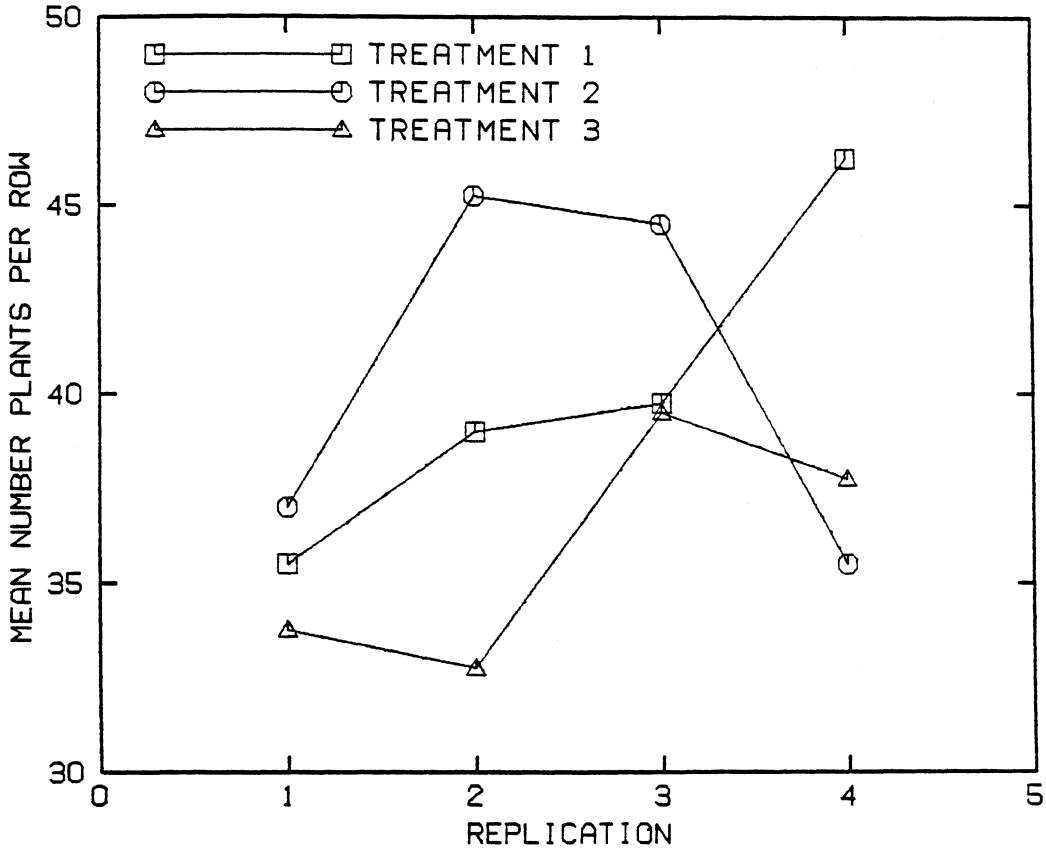

Figure 15. Broccoli emergence as influenced by replication.

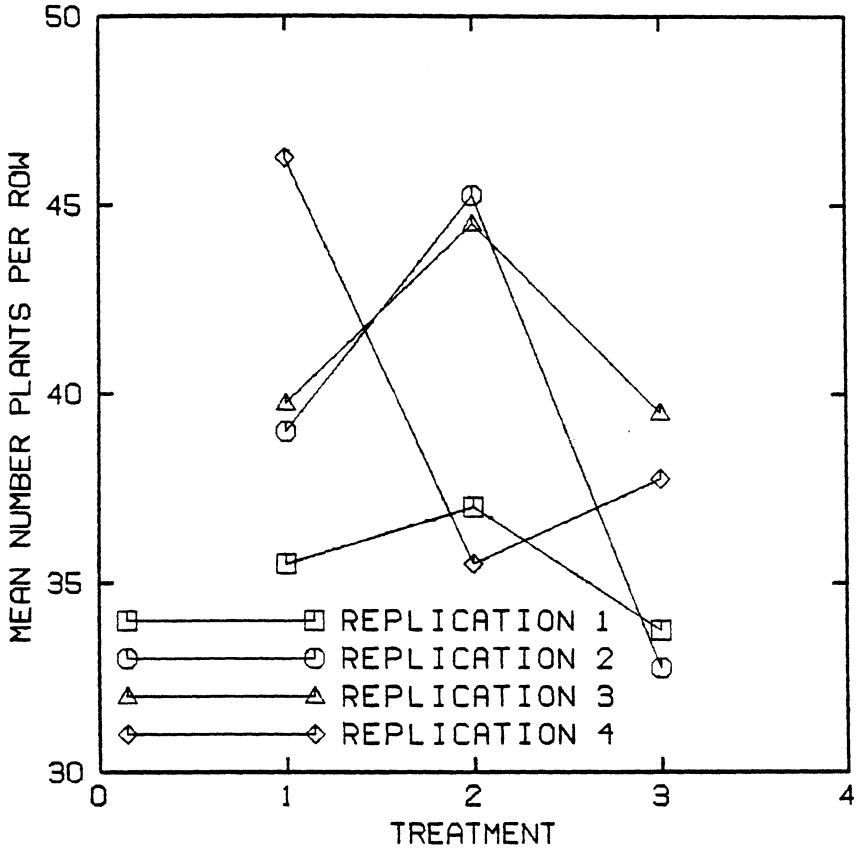

Figure 16. **Broccoli emergence as influenced by treatment.**

Table 5. Mean results for broccoli emergence.

Category	Mean number of Plants per row
FOR2	40 a
Ro-Till without secondary tillage	40 a b
Ro-Till with secondary tillage	36 b
Replication 1	35 c
Replication 2	39 d
Replication 3	41 d
Replication 4	38 d

Means followed by the same letter imply statistical equivalence according to Duncan's Multiple Range Test at a 0.05 alpha level.

which was higher than the emergence in replication 1. Replication 1 was located farthest from the source of irrigation water and it is doubtful that the sprinkler gun was extended beyond the far side of the experimental plot. On the other hand, the sprinkler gun was recoiled more than its effective radius past the near edge of the experimental plot. Therefore, the more distant portions of the experimental plot, where replication 1 was located, received less water, due to the less time that it was irrigated, than the other portions.

The significance of the treatment effect implies that differences occurred in the number of plants that emerged in the treatments. A Duncan's multiple range test comparing the mean emergence for each treatment shows that treatments FOR2 and Ro-Till without secondary tillage, produced statistically the same emergence, which was higher than Ro-Till with secondary tillage.

The lower germination with the Ro-Till machine followed by secondary tillage implies that the secondary tillage supplied by the rototiller in the FOR2 machine was probably excessive on the pretilled soil and pulverized the soil too much. This increased soil disruption allowed the soil to become more dense when wetted, whereby sinkage occurred and a crust was more easily formed on the surface when the soil dried. The soil movement from the sinkage, in addition to the crusting potential, probably reduced germination.

Theoretical seed spacing in these experiments was 95 mm, implying that 63 seeds should have been planted per 6 m row if one seed was dropped from each seed cell in the seed belt.

