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The Effect of Various Root Characteristics on Root-pulling Resistance of 44 Inbred Lines of Corn

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THE EFFECT OF VARIOUS ROOT CHARACTERISTICS ON ROOT-PULLING RESISTANCE OF 44 INBRED LINES OF CORN

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This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Major Advisor Date

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J.R.J.

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INTRODUCTION

Many corn breeders from both commercial corn companies and publicly supported research programs have used some form of a plant pulling technique to measure root strength or root lodging resistance. Root-pulling devices also have been used in an attempt to measure the rootworm tolerance of corn lines or hybrids in soils highly infested with rootworms. References can be found in the literature of the use of such methods, but few reports are available of detailed field studies of the relationship of upper root system characteristics of corn inbred lines to pulling resistance differences. Information is needed on the importance that specific root characteristics have in drought tolerance, high plant population response, rootworm tolerance, and root lodging resistance. Information also is needed on the repeatability of those root characteristics under different environmental conditions. If such characteristics are repeatable to an acceptable degree, then further investigations can be initiated in an attempt to establish their relative importance in corn production.

The purposes of this study were to determine (1) the range of root-pulling resistance that exists among inbred lines, (2) the repeatability of root-pulling measurements as well as other root characteristics in differing environmental conditions, and (3) the relationship between root pulling resistance and root characteristics such as root spread, root dry weight, root abundance, and root rot resistance.

REVIEW OF LITERATURE

Studies on corn root improvement have not kept pace with the progress made for upgrading above-ground plant characteristics such as yield, disease resistance, and stalk strength.

Much of the improvement of corn roots has resulted from the use of various forms of a root-pulling device. Root-pulling devices were used as early as 1924 (24), in measuring root strength under rootworm infested soils as well as non-infested soils.

Ortman, Peters, and Fitzgerald (15) studied the use of a vertical pull device that measured root-pulling resistance. Their study of corn inbred lines was one of the first extensive field studies attempted in the search for techniques to measure rootworm tolerance. They found no significant correlation between root spread, or the angle of root growth in relation to the stalk, and root-pulling resistance. However, the visual rating of relative size and symmetry of the root system was highly correlated with root-pulling resistance. They also found a high correlation between the number of roots on the second complete node of crown roots and root-pulling resistance. Their summary suggested that "a root-pulling resistance measurement is an efficient means of obtaining quantitative data that should be freer of subjective biases than some other determinations".

Nass and Zuber (11) used a root-pulling device in studying corn root development in field versus greenhouse experiments. They grew 40 corn genotypes in sand culture and evaluated the roots 28 and 35 days after planting. Root-clump weight and root-pulling resistance of mature plants in the field were significantly and positively correlated with total root weight, root volume, and weight of nodal roots and negatively correlated with the percentage of seminal roots of plants grown in the greenhouse. They suggested that evaluation of corn roots grown in sand culture provided an efficient method for identifying genotypes with superior root types at an early stage of plant growth. They concluded by suggesting that corn genotypes with vigorous root systems early in plant development tend to have superior root systems at maturity. They pointed out the significance of this technique in regard to developing rootworm tolerant lines.

Corn rootworm resistance found to date would have to be classified as tolerance. Tolerance in corn germplasm appears to be (1) the ability of the corn plant to produce adventitious or crown roots at a rapid rate during the period in late June and early July when rootworm larva are most active, or (2) the ability to produce many secondary roots as a regrowth response following rootworm attack.

Owens, Peters, and Hallauer (16) described four types or traits of tolerance to corn rootworms: (1) decreased feeding damage, (2) decreased root lodging, (3) increased root size, and (4) increased secondary root development. They described resistance, in a practical sense, as "all the heritable traits of a plant that lessen insect damage even though plants of the same species and environment receive greater damage". Estimates of heritability of 221 random inbred lines from Iowa Stiff Stalk Synthetic indicated that selection on the basis of rootworm feeding damage alone would be ineffective. Heritability values for root sizes, secondary roots, and root lodging indicated that gains could be expected from selection for each of these traits. Genotypic, phenotypic, and error correlations indicated that selection for larger root systems might result in superior secondary root development, reduced feeding damage, and reduced lodging. Their summary of the study emphasized that selection for rootworm tolerance is simultaneous for each of the four root traits listed above.

Root rot susceptibility as well as root volume deficiency may cause an inferior root system. Hornby and Ullstrup (7) reported that root rot is caused by a complex of organisms including such fungal genera as <u>Fusarium</u> and <u>Diplodia</u>. Root and stalk rot of corn were considered successive phases of a disease which commences in the roots. Root rot was reported to precede stalk rot by 3-5 days. Barren plants or those with nubbin ears did not develop stalk or root rot to an appreciable degree whereas crowded or defoliated plants became more susceptible. In their study of root rot, they found that rhizosphere counts remained relatively low for all genotypes until 77 days after emergence, when rapid increases occurred in all but one resistant line. Several authors (4, 7, 8, 9) have reported that the numbers of fungal units associated with the roots increases tremendously after the early milk stage due to a root volume stabilization or plateau and to an apparent increase in susceptibility to rot-causing organisms.