Based on calibration tests, the Stanhay seeders used in this experiment were estimated to be 90% efficient, meaning that only 90% of the seed placement points at 95 mm spacing in the furrow actually received a seed. This inefficiency is due to the inability of the seed belt to capture and retain a seed in its holes 100% of the time. The seed used was tested for germination by the seed company and only 92% of the seed germinated under laboratory conditions. These inefficiencies imply that only 83% of the theoretical number of seed planted were actually placed in the soil and had the potential to germinate. Therefore, the actual percent germination is calculated from:

$$P_a = \frac{P_t}{F} \qquad [12]$$

where, P_a = % actual germination

P_t = % theoretical germination

F = 0.83 = inefficiency factor = (0.90x0.92)

This calculation then gives actual average germination percentages of 77%, 77%, and 69% for treatments FOR2, Ro-Till without secondary tillage, and Ro-Till with secondary tillage, respectively. The two highest germination percentages are adequate for commercial production of broccoli. The lower percentage suggests that secondary tillage following the Ro-Till is unnecessary and possibly harmful.

6.2 Aggregate Size Analysis

6.2.1 Irrigation Uniformity Analysis

The results from measuring the irrigation in one of the experimental plots using several rain gauges as described in section 5.2.2 show a uniform pattern over the area where samples were collected. Figure 17 is a diagram of sprinkler heads in the experimental plot overlaid with the location of rain gauges and the amount of water collected in each gauge in a 110 minute period. The coefficient of uniformity as defined in section 5.2.2 was 67.4%. This value is considered to be within acceptable limits and implies that nearly uniform amounts of irrigation occurred throughout the experimental plot where samples were taken. Reasons for variations in irrigation delivered occurred because of the following three reasons: 1) irrigation equipment used, 2) geometrical layout, and 3) wind. The sprinkler heads used in the experiment were all of the same type, but varying amounts of wear due to past use caused some of them to rotate faster than others. The speed of rotation is indicative of the pressure at the nozzle and nozzle pressure dramatically influences the amount of

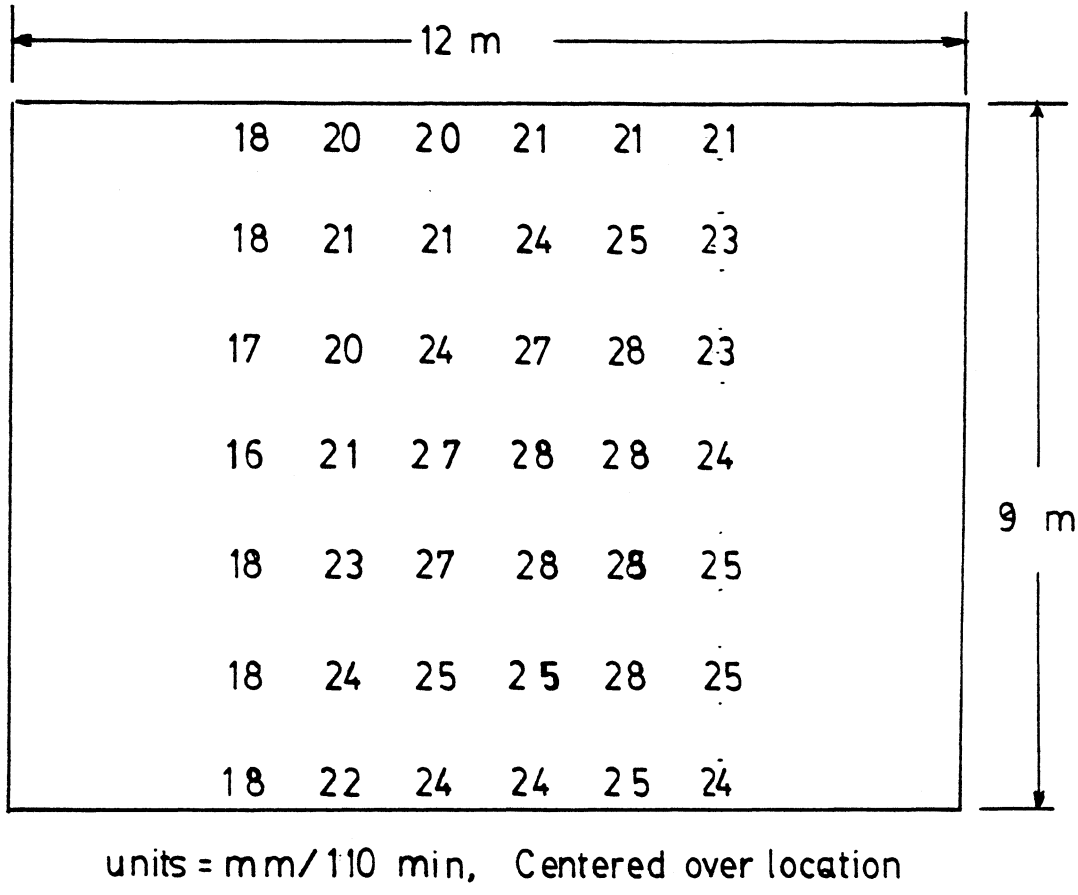

Figure 17. Experimental plot overlaid with rain gauge locations.

flow through the orifice. Pressure drops in the irrigation pipes can also cause nonuniform pressure at the sprinkler heads. The geometrical layout can also influence the irrigation uniformity due to the rainfall patterns that result from a single sprinkler head. Careful geometrical layout, where proper overlapping of the sprinklers effective diameter occurs, can reduce the variation in rainfall delivered due to geometry. The wind can cause drastic changes in the rainfall pattern especially at the borders on the windward side of an experimental plot. To overcome variations due to wind, sprinkler heads were placed past the edge of the experimental plot.

6.2.2 Moisture Content Analysis

Uniform irrigation does not ensure that the moisture content throughout the plot will be uniform. Therefore, moisture contents were analyzed to determine uniformity within each plot and also to determine if the three plots in each irrigation level were at the same moisture content. Comparisons between moisture contents in each of the three irrigation levels were also performed to determine if there were actual statistical differences.

Moisture content values for each of the nine plots in the experiment were statistically analyzed in a one-way ANalysis Of VAriance (ANOVA) to determine if the moisture content was uniform in each plot. Since three samples were taken from each treatment within each plot, and there were twelve different treatments in each plot, a total of 36 values were used in each of the nine one-way ANOVAs. The values for each plot were classified according to their corresponding treatment. ANOVA tables for each of the nine statistical tests are shown in Tables 6 through 14.

Table 12 contains data for the plot in which rain gauges were used to test uniformity as discussed in the previous section. All of the moisture contents in this plot were statistically the same and can be represented by their mean. This result substantiates the result found using rain gauges, which implied uniform irrigation.

Analysis of moisture content data from the other plots did not consistently show uniform moisture content levels. Two of the three plots with no irrigation produced nonuniform moisture

Table 6. ANOVA table for low moisture content results from replication 1.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	11	157.68	14.33	9.76(S)
ERROR	24	35.24	1.46	PR > F 0.0001
CORRECTED TOTAL	35	192.93		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.82	8.10	1.21	14.97

S=Significant, N=Nonsignificant

Table 7. ANOVA table for low moisture content results from replication 2.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	11	190.48	17.31	17.42(S)
ERROR	24	23.86	0.99	PR > F 0.0001
CORRECTED TOTAL	35	214.34		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.89	6.1	1.00	16.40

S=Significant, N=Nonsignificant

Table 8. ANOVA table for low moisture content results from replication 3.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	11	132.82	12.07	2.27(N)
ERROR	24	127.87	5.33	PR > F 0.0455
CORRECTED TOTAL	35	260.70		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.51	17.28	2.31	13.36

S=Significant, N=Nonsignificant

Table 9. ANOVA table for medium moisture content results from replication 1.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	11	33.18	3.02	5.81(S)
ERROR	24	12.46	0.52	PR > F 0.0002
CORRECTED TOTAL	35	45.64		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.73	3.8	0.72	18.73

S=Significant, N=Nonsignificant

Table 10. ANOVA table for medium moisture content results from replication 2.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	11	37.00	3.36	4.16(S)
ERROR	24	19.39	0.81	PR > F 0.0017
CORRECTED TOTAL	35	56.39		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.66	4.85	0.90	18.52

S=Significant, N=Nonsignificant

Table 11. ANOVA table for medium moisture content results from replication 3.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	11	49.53	4.50	9.27(S)
ERROR	24	11.66	0.49	PR > F 0.0001
CORRECTED TOTAL	35	61.20		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.81	4.37	0.70	15.95

S=Significant, N=Nonsignificant

Table 12. ANOVA table for high moisture content results from replication 1.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	11	27.49	2.50	2.27(N)
ERROR	24	26.47	1.10	PR > F 0.0455
CORRECTED TOTAL	35	53.96		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.51	5.2626	1.05	19.96

S=Significant, N=Nonsignificant

Table 13. ANOVA table for high moisture content results from replication 2.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	11	10.93	0.99	0.81(N)
ERROR	24	29.27	1.22	PR > F 0.6265
CORRECTED TOTAL	35	40.19		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.27	6.03	1.10	18.31

S=Significant, N=Nonsignificant

Table 14. ANOVA table for high moisture content results from replication 3.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	11	21.86	1.99	2.80(N)
ERROR	24	17.05	0.71	PR > F 0.0170
CORRECTED TOTAL	35	38.92		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.56	4.76	0.84	17.70

S=Significant, N=Nonsignificant

contents as shown by their significant F-values. This result implies that the moisture content in all of the plots was probably not uniform before the experiments were performed. Reasons for this initial variability include changes in soil conditions in the field or variations in the amount of ground cover.

An examination of the F-values for the three plots at the medium irrigation level show that none of these had uniform moisture content levels. This phenomenon might be explained by initial variations in moisture content levels, nonuniform irrigation, leaks in the irrigation piping during start-up and shut-down, or changes in soil conditions.

An examination of the F-values for the three plots at the high irrigation level show that they all had uniform moisture content levels. This uniformity is due to the high amount of water that was added to these three plots. The large amount of water probably increased the moisture content to field capacity, thereby ensuring that all of the micropores in the soil were full of water, and thereby causing the initial variations in moisture content to diminish. Drying and natural draining of the soil during the night probably caused the macropores to be void of water by the following morning. Uniform evaporation from the micropores then occured, resulting in uniform water loss from a constant moisture level.

Although some of the plots exhibited nonuniform irrigation levels, it is informative to compare each of the three plots within each irrigation level to determine if a specific irrigation level is an accurate description of the three plots. Three one-way ANOVAs were employed in this analysis. Each ANOVA used 108 moisture content values, grouped only according to the plot from which they came. Tables 15, 16,and 17 show the ANOVA results for these three tests.

The analysis for the irrigation level with no water applied shows that each of the three blocks exhibited significantly different moisture contents. The other irrigation levels exhibited similar results. Even though each of the plots at the highest irrigation level had uniform moisture contents, the three plots had significantly different mean moisture content values.

Possible explanations for different moisture contents in the blocks evolve from irrigation piping or from varying soil conditions. Pressure drops in the piping cause different amounts of flow through the sprinkler orifice, which in turn causes different amounts of water to reach the soil sur-

Table 15. ANOVA table for moisture content results from low irrigation level.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	2	166.44	83.22	13.08(S)
ERROR	105	667.97	6.36	PR > F 0.0001
CORRECTED TOTAL	107	834.41		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.20	16.92	2.52	14.91

S=Significant, N=Nonsignificant

Table 16. ANOVA table for moisture content results from medium irrigation level

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	2	172.85	86.43	55.60(S)
ERROR	105	163.22	1.55	PR > F 0.0001
CORRECTED TOTAL	107	336.07		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.51	7.03	1.25	17.73

S=Significant, N=Nonsignificant

Table 17. ANOVA table for moisture content results from high irrigation level.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	2	97.79	48.89	38.58(S)
ERROR	105	133.07	1.27	PR > F 0.0001
CORRECTED TOTAL	107	230.86		

R-SQUARE	C.V.	ROOT MSE	MC MEAN
0.42	6.03	1.13	18.66

S=Significant, N=Nonsignificant

face. Soil conditions can influence the amount of water retained in the soil. The field was assumed to be of a uniform soil type and of uniform soil characteristics, including bulk density and cover crop growth. Although bulk density was not measured, it is the most easily measured variable that can influence water retention. Bulk density affects the amount of micropores and macropores which directly affects water retention.

Although each plot was not uniform in moisture content and the three plots in each irrigation level were not at the same moisture content, it is still possible to analyze the complete experiment as previously intended. The statistical method shown in section 5.2.1 analyzes the experiment based on the initial preset levels of a variable and not based on what those levels actually were. In this case the irrigation was controlled to deliver three separate irrigation levels low, medium, and high. The intended outcome was to obtain three separate and distinct moisture content levels that correspond to the three irrigation levels. Even though the intended outcome did not occur, it was still possible to examine if significant results were obtained using the three preset irrigation levels in addition to the other preset levels.

An examination of the moisture contents in each plot shows that the mean moisture content for replication 1 was less than that for replication 2, which was less than that for replication 3. Therefore, a significant replication effect should be expected in the overall model. In light of this result, the replication variable was justifiably dropped from the model in order to provide more degrees of freedom to the experimental error.

An alternative to using preset levels is to use the measured outcome of a variable as a covariate in an analysis of covariance. This type of analysis subtracts the variability in the model due to moisture content from the error variability, resulting in a more powerful model. A drawback to this type of analysis is that it cannot analyze the effect of the three levels of irrigation, which is one of the intended results of the experiment.

6.2.3 Aggregate Sieving Analysis

The raw data from the 324 aggregate sieving tests were used in a FORTRAN program which calculated several characteristic numbers for each test. The FORTRAN program calculated the weight in each sieve, the percent of the total weight in each sieve, the cumulative percent in each sieve, the common logarithm of the cumulative percent in each sieve, the mean weight diameter, and the slope of the least squares line from a graph of the common logarithm of the percent greater than a sieve opening size versus the sieve opening size. These data were then examined to see if any showed potential to be good characteristic numbers of their distribution.