Holbert and Koehler (6) found fundamental differences in the root systems of various corn inbred lines. Root rot susceptible lines seemed to have root volume deficiencies as compared to their vegetative growth above ground. They found significant differences of root pith and cortex cell arrangements between root rot resistant and susceptible lines. The cells of the resistant line were closely united so that the cells had an angular shape. The corners were usually reinforced by extra thickenings. The cells of the susceptible line were round, not closely bound, and did not have an apparent thickening in spaces between cells.

Reports of root rot severity and its relationship to yield are not common in the literature. However, Semeniuk (19) found corn yields at three experimental locations in Iowa to be lower in those rotations where root rot was more severe and where secondary roots were less abundant. His summary indicated that decreases in yield and plant vigor and increases in root rot severity appeared associated.

Nagel, Shank, Dirks and Kratochvil (12) studied the relationship of root rot resistance and root spread on yield and maturity of corn. Roots of topcross progenies were dug with a mechanical digger and visually rated for spread, abundance, and rot resistance. Correlations between these measurements and yield and moisture at harvest were significant at the 1% level of probability with secondary root abundance correlations being one of the most useful morphological characters rated.

Other root morphology studies have dealt mainly with the influence of soil temperature on various root characteristics. Hayes (5) suggested that the horizontal growth or spread of the upper root system was a result of low subsoil temperature. He hypothesized that roots developing from nodes early in the spring grew horizontally for some time before turning downward because soil temperature was warmer in the upper soil levels. As the soil temperature increased, the later developing roots from the higher stem nodes grew downward at once.

Porter and Moragham (17) studied the differential response of two corn inbreds to varying root temperatures. At a constant soil temperature of 28°C, one line developed an abnormality in growth that resembled a calcium deficiency response.

Mosher and Miller (10) studied the influence of soil temperature on corn roots in the greenhouse. They observed that horizontal growth before turning downward was generally greatest for the first nodal roots and least for the fourth nodal roots. Roots from the fifth and subsequent nodes grew nearly straight down. They concluded by stating, "From the preceding observations it would appear that if corn were planted after the soil 'warmed up', all of the roots would grow in a vertical direction from their nodes."

In root-related inheritance studies, Semeniuk (18) found significantly different root rot ratings for secondary roots among 25 inbred lines in August, 1944 and 1945. The ratings for the two years were highly correlated. W_r-V_r graphing of F_1 data supplied evidence that some inbred lines carried a preponderance of dominant genes for low rot ratings and for high root abundance, while others carried a preponderance of recessive genes for those same characteristics.

In a comparative study of the seasonal root development of some inbred lines, Spencer (20) found that certain hereditary factors other than time of maturity influenced the maximum dry weight of the crown roots. He noted a striking difference among the four inbred lines studied in the development of lateral roots.

Ortman and Gerloff (14) studied 22 corn inbred lines in an effort to identify root characteristics that might be important in rootworm tolerance. Some very weak rooted lines did not respond to changing environments whereas other lines did so with varying degrees. Some lines developed extensive root systems even under severe stress. They estimated the coefficient of variation for pulling resistance to be near 30% and root recovery to be 75-80% when compared to that of excavation techniques.

Zuber (25) evaluated corn root systems under various environments and concluded that root-pulling resistance is a highly heritable trait.

MATERIALS AND METHODS

Forty-one corn inbred lines of medium maturity were selected from corn breeding programs at the University of Minnesota, South Dakota State University, and the USDA Northern Grain Insect Research Laboratory located near Brookings, South Dakota. In addition, eight inbred lines were included from various other experiment stations. Some of the inbred lines were selected because of their specific root characteristics, however, only limited root information was available on the majority of the lines selected. (See appendix Table 1 for more information about the parental background of the lines.)

The 49 lines were planted at two locations for two years. One location was on the Southeast South Dakota Experiment Farm near Centerville, South Dakota. The other was part of the Northern Grain Insect Research Laboratory plots near Brookings, South Dakota. At Centerville the 1974 experiment was grown on Egan silty clay loam soil following a soybean crop, and the 1975 experiment was grown on a Whitewood silty clay loam soil following an oats crop. At Brookings the experiments were grown on Brookings silty clay loam with the 1974 test following a corn crop and the 1975 test following green soybean plowdown. Normal fertilization rates were applied in both years at both locations. A soil insecticide was applied at planting time both years at Brookings to prevent any possible rootworm damage, but no insecticide was used at Centerville.

In 1974 the lines were evaluated for root-pulling resistance, root dry weight, and root spread. In 1975, the lines were visually rated for root rot resistance and for total, crown and secondary root abundance in addition to the characters evaluated in 1974. Silking dates were recorded during both years at Brookings and were used as a measure of maturity.

Each entry was replicated four times at each location in a 7 X 7 lattice design, with one row plots 12 m long. Kernels were hand-planted 25 cm apart with 100 cm row spacings at Brookings and 30 cm apart with 75 cm row spacings at Centerville. Approximately 10 days after the original planting, seed of a purple-plant-marker inbred line was used to replant in places where the originally planted seed failed to germinate. Only nonconsecutive plants that were bordered on both sides by other plants were used for obtaining pulling resistance data. Plants adjacent to either a vacant space or another plant that had been pulled were not used because of possible biases due to noncompetitiveness or to soil disturbances from pulling the adjacent plant. This procedure allowed data to be collected on a maximum of 20 competitive plants per plot.

Root-pulling resistance was measured as the kilograms of force required to lift a plant vertically from the soil. Force was exerted through a bar attached from a bipod through a dynamometer to a clamp secured around the base of the plant just above the soil. (See Figure 1, A-B* for the specific root-pulling apparatus used in this study.) Root-pulling resistance was measured at the pretassel or boot stage (pull 1) and three weeks after silking or the milk stage (pull 2) in both years. Additional pulling data were obtained in 1975 at Brookings at eight weeks after silking or the mature plant stage (pull 3). Five plants of each entry were pulled from each of four replications in all of the above stages.

Root spread and root dry weights were determined on roots from the second pull. After being pulled, the five roots from each plot were shaken free of soil, cut from the stalk just above the top node of roots, and sacked. Later the roots were washed, measured for spread at the widest portion of the root, and dried to a constant weight at 70°C. (See Figure 1C for the technique used to measure root spread.) After drying, the individual roots from each plant were cut free from the stem with a large pruning shear, bulked within each plot, and weighed on an analytical balance.

Initial plans for 1975 were to take visual ratings on roots from a third pull at both locations, but severe drought at Centerville necessitated taking ratings at the location on roots from the second pull. Root rot ratings were not taken at Centerville due to the severe drought conditions. All root

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* All figures may be found in the appendix.

ratings at Brookings were taken on roots from the third pull.

An understanding of the terminology used in rating of the corn root system is essential to this study. A crown root is any one of the large roots arising from the stem of the plant. The term crown roots is often used interchangeably with nodal roots. Any roots growing laterally from a crown root are referred to as secondary roots. A root node (whorl) refers to the area on the stem from which the crown roots arise. This terminology is identical to that used by Eiben and Peters (2). Total, crown, and secondary root abundance were rated on a scale of 1-10 with a "10" rating signifiying a large quantity of the specific type or types of roots being rated. Root rot ratings were also based on a scale of 1-10 with a "10" rating signifying a severely rotted root.

Four entries were selected at random and five roots per entry in each replication were dug with a spade to compare with the roots removed by pulling. The resulting root clump was approximately 40 cm in diameter and 30 cm in depth. Digging was accomplished as carefully as possible to keep root breakage at a minimum. By comparing pulled versus dug roots of each of the four entries, it was possible to determine the percentage of roots lost by pulling. The same four entries were compared at both locations for both years.

Poor germination of seed led to extensive missing data for five of the entries. They were subsequently dropped and this reduced the total number of entries in the experiment to 44. Analyses of variance was calculated on the basis of a randomized complete block rather than a 7 X 7 lattice design as originally planned.

RESULTS AND DISCUSSION

I. Root Recovery by Pulling versus Digging

The ratio of upper root system recovered by pulling versus digging of four inbred lines of corn is shown in Table 1.

The mean percent of root dry weight recovery for the four entries at two locations for two years was 88.1. This is similar to the recovery percentage of 75-80% estimated by Ortman and Gerloff (14) in their root-pulling study. The mean dry weight recovery percentage for the four entries was higher at Centerville than at Brookings. Drought conditions at Centerville were severe in both years, and root development for most lines was minimal. These conditions lead to shallow root penetration and apparently give a high root recovery percentage. Growing conditions at Brookings were good in both years, and root development for most entries was probably near optimum. Such conditions lead to deep root penetration and apparently give a relatively lower root recovery percentage. The dry, compacted soil at Centerville did not seem to affect root recovery by pulling. Inbred SD1-1261 which had the largest root system of the four entries had the lowest recovery percentage at both locations. The same trend was apparent for root spread measurements. However, pulling did not seem to affect root spread measurements as extremely as it did root dry weight.

Table 1. Ratio[a] of upper root system recovered by pulling versus digging for four inbred lines of corn in 1974 and 1975.

Entry	Root dry wt.			Root spread		
	Brookings 2 yr. ave.	Centerville 2 yr. ave.	Location mean	Brookings 2 yr. ave.	Centerville 2 yr. ave.	Location mean
A619	91.7	89.2	90.5	93.3	100.6	97.0
SD1-1261	77.5	82.3	79.9	89.0	94.7	91.9
SDP309	82.2	97.4	89.8	95.1	97.3	96.2
W64A	82.2	102.0	92.1	90.4	101.6	96.0
mean	83.4	92.7	88.1	91.9	98.5	95.3

[a] Expressed in percent, (pulled ÷ dug) x 100

II. Differences Among Genotypes for Root-Pulling Resistance

Identifying those lines that have high root-pulling resistance in early July when corn rootworms are the most active was one of the major objectives of this study. Many plant breeders feel that high root volume in late June and early July is one of the most important traits that contributes to rootworm tolerance. It should be emphasized at this point that all data gathered in this study of root-pulling resistance was from rootworm-free plants. Root-pulling resistance values at pull 1 of 44 inbred lines of corn are shown in Table 2.

The mean square among entries for pull 1 is shown in Table 3 and is highly significant. This difference among genotypes supports the findings of many other researchers when studying root-pulling resistance. A number of the entries had high pulling resistance at this pre-tassel stage. Inbreds NG72227, NG72312, NG72317, SD1-1261, SD10, SD30 and W202 are examples of lines that apparently develop extensive root systems early in the growing season. Inbreds A427, A619, A660, W117 and W182E are examples of lines that had relatively low pulling resistance. Mean pulling values varied widely among the four environments, ranging from 90.0 kg at Centerville in 1975 to 174.1 kg at Brookings in 1975. The relative pulling resistance of the individual lines was reasonably consistent, however, in spite of the wide differences in the environments

Table 2. Root-pulling resistance (kg) at pull 1 of 44 inbred lines of corn.