An examination of several graphs of the common logarithm of the percent greater than a sieve size versus the sieve opening size for several sievings showed a linear trend (Figure 18). A statistical analysis using simple linear regression for each of the 324 sets of data proved that a straight sloped line is a very good representation of the data since all of the tests were highly significant. R^2 values were above 0.90 indicating little spread about the regression line. The estimated intercept for all of the tests was close to 2.0 since the $\log_{10}$ of 100 has a value of 2. The slope of the regression line varied greatly for each test; therefore, it was used as a response in a further statistical analysis that examined the effects of the irrigation level, tiller depth, tiller RPM, and tractor speed on the response. An appropriate statistical model was shown in section 5.2.1. The ANalysis Of VAriance (Table 18) showed high significance and a low R^2 value of 0.22. This low R^2 value implies that the data was not represented very well by the linear model description. Although other responses also need to be analyzed it is interesting to note that interactions occurred and that the tiller depth and the tiller RPM explained most of the variation in the response of slope.

The same model was used to analyze how the model descriptors affected other responses. Other responses used were the percent of the sieve sample greater than a sieve opening. Each of the sieve sizes were used from 19 mm to 0.297 mm. ANOVA results are shown in Tables 19-25. Highly significant results occurred for all seven analyses with the major difference between tests being the R^2 value. It is desirable to have a high R^2 value so that linear prediction models can be derived. However, a low R^2 value is not entirely bad since it simply states that only a small amount

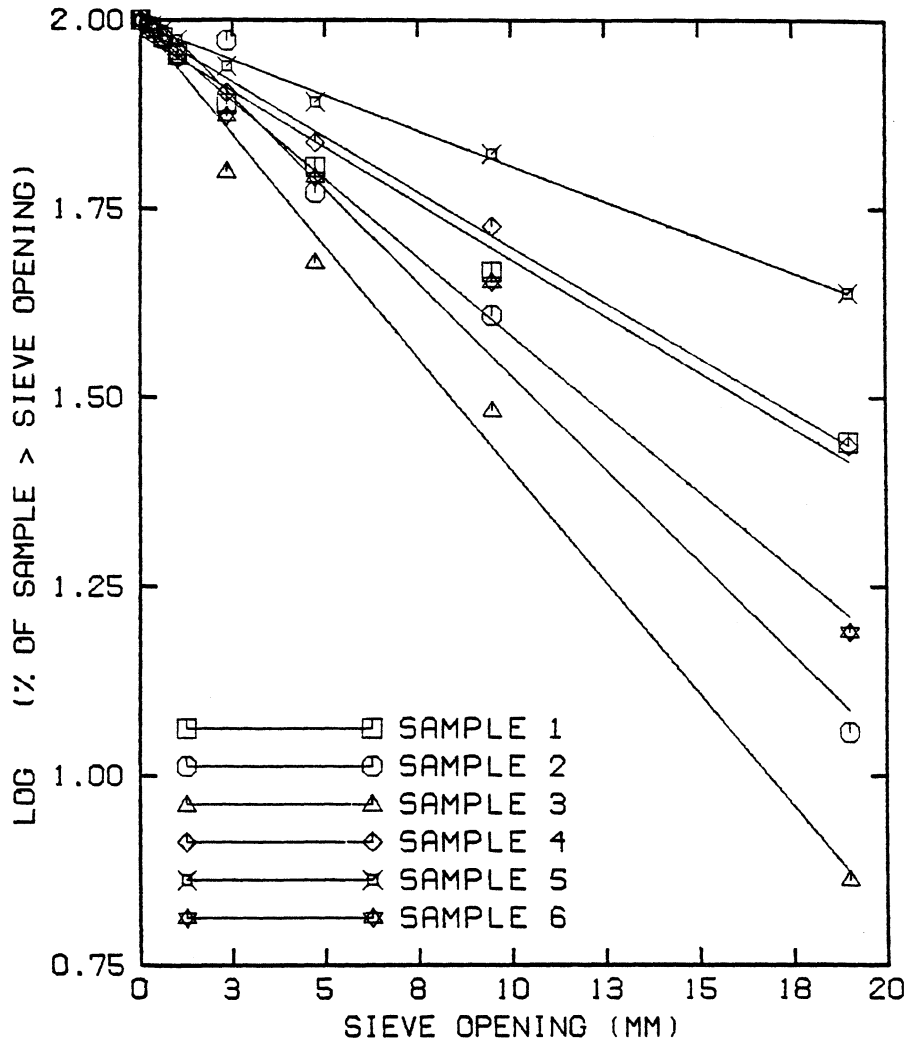

Figure 18. Common logarithm of the percent greater than a sieve size as influenced by the sieve opening size for several sievings.

Table 18. ANOVA table using slope as the response.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	35	0.10	0.003	2.28(S)
ERROR	288	0.37	0.001	PR > F 0.0001
CORRECTED TOTAL	323	0.48		

R-SQUARE	C.V.	ROOT MSE	SLOPE MEAN
0.22	57.34	0.036	-0.063

SOURCE	DF	ANOVA SS	F VALUE	PR > F	S/N
TD	1	0.01544497	11.89	0.0006	S
TS	1	0.00219336	1.69	0.1948	N
TRPM	2	0.03287390	12.66	0.0001	S
IRR	2	0.00249964	0.96	0.3832	S
TD*TS	1	0.00576756	4.44	0.0360	N
TD*TRPM	2	0.00176060	0.68	0.5085	N
TD*IRR	2	0.01628004	6.27	0.0022	N
TRPM*TS	2	0.00069002	0.27	0.7669	N
TS*IRR	2	0.00090469	0.35	0.7062	S
TRPM*IRR	4	0.00339423	0.65	0.6249	N
TD*TRPM*TS	2	0.00477038	1.84	0.1612	N
TD*TS*IRR	2	0.00169401	0.65	0.5217	N
TRPM*TS*IRR	4	0.00711674	1.37	0.2444	N
TD*TRPM*IRR	4	0.00367153	0.71	0.5879	N
TD*TRPM*TS*IRR	4	0.00440586	0.85	0.4957	N

S=Significant, N=Nonsignificant

Table 19. ANOVA table using percent greater than 19 mm as the response.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	35	5680.49	162.30	2.33(S)
ERROR	288	20050.52	69.62	PR > F 0.0001
CORRECTED TOTAL	323	25731.01		

R-SQUARE	C.V.	ROOT MSE	%>19 mm MEAN
0.22	77.12	8.34	10.82

SOURCE	DF	ANOVA SS	F VALUE	PR > F	S/N
TD	1	748.63040123	10.75	0.0012	S
TS	1	204.33114198	2.93	0.0878	N
TRPM	2	1821.91351852	13.08	0.0001	S
IRR	2	804.22166667	5.78	0.0035	S
TD*TS	1	162.27929012	2.33	0.1279	N
TD*TRPM	2	5.55413580	0.04	0.9609	N
TD*IRR	2	713.42302469	5.12	0.0065	S
TRPM*TS	2	158.70006173	1.14	0.3213	N
TS*IRR	2	3.75191358	0.03	0.9734	N
TRPM*IRR	4	217.23314815	0.78	0.5389	N
TD*TRPM*TS	2	51.18561728	0.37	0.6927	N
TD*TS*IRR	2	331.04265432	2.38	0.0946	N
TRPM*TS*IRR	4	156.23549383	0.56	0.6911	N
TD*TRPM*IRR	4	228.94549383	0.82	0.5119	N
TD*TRPM*TS*IRR	4	73.03771605	0.26	0.9020	N