Entry	Brookings 1974 (7/17)[a]	Brookings 1975 (7/28)[a]	Brookings location mean	Centerville 1974 (8/22)[a]	Centerville 1975 (8/25)[a]	Centerville location mean
A238	98.4	145.0	121.7	107.4	56.8	82.1
A344	98.2	136.3	117.2	94.7	79.0	86.8
A427	77.9	148.0	113.0	85.5	77.3	81.4
A556	104.8	168.3	136.5	91.4	78.3	84.8
A619	88.7	132.8	110.7	90.9	77.3	84.1
A624	99.3	169.0	134.2	88.3	73.8	81.0
A629	89.8	140.5	115.2	84.2	76.5	80.3
A632	93.0	147.5	120.3	101.7	76.3	89.0
A634	108.7	180.3	144.5	124.5	101.3	112.9
A648	122.7	159.0	140.8	105.2	95.0	100.1
A657	136.0	198.8	167.4	123.4	117.8	120.6
A659	89.4	181.8	135.6	98.2	75.0	86.6
A660	72.0	146.8	109.4	63.2	69.3	66.2
A70-12	72.7	115.3	94.0	68.2	66.5	67.3
C123	96.0	151.3	123.6	100.7	79.8	90.2
MS214	98.3	153.8	126.0	81.7	78.5	80.1
NG72227	161.5	228.8	195.1	123.2	125.5	124.3
NG72232	143.4	208.5	176.0	138.2	118.5	128.4
NG72254	121.4	186.0	153.7	114.9	95.3	105.1
NG72303	147.1	213.8	180.4	132.6	112.8	122.7
NG72309	122.1	182.5	152.3	111.6	86.5	99.0
NG72312	151.8	213.5	182.7	122.9	111.8	117.3
NG72314	146.2	198.0	172.1	122.5	101.8	112.1
NG72317	150.7	214.5	182.6	124.3	103.8	113.9
NG72325	104.0	172.0	138.0	112.0	92.0	102.0
NG72335	123.8	212.5	168.2	124.2	94.3	109.2
NG72336	129.6	215.0	172.3	149.0	97.8	123.4
NG72353	122.6	180.0	151.3	113.0	83.5	98.3
NG72358	139.4	199.8	169.6	125.7	92.8	109.2
Oh545	86.3	151.0	118.6	78.3	71.3	74.8
SD1-1261	146.7	210.3	178.5	131.2	122.8	127.0
SD1-1412	114.9	176.5	145.7	108.7	97.3	103.0
SD1-1434	131.1	213.8	172.4	126.8	123.5	125.1
SD10	154.5	193.5	174.0	124.6	112.3	118.4
SD23	94.1	142.5	118.3	93.7	74.5	84.1
SD29	105.0	156.5	130.7	107.4	80.0	93.7
SD30	140.4	206.5	173.4	133.2	118.0	125.6
SDP2A	103.3	151.0	127.1	87.4	71.8	79.6
SDP309	108.6	168.8	138.7	79.3	83.5	81.4
SDP317W	98.9	176.8	137.8	96.1	90.8	93.4
W64A	100.5	154.8	127.6	108.8	92.8	100.8
W117	76.6	116.0	96.3	78.4	65.0	71.7
W182E	61.1	130.0	95.6	69.5	62.0	65.8
W202	133.1	212.8	172.9	123.5	98.8	111.1
mean	112.8	174.1	143.4	106.1	90.0	98.1

[a] date of pull

Table 3. Mean squares for four variables from the analyses of variance at Brookings and Centerville, 1974 and 1975.

Source of variation	Degrees of freedom	Pull 1	Pull 2	Root dry weight	Root spread
R[a]	3	877.45	513.71	36.06	5.33
E[b]	43	8198.30**	14897.87**	307.22**	92.45**
R x E	129	219.83	443.39	8.88	1.46
L[c]	1	362841.63**	1394270.00**	3745.40**	310.72*
R x L	3	1005.14	2293.58	10.31	10.71
E x L	43	588.49**	1834.59**	27.53**	4.87**
R x E x L	129	207.77	405.38	8.67	1.35
Y[d]	1	89462.44**	2062.43	1233.86**	199.01**
R x Y	3	833.93	686.89	34.09	3.28
E x Y	43	297.86*	787.71*	17.86**	6.35**
R x E x Y	129	203.96	488.12	8.70	1.36
L x Y	1	263790.25**	8360.28	2.56	220.62*
R x L x Y	3	637.44	3501.39	31.66	8.78
E x L x Y	43	354.92*	500.83	15.51*	4.96**
R x E x L x Y	129	203.45	488.27	10.09	1.45
Total	703				

*, ** Significant at the 1 and 5% levels of probability, respectively.

[a] Replications (random)
[b] Entries (fixed)
[c] Locations (fixed)
[d] Years (fixed)

indicated by the differences in mean pulling values among environments. Figure 2 illustrates the wide range of root development at pull 1 among several inbred lines of corn.

Root volume reaches a maximum by silking time or shortly thereafter, and steadily decreases as maturity is approached. It was for this reason that pull 2 was made approximately three weeks after silking. Root-pulling resistance values at pull 2 of 44 inbred lines of corn are shown in Table 4.

The mean square among entries for pull 2 is shown in Table 3 and is highly significant. A number of those entries that had high pulling resistance at pull 1 also had high pulling resistance at pull 2. Inbreds NG72227, NG72312, NG72317, SD1-1261, SD30 and W202 are examples of lines which responded in this manner. Other inbreds such as NG72254, NG72303 and SD10 that were high at pull 1, were only slightly above average at pull 2.

None of the entries responded between pulls 1 and 2 in such an extreme manner as inbred A659. It was below average in pulling resistance at pull 1, but was well above average at pull 2. Its pulling resistance increased by 142.5 kg between pulls 1 and 2 at Brookings in 1974. This increase was nearly 40 kg greater than most of the entries. Inbreds A624 and NG72335 responded similarly, but to a lesser degree. Inbred A659 and five other lines are shown in Figures 3-5 to illustrate

Table 4. Root-pulling resistance (kg) at pull 2 of 44 inbred lines of corn.

Entry	Brookings			Centerville		
	1974 (8/22)[a]	1975 (8/25)[a]	location mean	1974 (8/27)[a]	1975 (8/28)[a]	location mean
A238	185.6	154.0	169.8	95.5	58.0	76.7
A344	130.5	152.0	141.3	85.9	80.3	83.1
A427	150.4	149.5	149.9	85.3	90.3	87.8
A556	167.4	155.0	161.2	97.9	88.8	93.3
A619	162.4	164.5	163.4	91.8	93.8	92.8
A624	177.9	201.8	189.8	113.5	96.8	105.1
A629	146.3	153.0	149.6	85.5	78.5	82.0
A632	168.7	138.5	153.6	91.1	69.8	80.4
A634	219.2	192.3	205.7	134.9	87.0	111.0
A648	174.7	171.5	173.1	113.2	85.5	99.3
A657	208.9	205.5	207.2	112.0	102.3	107.1
A659	231.9	239.5	235.7	114.5	101.0	107.8
A660	141.7	154.0	147.9	63.9	81.0	72.4
A70-12	161.8	136.3	149.0	76.3	79.8	78.0
C123	173.4	166.3	169.8	96.3	108.3	102.3
MS214	201.7	199.8	200.7	104.9	113.3	109.1
NG7227	239.8	265.8	252.8	144.7	129.5	137.1
NG72232	209.8	225.5	217.6	134.0	126.5	130.3
NG72254	181.2	194.8	188.0	114.2	113.3	113.7
NG72303	184.9	225.5	205.2	117.3	117.5	117.4
NG72309	205.3	197.8	201.5	111.6	97.5	104.5
NG72312	264.4	268.8	266.6	158.6	118.5	138.6
NG72314	234.0	243.3	238.6	134.4	128.8	131.6
NG72317	297.0	250.0	273.5	131.4	103.3	117.3
NG72325	176.1	184.3	180.2	97.5	96.5	97.0
NG72335	258.3	274.0	266.2	166.7	139.8	153.2
NG72336	251.8	282.8	267.3	162.4	129.3	145.8
NG72353	177.9	198.0	188.0	114.5	108.3	111.4
NG72358	204.1	204.8	204.4	119.9	110.0	114.9
Oh545	159.6	155.8	157.7	72.3	75.5	73.9
SD1-1261	240.5	234.3	237.4	137.9	126.8	132.3
SD1-1412	201.8	173.8	187.8	100.9	106.3	103.6
SD1-1434	234.2	259.8	247.0	133.0	134.8	133.9
SD10	185.7	217.3	201.5	115.8	109.8	112.8
SD23	145.4	157.3	151.3	85.6	90.8	88.2
SD29	163.9	162.8	163.3	113.2	83.8	98.5
SD30	217.1	230.8	223.9	149.8	121.8	135.8
SDP2A	167.8	165.8	166.8	93.3	63.8	78.5
SDP309	210.8	193.8	202.3	96.7	90.8	93.7
SDP317W	166.7	199.5	183.1	114.4	93.0	103.7
W64A	191.5	183.0	187.3	109.8	90.0	99.9
W117	137.6	120.5	129.1	67.6	67.5	67.5
W182E	118.3	153.0	135.6	60.0	74.5	67.2
W202	238.1	263.0	250.6	133.5	137.5	135.5
mean	192.4	195.9	194.1	110.3	100.0	105.1

[a] date of pull

their respective root development between pulls 1 and 2.

The magnitude of the pulling resistance values was strikingly different between locations at pull 2 as well as at pull 1. The relative pulling resistance of individual lines, such as A344, A427, A660, NG7227, NG72336 and SD30, was reasonably consistent in spite of severe drought conditions in both years at Centerville.

Table 5 shows the correlation coefficients between locations and years for pulls 1 and 2. All correlations were positive and highly significant.

The entries x locations interaction mean squares for pulls 1 and 2, although much smaller than that associated with entries mean squares, were highly significant. The entries x years interaction mean squares for both pulls were significant at the .05 level. The years and the locations x years mean square for pull 1 were highly significant, but non-significant for pull 2. One reason for the significance may have been the later date at which pull 1 was made in 1975 as compared to 1974. The later date of pull 1 in 1975 seemed to have a significant effect at Brookings, but the severe drought at Centerville suppressed this interaction.