S=Significant, N=Nonsignificant

Table 20. ANOVA table using percent greater than 9.5 mm as the response.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	35	12499.21	357.12	2.52(S)
ERROR	288	40795.34	141.65	PR > F 0.0001
CORRECTED TOTAL	323	53294.55		

R-SQUARE	C.V.	ROOT MSE	%>9.5 mm MEAN
0.23	41.43	11.90	28.73

SOURCE	DF	ANOVA SS	F VALUE	PR > F	S/N
TD	1	1020.09262346	7.20	0.0077	S
TS	1	111.77188272	0.79	0.3751	N
TRPM	2	5025.22722223	17.74	0.0001	S
IRR	2	1699.34462963	6.00	0.0028	S
TD*TS	1	337.94694444	2.39	0.1235	N
TD*TRPM	2	156.70598765	0.55	0.5757	N
TD*IRR	2	1614.53635802	5.70	0.0037	S
TRPM*TS	2	186.89080247	0.66	0.5178	N
TS*IRR	2	59.87450617	0.21	0.8096	N
TRPM*IRR	4	653.97925926	1.15	0.3313	N
TD*TRPM*TS	2	174.43722222	0.62	0.5410	N
TD*TS*IRR	2	451.62055556	1.59	0.2049	N
TRPM*TS*IRR	4	491.95419753	0.87	0.4833	N
TD*TRPM*IRR	4	205.80197531	0.36	0.8347	N
TD*TRPM*TS*IRR	4	309.02555555	0.55	0.7025	N

S=Significant, N=Nonsignificant

Table 21. ANOVA table using percent greater than 4.76 mm as the response.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	35	13770.87	393.45	2.91(S)
ERROR	288	38991.25	135.39	PR > F 0.0001
CORRECTED TOTAL	323	52762.12		

R-SQUARE	C.V.	ROOT MSE	%>4.760 mm MEAN
0.26	25.78	11.64	45.13

SOURCE	DF	ANOVA SS	F VALUE	PR > F	S/N
TD	1	596.71632716	4.41	0.0367	S
TS	1	36.33410494	0.27	0.6048	N
TRPM	2	4817.83524692	17.79	0.0001	S
IRR	2	3818.39339507	14.10	0.0001	S
TD*TS	1	243.53336420	1.80	0.1809	N
TD*TRPM	2	238.08746914	0.88	0.4162	N
TD*IRR	2	1562.54302469	5.77	0.0035	S
TRPM*TS	2	241.30487654	0.89	0.4113	N
TS*IRR	2	81.86302469	0.30	0.7393	N
TRPM*IRR	4	685.77882716	1.27	0.2833	N
TD*TRPM*TS	2	250.98376543	0.93	0.3969	N
TD*TS*IRR	2	279.25487654	1.03	0.3578	N
TRPM*TS*IRR	4	473.69216049	0.87	0.4794	N
TD*TRPM*IRR	4	124.91845679	0.23	0.9210	N
TD*TRPM*TS*IRR	4	319.62660494	0.59	0.6700	N

S=Significant, N=Nonsignificant

Table 22. ANOVA table using percent greater than 2.362 mm as the response.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	35	13307.32	380.21	4.45(S)
ERROR	288	24629.40	85.52	PR > F 0.0001
CORRECTED TOTAL	323	37936.73		

R-SQUARE	C.V.	ROOT MSE	%>2.362 mm MEAN
0.35	14.99	9.25	61.69

SOURCE	DF	ANOVA SS	F VALUE	PR > F	S/N
TD	1	285.61000000	3.34	0.0687	N
TS	1	4.27111111	0.05	0.8233	N
TRPM	2	3190.79858025	18.66	0.0001	S
IRR	2	6412.21783951	37.49	0.0001	S
TD*TS	1	159.32049383	1.86	0.1733	N
TD*TRPM	2	190.97722223	1.12	0.3288	N
TD*IRR	2	1090.56018519	6.38	0.0020	S
TRPM*TS	2	181.95388889	1.06	0.3465	N
TS*IRR	2	89.21055556	0.52	0.5941	N
TRPM*IRR	4	553.58086420	1.62	0.1697	N
TD*TRPM*TS	2	264.27006172	1.55	0.2151	N
TD*TS*IRR	2	155.78598765	0.91	0.4033	N
TRPM*TS*IRR	4	363.77444444	1.06	0.3748	N
TD*TRPM*IRR	4	66.30037036	0.19	0.9415	N
TD*TRPM*TS*IRR	4	298.68901236	0.87	0.4804	N

S=Significant, N=Nonsignificant

Table 23. ANOVA table using percent greater than 1.000 mm as the response.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	35	9526.78	272.19	8.53(S)
ERROR	288	9189.49	31.91	PR > F 0.0001
CORRECTED TOTAL	323	18716.27		

R-SQUARE	C.V.	ROOT MSE	%>1.000 mm MEAN
0.51	7.04	5.65	80.21

SOURCE	DF	ANOVA SS	F VALUE	PR > F	S/N
TD	1	32.30027778	1.01	0.3152	N
TS	1	0.06250000	0.00	0.9647	N
TRPM	2	1130.68018519	17.72	0.0001	S
IRR	2	6799.18055556	106.54	0.0001	S
TD*TS	1	52.24077161	1.64	0.2017	N
TD*TRPM	2	106.38129630	1.67	0.1906	N
TD*IRR	2	478.78574075	7.50	0.0007	S
TRPM*TS	2	91.66722223	1.44	0.2395	N
TS*IRR	2	48.90240741	0.77	0.4657	N
TRPM*IRR	4	233.66925926	1.83	0.1229	N
TD*TRPM*TS	2	120.71598764	1.89	0.1527	N
TD*TS*IRR	2	37.61598764	0.59	0.5553	N
TRPM*TS*IRR	4	239.38259258	1.88	0.1148	N
TD*TRPM*IRR	4	44.91740739	0.35	0.8426	N
TD*TRPM*TS*IRR	4	110.27864199	0.86	0.4859	N

S=Significant, N=Nonsignificant

Table 24. ANOVA table using percent greater than 0.589 mm as the response.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	35	7026.48	200.76	10.60(S)
ERROR	288	5456.11	18.94	PR > F 0.0001
CORRECTED TOTAL	323	12482.59		

R-SQUARE	C.V.	ROOT MSE	%>0.589 mm MEAN
0.56	4.98	4.35	87.37

SOURCE	DF	ANOVA SS	F VALUE	PR > F	S/N
TD	1	3.86777778	0.20	0.6517	N
TS	1	0.79012346	0.04	0.8383	N
TRPM	2	608.73080247	16.07	0.0001	S
IRR	2	5434.04024692	143.42	0.0001	S
TD*TS	1	22.61530864	1.19	0.2755	N
TD*TRPM	2	82.61722223	2.18	0.1149	N
TD*IRR	2	228.51629630	6.03	0.0027	S
TRPM*TS	2	58.80265433	1.55	0.2136	N
TS*IRR	2	24.86395062	0.66	0.5196	N
TRPM*IRR	4	168.64641976	2.23	0.0664	N
TD*TRPM*TS	2	71.48191357	1.89	0.1535	N
TD*TS*IRR	2	43.12913579	1.14	0.3218	N
TRPM*TS*IRR	4	166.48716048	2.20	0.0694	N
TD*TRPM*IRR	4	52.15259258	0.69	0.6006	N
TD*TRPM*TS*IRR	4	59.73753088	0.79	0.5335	N