III. <u>Effect of Changing Environment on Upper Root System Characteristics</u>

Another major objective was to study the effect of changing

Table 5. Correlation coefficients between locations and years for pulls 1 and 2 at Brookings (B) and Centerville (C), 1974 and 1975.

	Pull 1 B74	Pull 1 C74	Pull 2 B74	Pull 2 C74	Pull 1 B75	Pull 1 C75	Pull 2 B75	Pull 2 C75
Pull 1 - B74		.66**	.56**	.66**	.71**	.66**	.62**	.56**
Pull 1 - C74			.54**	.75**	.67**	.62**	.60**	.57**
Pull 2 - B74				.60**	.63**	.51**	.63**	.51**
Pull 2 - C74					.71**	.60**	.74**	.60**
Pull 1 - B75						.66**	.79**	.67**
Pull 1 - C75							.56**	.59**
Pull 2 - B75								.67**

** Significant at the 1% level of probability.

environment on upper root system characteristics.

A. Root dry weight

Root dry weights at the pull 2 stage of 44 inbred lines of corn are listed in Table 6.

The mean square among entries for root dry weight is shown in Table 3 and is highly significant. Eleven of the 13 entries submitted by the Northern Grain Insect Research Laboratory had very high root dry weights at both locations. These lines have resulted from intensive selection pressure for rootworm tolerance. Mean root dry weights for individual lines ranged from 4.33 g for W182E at Centerville to 26.87 g for NG72312 at Brookings. Severe drought at Centerville reduced root development and probably was one of the major factors in causing the highly significant entries x locations and entries x years interaction. The mean squares associated with these sources of variation were much smaller, however, than that associated with the main factor differences among entries.

B. Root spread

Root spread at the pull 2 stage of 44 inbred lines of corn are listed in Table 7.

The mean square among entries for root spread is shown in Table 3 and is highly significant. Mean root spread measurements for individual lines ranged from 11.3 cm for A556 at Centerville to 21.7 cm for A634 at Brookings.

Table 6. Root dry weight (g) at the pull 2 stage of 44 inbred lines of corn.

Entry	Brookings 1974	Brookings 1975	Brookings location mean	Centerville 1975	Centerville 1975	Centerville location mean
A238	12.98	8.89	10.93	6.46	3.11	4.79
A344	6.73	5.77	6.25	5.28	4.64	4.96
A427	10.95	10.29	10.62	9.42	6.78	8.10
A556	20.89	14.41	17.65	14.45	8.53	11.49
A619	10.52	9.80	10.16	7.81	4.64	6.23
A624	10.78	14.04	12.41	12.16	8.21	10.18
A629	10.99	10.60	10.79	8.91	6.96	7.94
A632	17.37	12.32	14.85	10.49	8.92	9.70
A634	22.88	16.21	19.55	12.58	8.56	10.57
A648	19.40	18.14	18.77	14.14	10.39	12.26
A657	18.75	14.15	16.45	10.60	7.99	9.29
A659	19.68	17.12	18.40	13.59	14.33	13.96
A660	17.66	13.97	15.82	7.28	9.05	8.16
A70-12	14.60	9.53	12.06	9.06	7.47	8.27
C123	11.05	8.92	9.99	7.52	6.85	7.18
Ms214	14.88	10.55	12.71	10.47	9.97	10.22
NG72227	22.95	22.02	22.48	23.16	15.38	19.27
NG72232	17.21	14.24	15.72	12.98	11.95	12.46
NG72254	14.33	12.43	13.38	9.65	9.72	9.68
NG72303	21.32	20.93	21.12	17.16	15.07	16.12
NG72309	23.34	18.24	20.79	14.47	11.75	13.11
NG72312	28.61	25.13	26.87	23.44	16.02	19.73
NG72314	24.57	21.20	22.89	15.86	13.06	14.46
NG72317	25.30	22.36	23.83	18.30	14.21	16.25
NG72325	12.84	9.87	11.35	9.48	6.81	8.15
NG72335	26.44	19.54	22.99	19.50	15.36	17.43
NG72336	24.22	22.75	23.49	17.76	13.99	15.87
NG72353	19.56	18.51	19.03	17.61	13.84	15.73
NG72358	21.42	15.28	18.35	11.05	9.94	10.49
Oh545	14.12	13.51	13.81	8.71	6.56	7.64
SD1-1261	19.99	18.35	19.17	21.27	14.21	17.74
SD1-1412	15.52	10.07	12.79	9.82	8.29	9.05
SD1-1434	22.08	19.87	20.97	17.72	14.14	15.93
SD10	19.21	19.49	19.35	15.90	11.55	13.72
SD23	10.92	9.91	10.42	7.72	8.55	8.13
SD29	19.25	13.33	16.29	14.70	8.51	11.61
SD30	19.18	17.12	18.15	19.61	14.55	17.08
SDP2A	15.21	12.38	13.80	9.39	6.04	7.72
SDP309	14.67	13.08	13.87	12.12	8.76	10.44
SDP317W	11.61	10.24	10.92	9.39	6.87	8.13
W64A	14.26	12.45	13.35	11.58	8.49	10.03
W117	12.77	10.48	11.62	7.20	4.94	6.07
W182E	7.08	6.92	7.00	4.83	3.83	4.33
W202	28.13	20.01	24.07	17.34	12.67	15.01
mean	17.41	14.64	16.03	12.68	9.80	11.24

Table 7. Root spread (cm) at the pull 2 stage of 44 inbred lines of corn.

Entry	Brookings 1974	Brookings 1975	Brookings location mean	Centerville 1974	Centerville 1975	Centerville location mean
A238	20.2	17.4	18.8	18.0	10.0	14.0
A344	15.2	14.6	14.9	13.7	14.0	13.8
A427	15.2	17.9	16.5	17.0	13.7	15.4
A556	12.7	12.9	12.8	12.1	10.5	11.3
A619	15.8	17.5	16.6	16.7	11.8	14.3
A624	15.8	16.3	16.0	14.5	13.4	13.9
A629	16.1	14.8	15.4	15.5	14.1	14.8
A632	20.1	15.7	17.9	17.7	17.3	17.5
A634	22.8	20.7	21.7	20.8	16.1	18.5
A648	15.7	18.2	16.9	15.9	14.0	14.9
A657	15.6	14.2	14.9	16.3	13.8	15.1
A659	15.8	17.1	16.4	14.2	14.9	14.5
A660	15.0	14.5	14.7	12.4	13.5	12.9
A70-12	17.3	14.2	15.7	17.0	14.3	15.6
C123	14.4	13.9	14.2	12.9	11.6	12.2
Ms214	14.3	17.2	15.7	14.6	12.8	13.7
MG72227	20.6	20.3	20.5	21.8	18.1	20.0
NG72232	15.0	13.9	14.4	13.6	12.7	13.1
NG72254	14.3	15.7	15.0	13.8	12.9	13.4
NG72303	18.4	18.6	18.5	18.7	17.2	17.9
NG72309	17.3	18.2	17.8	17.6	15.4	16.5
NG72312	20.3	20.0	20.1	19.2	17.8	18.5
NG72314	21.4	21.1	21.3	19.2	16.5	17.8
NG72317	19.7	19.7	19.7	18.4	16.9	17.6
NG72325	13.2	13.2	13.2	11.4	12.0	11.7
NG72335	21.0	21.5	21.3	21.3	18.5	19.9
NG72336	20.4	21.4	20.9	22.3	17.5	19.9
NG72353	15.8	15.6	15.7	18.1	13.1	15.6
NG72358	14.7	14.5	14.6	13.1	12.5	12.8
Oh545	20.4	19.1	19.7	20.0	15.4	17.7
SD1-1261	18.1	18.2	18.2	20.5	16.8	18.7
SD1-1412	17.2	18.2	17.7	19.1	16.0	17.5
SD1-1434	18.1	19.3	18.7	20.7	17.7	19.2
SD10	17.0	20.3	18.6	16.9	16.1	16.5
SD23	15.6	15.4	15.5	14.1	14.7	14.4
SD29	17.3	18.8	18.1	17.7	15.4	16.5
SD30	21.0	20.7	20.8	23.1	19.6	21.4
SDP2A	19.6	20.1	19.9	18.6	15.2	16.9
SDP309	13.0	13.8	13.4	12.1	11.3	11.7
SDP317W	16.3	17.0	16.6	17.0	14.9	15.9
W64A	17.8	17.1	17.4	19.1	16.0	17.5
W117	17.6	16.3	16.9	17.3	14.4	15.8
W182E	14.0	15.3	14.6	13.5	12.3	12.9
W202	15.7	15.2	15.5	15.6	15.1	15.3
mean	17.1	17.2	17.1	16.9	14.7	15.8

Root spread measurements did not seem to be as severely affected by the drought as did root dry weights. The root spread of a number of lines seemed to be remarkably consistent between years and locations (Figure 6). The entries x locations and entries x years interactions were highly significant, however, the mean squares associated with these were much smaller than that associated with the main factor differences among entries. Figures 7-9 illustrate the consistency in root spread of individual lines between locations. Figures 10-12 show the range of root spread evident in this study.

Table 8 shows the correlation coefficients between locations and years for pull 2, root dry weight, and root spread. All correlations between pull 2 and root dry weight, regardless of the location or year, were positive and highly significant. This supports the findings of other reports suggesting that both root dry weight and root volume are highly correlated with pulling resistance. There seemed to be a trend in this study for a significant positive correlation between root spread and pulling resistance. Ortman, Peters and Fitzgerald (15) found no significant correlation between root spread and pulling resistance.

C. Root abundance ratings

Root abundance ratings of 44 inbred lines of corn at two locations in 1975 are shown in Table 9.

Table 8. Correlation coefficients between locations and years for pull 2, root dry weight and root spread at Brookings (B) and Centerville (C), 1974 and 1975.

	Pull 2 B74	Pull 2 C74	Root dry wt B74	Root dry wt C74	Root Spread B74	Root Spread C74	Pull 2 B75	Pull 2 C75	Root dry wt B75	Root dry wt C75	Root Spread B75	Root Spread C75
Pull 2 - B74		.60**	.67**	.59**	.37*	.34*	.63**	.51**	.61**	.58**	.38*	.38*
Pull 2 - C74			.63**	.75**	.40**	.49**	.74**	.60**	.66**	.62**	.52**	.49**
Root dry wt - B74				.82**	.46**	.39*	.67**	.51**	.82**	.71**	.44**	.48**
Root dry wt - C74					.40**	.52**	.72**	.59**	.82**	.74**	.52**	.57**
Root spread - B74						.75**	.33*	.14	.45**	.31*	.71**	.63**
Root spread - C74							.40**	.22	.44**	.34*	.74**	.68**
Pull 2 - B75								.67**	.77**	.72**	.47**	.51**
Pull 2 - C75									.55**	.69**	.24	.39*
Root dry wt - B75										.76**	.56**	.55**
Root dry wt - C75											.39*	.62**
Root spread - B75												.63**

*, ** Significant at the 1 and 5% levels of probability, respectively.