S-Significant, N=Nonsignificant

Table 25. ANOVA table using percent greater than 0.297 mm as the response.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	35	3059.23	87.41	12.73(S)
ERROR	288	1977.24	6.87	PR > F 0.0001
CORRECTED TOTAL	323	5036.48		

R-SQUARE	C.V.	ROOT MSE	%>0.297 mm MEAN
0.61	2.79	2.62	93.82

SOURCE	DF	ANOVA SS	F VALUE	PR > F	S/N
TD	1	0.37345679	0.05	0.8157	N
TS	1	1.69000000	0.25	0.6202	N
TRPM	2	180.12450618	13.12	0.0001	S
IRR	2	2497.16117284	181.86	0.0001	S
TD*TS	1	7.53197531	1.10	0.2958	N
TD*TRPM	2	38.44524692	2.80	0.0625	N
TD*IRR	2	68.92524692	5.02	0.0072	S
TRPM*TS	2	26.05500001	1.90	0.1518	N
TS*IRR	2	6.89240741	0.50	0.6059	N
TRPM*IRR	4	83.53827161	3.04	0.0177	N
TD*TRPM*TS	2	21.21154320	1.54	0.2151	N
TD*TS*IRR	2	20.39376543	1.49	0.2282	N
TRPM*TS*IRR	4	60.88148147	2.22	0.0673	N
TD*TRPM*IRR	4	25.41382715	0.93	0.4495	N
TD*TRPM*TS*IRR	4	20.59382717	0.75	0.5588	N

S=Significant, N=Nonsignificant

of the variability in the data can be adequately described by the model descriptors. As the size of the sieve openings decreased, the R^2 value increased.

Another statistical analysis was performed to examine if the MWD was a plausible alternative for the response. The MWD was calculated using a modified version of Simpson's rule (Purcell, 1978) which calculates the area under a quadratic fitted to three data points. Simpson's rule could not be used directly in this application because the data points on the abscissa were not equally spaced apart. Therefore, the equations used to derive Simpson's rule were used to derive a similar expression for unequal spacing of values on the abscissa. The derivation is shown in Appendix B and the final results are:

$$AR = A\frac{X_3^3}{3} + B\frac{X_3^2}{2} + CX_3 - A\frac{X_1^3}{3} - B\frac{X_1^2}{2} - CX_1 \qquad [13]$$

$$A = \frac{Y_3 - Y_1 + \dfrac{(X_3 - X_1)(Y_1 - Y_2)}{X_2 - X_1}}{X_3^2 - X_1^2 + \dfrac{(X_3 - X_1)(X_1 - X_2^2)}{X_2 - X_1}} \qquad [14]$$

$$B = \frac{Y_2 - AX_2^2 - Y_1 + AX_1}{X_2 - X_1} \qquad [15]$$

$$C = Y_1 - AX_1^2 - BX_1 \qquad [16]$$

where, AR = area under quadratic defined by $(X_1, Y_1),(X_2, Y_2),(X_3, Y_3)$

X_1 = abscissa value at point 1

X_2 = abscissa value at point 2

X_3 = abscissa value at point 3

Y_1 = ordinate value at point 1

Y_2 = ordinate value at point 2

Y_3 = ordinate value at point 3

An example aggregate size distribution is shown in Figure 19 where the MWD is the shaded area below the curve and between the sieve size limits of 0 cm and 38 cm. Therefore, calculation

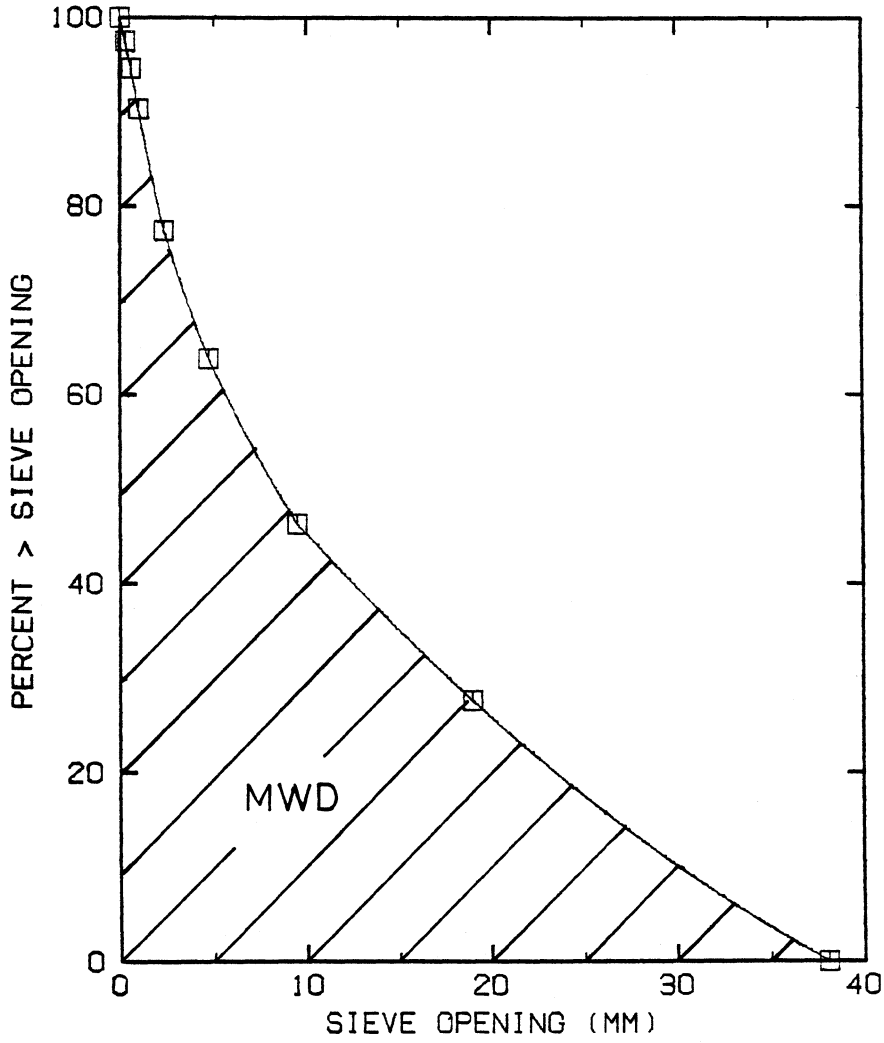

Figure 19. Example aggregate size distribution showing MWD.

of the MWD only involves the summation of areas as calculated in Equation 13 for each successive set of three data points. ANOVA results using the MWD as the response are shown in Table 26. Highly significant results occurred with relatively low R^2 values.

Table 27 shows the summary statistics for all of the responses analyzed for aggregate size distributions. These summary statistics allow the selection of the best response based upon the significance of the model and the R^2 statistic. The percent of the sieve sample greater than the number 50 sieve was chosen as the best overall response.

The MAXR subroutine within the Statistical Analysis Subroutine SAS (SAS Institute Inc.) was chosen for the selection of a regression formula suitable for analyzing the effect of the regressors on the response of percent greater than. The regressors used were the four field parameters, tiller depth (TD), tractor speed (TS), tiller rpm (TRPM), and irrigation level (IRR). The MAXR routine determines the best 1,2,3, and 4 variable model based on the maximization of the R^2 statistic. A high R^2 value indicates the amount of variability in the response explained by the model parameters. In addition to the R^2 statistic, the Cp statistic, or Mallow's statistic, should also be examined to determine if the model has been over specified (too many regressors), or under specified (too few regressors). A Cp value equal to or less than the number of regressors in the model is desirable.

The MAXR procedure indicated that a two variable model resulted in the highest R^2 value and the least Cp value. The model is:

$$r = b_0 + b_1 \times IRR + b_2 \times TRPM + e_i \qquad [17]$$

where, r = response = percent of sieve size greater than # 50 sieve

b_0 = 88.917 = intercept estimate

b_1 = 3.308 = irrigation coefficient estimate

IRR = irrigation level

b_2 = -0.858 = tiller RPM coefficient estimate

TRPM = tiller RPM level

e_i = random error

Table 26. ANOVA table using MWD as the response.

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE
MODEL	35	164.55	4.70	4.35(S)
ERROR	288	311.09	1.08	PR > F 0.0001
CORRECTED TOTAL	323	475.64		

R-SQUARE	C.V.	ROOT MSE	MWD MEAN
0.35	10.50	1.04	9.90

SOURCE	DF	ANOVA SS	F VALUE	PR > F	S/N
TD	1	5.49459645	5.09	0.0249	S
TS	1	0.74563225	0.69	0.4068	N
TRPM	2	40.43186101	18.72	0.0001	S
IRR	2	75.79875764	35.09	0.0001	S
TD*TS	1	2.42027163	2.24	0.1355	N
TD*TRPM	2	1.76236375	0.82	0.4433	N
TD*IRR	2	13.40718601	6.21	0.0023	S
TRPM*TS	2	2.62753939	1.22	0.2979	N
TS*IRR	2	0.59227124	0.27	0.7604	N
TRPM*IRR	4	6.54189123	1.51	0.1981	N
TD*TRPM*TS	2	2.45448623	1.14	0.3225	N
TD*TS*IRR	2	3.23143638	1.50	0.2258	N
TRPM*TS*IRR	4	4.64734070	1.08	0.3688	N
TD*TRPM*IRR	4	1.68855549	0.39	0.8152	N
TD*TRPM*TS*IRR	4	2.70936790	0.63	0.6436	N

S=Significant, N=Nonsignificant

Table 27. Summary aggregate analysis statistics.

Response	Calculated F-value	S=significant I=insignificant	R-squared
Slope	2.28	S	0.22
%>19.000 mm	2.33	S	0.22
%>9.500 mm	2.52	S	0.23
%>4.760 mm	2.91	S	0.26
%>2.362 mm	4.45	S	0.35
%>1.000 mm	8.53	S	0.51
%>0.589 mm	10.60	S	0.56
%>0.297 mm	12.73	S	0.61
MWD	4.35	S	0.35

This model shows that the irrigation level in conjunction with the tiller RPM are the only two factors that contribute to the response. Therefore, the tractor speed and the tiller depth were insignificant. This model also shows that high irrigation levels produced smaller aggregates than low levels and that a high tiller RPM produced more smaller aggregates than a low tiller RPM.

Only one significant interaction existed in the original specification of this model and it was between the tiller depth and the irrigation level. A possible explanation of this interaction is that drier soil prohibited the tiller from reaching its maximum depth which indirectly influenced the response.

6.2.4 Seedbed Geometry Results

Summary statistics from the measurements of the seedbed geometry are shown in Table 28. Several trends in this table should be emphasized. The low irrigation level resulted in the only occasion when the top of the seedbed was above the initial soil level. The deeper tiller depth resulted in a 5 mm deeper seedbed depth as expected. The tractor speed only affected the tiller depth resulting in a deeper depth at a higher tractor speed than at a lower speed. The tiller RPM also influenced the seedbed depth. Increasing the RPM increased the seedbed depth. Average geometries for all treatments were:

seedbed width = 7 cm

seedbed height = 4 mm below initial ground level

seedbed depth = 35 mm

6.3 Conformance to System Criteria

In order to further demonstrate the ability of the FOR2 machine, its performance was compared with the acceptable system criteria stated in Section 4.1.

1. FOR2 operated successfully in 15 cm high wheat stubble without adverse performance.

Table 28. Summary seedbed geometry results.

Category	Seedbed width (cm)	Seedbed height above initial ground level (mm)	Seedbed Depth (mm)
IRRIGATION LEVEL			
LOW	6.4	+1	39
MEDIUM	6.9	-8	28
HIGH	7.6	-4	37
TILLER DEPTH			
SHALLOW	7.7	-7	32
DEEP	6.1	0	37
TRACTOR SPEED			
LOW	7.0	-3	32
HIGH	6.9	-4	37
TILLER RPM			
LOW	6.7	-1	28
MEDIUM	7.1	-8	36
HIGH	7.1	-2	41
OVERALL MEANS	7	-3.5	34.5

2. The trash clearing discs on FOR2 effectively removed the majority of the trash from the seedbed area.

3. Soil granulation was adequate to provide good soil flow around the furrow opener in all plots except when they were very wet.

4. The final seedbed level was below the initial ground level in most tests, but ditches on both sides of the row prevented soil movement on top of the seed during heavy rains.

5. The seedbed had relatively uniform width (between 5 cm and 12 cm) and depth (between 2 cm and 5 cm).

6. The top surface of the seedbed was relatively smooth except where large depressions occured in the fields prior to seeding.

7. The direct seeder and the seedbed preparation unit were coupled on the same implement.

8. FOR2 was three-point hitch mounted to a 35 kW tractor. A two-row machine could easily be mounted to this same tractor.

9. The FOR2 geometrical constraints allowed the planter to track in the tilled strip. This feature worked well during most tests.

10. Power requirements were minimized by using a minimal number of ground engaging tools.

11. Tillage action was minimized by operating at low speeds and by tilling a very narrow strip.

7.0 Summary and Conclusions

The FOR2 machine performed well and produced commercially acceptable broccoli stands. The spacious rototiller housing used on FOR2 enabled it to till a narrow strip without clogging. Direct seeding in the tilled strip was made possible through pivoting the planter and using geometrically derived dimensions which theoretically force proper tracking.

Statistical analyses indicated that the aggregate size distribution was influenced directly by the irrigation level (low, medium, high) and indirectly by the tiller RPM (195, 300, 390 r/min). High irrigation levels produced smaller aggregates than low irrigation levels and a high tiller RPM produced more smaller aggregates than a low tiller RPM. The aggregate size distribution was characterized by the percentage of the sieve sample greater than 0.297 mm.

Eventhough this research did not address the influence of aggregate size distribution on plant growth, it is a first step to quantify the ability of a soil working machine to produce a variety of aggregate size distributions. This research therefore enables further studies to be made on plant growth using the limitations of aggregate size distributions produced by FOR2.

The previously reported results and analyses revealed:

1. The Vegetable Emergence System (VES) machine was incapable of direct seeding conservation tillage broccoli because of poor residue incorporation and tiller clogging.
2. The VES machine could not operate effectively on a contour due to the inability of the planter to track in the tilled strip.
3. The modified VES machine with trash clearing discs caused a severe seedbed depression that was very susceptible to high erosion losses.
4. Acceptable system criteria for conservation tillage equipment for broccoli were developed.
5. The FOR2 machine meets most of the acceptable system criteria and can produce commercially acceptable stands of broccoli.

6. FOR2's performance was quantitatively evaluated in terms of seedbed aggregate analysis, resulting in an equation in which the irrigation level and the tiller RPM effect the amount of soil in the seedbed that can pass through a number 50 sieve.

7. Experiments showed that broccoli emergence using FOR2 was the same as the Ro-Till machine without secondary tillage and greater than the Ro-Till machine with secondary tillage.

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Appendix A. Terms and Definitions

Term	*Definition*
Combined Tillage Operations	Operations simultaneously utilizing two or more different types of tillage tools or implements (subsoil-lister, lister-planter, or plow planter combinations) to simplify, control or reduce the number of trips over a field. (ASAE Standard EP291.1, Terminology and definitions for soil tillage and soil tool relationships).
Conservation Tillage	Any tillage and planting system that retains at least 20% residue cover on the soil surface after planting or drilling (Dickey et al., 1986) or any tillage or planting system which leaves at least 30% of the soil surface covered with residue after planting (Conservation Tillage Information Center, 1984).
Furrow Depth	Depth of depression below a specified initial or subsequent soil surface (ASAE Standard EP291.1).
Minimum Tillage	The minimum soil manipulation necessary for crop production or for meeting tillage requirements under the existing soil conditions (ASAE Standard EP291.1).
Mulch Tillage	Tillage or preparation of the soil in such a way that plant residues or other mulching materials are specifically left on or near the surface (ASAE Standard EP291.1).
No-Tillage Planting	A procedure whereby planting is made directly into an essentially unprepared seedbed (ASAE Standard EP291.1).

Optimum Tillage	An idealized system which permits a maximized net return for a given crop under given conditions (ASAE EP291.1).
Precision Tillage	By common usage, subsoiling under the plant row prior to planting (ASAE Standard EP291.1).
Pulverization	See soil shatter
Reduced Tillage	A system in which the primary tillage operation is performed in conjunction with special planting procedures in order to reduce or eliminate secondary tillage operations (ASAE Standard EP291.1).
Ridge Height	Height of soil above a specified (initial or subsequent) soil surface (ASAE Standard EP291.1).
Root Bed	The soil profile modified by tillage or amendments for use by plant roots (ASAE Standard EP291.1).
Root Zone	That part of the soil profile exploited by the roots of plants (ASAE Standard EP291.1).
Rotary Tillage	A tillage operation employing power driven rotary action to cut, breakup, and mix soil (ASAE S414).
Rotary tiller	A primary or secondary tillage implement used for broadcast or strip tillage (ASAE Standard S414, Terminology and definitions for agricultural tillage implements).

Seedbed	The soil zone which affects the germination and emergence of seeds (ASAE Standard EP291.1).
Soil Structure	The physical constitution of a soil material as expressed by the size, shape, and arrangement of the solid particles and voids, including both the primary particles to form compound particles and the compound particles themselves (Brewer, 1964).
Soil Shatter	The general fragmentation of a soil mass resulting from the action of tillage forces (ASAE Standard EP291.1).
Strip Tillage	A system in which only isolated bands of soil are tilled (ASAE Standard EP291.1).
Tillage	The mechanical manipulation of soil for any purpose; but in agriculture the term is usually restricted to the changing of soil conditions for crop production (ASAE Standard EP291.1).
Tillage Action	The action of a tillage tool in executing a specific form of soil manipulation such as soil cutting, shattering or inversion (ASAE Standard EP291.1).
Tillage Implement	Single or groups of soil working tools together with power, transmission, structure, control, and protection systems present as an integral part of the machine (ASAE Standard EP291.1).
Tillage Objective	A desired soil condition that is to be produced by one or more tillage actions (ASAE Standard EP291.1).

Tillage, Primary	That tillage which constitutes the initial major soil working operation. It is normally designed to reduce soil strength, cover plant materials and rearrange aggregates (ASAE Standard EP291.1).
Tillage Requirement	The soil physical conditions, which after a complete evaluation of basic utilitarian and economic requirements are deemed necessary and can be feasibly produced by tillage (ASAE Standard EP291.1).
Tillage, Secondary	Any of a group of different tillage operations, following primary tillage, which are designed to create refined soil conditions before the seed is planted (ASAE Standard EP291.1).
Tillage Tool	An individual soil working element (ASAE Standard EP291.1).
Tillage Tool, Complex	Tools which rotate or move so that they present a varying boundary and contact area to the soil (ASAE Standard EP291.1).
Tillage Tool, Dynamic	Tillage tools which are powered so that some of their movements are in directions other than along the line of travel (ASAE Standard EP291.1).
Tillage Tool, Multipowered	A tillage tool powered by more than one form of power, such as draft and rotating power or draft and electrical power (ASAE Standard EP291.1).

Appendix B. Derivation of Modified Simpson's Rule

Three data points (X_1, Y_1),(X_2, Y_2), and(X_3, Y_3) can be fit with a quadratic equation of the form:

$$Y = AX^2 + BX + C \quad [1]$$

Therefore:

$$Y_1 = AX_1^2 + BX_1 + C \quad [2]$$

$$Y_2 = AX_2^2 + BX_2 + C \quad [3]$$

$$Y_3 = AX_3^2 + BX_3 + C \quad [4]$$

Simultaneously solving 2, 3, and 4 for A, B, and C yields:

$$A = \frac{Y_3 - Y_1 + \frac{(X_3 - X_1)(Y_1 - Y_2)}{X_2 - X_1}}{X_3^2 - X_1^2 + \frac{(X_3 - X_1)(X_1 - X_2^2)}{X_2 - X_1}} \quad [5]$$

$$B = \frac{Y_2 - AX_2^2 - Y_1 + AX_1}{X_2 - X_1} \quad [6]$$

$$C = Y_1 - AX_1^2 - BX_1 \quad [7]$$

Integration of 1 yields the area under the quadratic from X_1 to X_3.

$$AREA = A\frac{X_3^3}{3} + B\frac{X_3^2}{2} + CX_3 - A\frac{X_1^3}{3} - B\frac{X_1^2}{2} - CX_1 \quad [8]$$

Substitution of equations 5, 6, and 7 into 8 yields the area under the quadratic in terms of the abscissa and ordinate values for the three data points. Therefore, calculation of the MWD defined by nine coordinate pairs involves the summation of the area under four quadratics.

When the abscissa values are equally spaced apart, $X_3 - X_2 = X_2 - X_1$, equation 8 yields the same result as Simpson's equation. For completeness, Simpson's equation to calculate the area

under a quadratic defined by three data points, when the abscissa values are equally spaced apart is (Purcell, 1978):

$$A = \frac{h}{3}(Y_1 + 4Y_2 + Y_3) \qquad [9]$$

where, A = AREA

$h = X_2 - X_1 = X_3 - X_2$

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