Table 9. Root abundance ratings of 44 inbred lines of corn at two locations in 1975.

	Root Abundance[a]					
	Total		Crown		Secondary	
Entry	Brookings[b]	Centerville[c]	Brookings[b]	Centerville[c]	Brookings[b]	Centerville[c]
A238	4.0	2.3	3.8	2.5	3.3	3.0
A344	2.8	3.3	2.8	3.5	1.0	1.3
A427	3.8	3.8	3.8	3.5	3.5	5.0
A556	4.5	3.8	4.3	3.5	4.0	5.5
A619	4.8	3.3	5.5	3.3	4.8	3.8
A624	5.0	4.0	5.5	4.3	1.5	4.0
A629	3.5	3.0	3.5	3.8	1.8	1.0
A632	5.0	3.5	5.0	3.8	3.0	3.5
A634	6.0	4.3	6.3	4.5	3.8	3.5
A648	5.3	4.5	4.8	4.8	5.3	6.0
A657	5.5	4.5	5.3	4.5	3.8	3.0
A659	4.8	4.8	4.3	4.5	4.0	5.0
A660	5.0	3.3	4.0	3.3	5.3	5.8
A70-12	4.8	3.5	4.0	3.0	5.0	5.8
C123	3.8	3.0	3.8	4.0	1.8	1.8
Ms214	4.5	4.0	4.3	3.3	3.8	7.0
NG72227	7.3	6.5	7.3	6.3	4.5	6.0
NG72232	4.8	5.3	5.3	5.0	2.0	6.0
NG72254	4.8	3.8	4.8	4.0	2.8	4.5
NG72303	5.3	5.3	5.5	5.0	3.3	7.0
NG72309	5.8	5.3	6.0	5.0	4.0	6.0
NG72312	7.3	6.0	7.3	5.3	5.0	6.5
NG72314	6.5	4.8	7.3	5.0	3.8	4.8
NG72317	6.0	5.3	6.0	5.0	4.0	6.0
NG72325	3.8	3.8	3.8	3.8	2.0	3.5
NG72335	6.8	6.0	7.0	6.5	3.8	5.3
NG72336	6.0	5.8	6.5	5.8	2.8	6.0
NG72353	6.3	4.3	6.3	3.3	5.5	6.3
NG72358	5.0	4.5	5.3	4.5	2.8	5.0
Oh545	5.0	3.0	4.8	2.8	4.0	4.8
SD1-1261	7.0	6.0	6.5	5.0	6.0	7.0
SD1-1412	5.5	3.8	5.8	4.0	3.0	2.3
SD1-1434	7.5	5.8	8.0	5.3	3.8	6.8
SD10	4.5	5.3	4.8	5.5	2.8	3.5
SD23	4.0	4.5	3.8	3.8	3.3	5.0
SD29	5.3	3.5	5.5	3.8	2.5	4.0
SD30	6.0	6.3	6.8	6.3	3.5	6.0
SDP2A	5.0	3.8	5.3	3.8	2.5	3.5
SDP309	4.8	4.3	4.3	3.8	5.0	6.0
SDP317W	5.0	4.3	4.0	4.3	5.3	5.8
W64A	5.0	5.0	4.8	5.0	1.5	2.8
W117	4.8	3.0	4.8	3.5	2.8	2.0
W182E	4.5	2.3	4.8	3.0	1.8	2.5
W202	7.0	5.3	6.5	4.8	7.3	8.0
mean	5.2	4.3	5.2	4.3	3.5	4.7

[a] 1 = low abundance, 10 = high abundance

[b] Ratings taken on roots from pull 3

[c] Ratings taken on roots from pull 2

The mean squares among entries for the three root abundance ratings in Table 10 are highly significant. Ratings for total root abundance ranged from 2.3 for A238 and W182E at Centerville to 7.5 for SD1-1434 at Brookings. Ratings for crown root abundance ranged from 2.5 for A238 at Centerville to 8.0 for SD1-1434 at Brookings. Ratings for secondary root abundance ranged from 1.0 for A344 and A629 to 8.0 for W202. Total and crown root abundance ratings between locations for individual lines were similar even though root development was severely inhibited due to drought at Centerville. Similarities exist because each location was read independently of the other with inbred W117 used at both locations as the low root mass standard by which all other entries were compared. The mean secondary root abundance rating was higher at Centerville than at Brookings. This may have been the result of drought conditions at Centerville which induced extensive secondary root proliferation.

Table 11 shows the correlation coefficients between locations for three root abundance ratings.

Correlations between total and crown root abundance at both locations were positive and highly significant. The high positive correlation suggests that either one or the other, but not both, be used in future investigations of this nature.

Table 10. Mean squares for three root abundance ratings from the analyses of variance at Brookings and Centerville, 1975.

Source of variation	Degrees of freedom	Total root abundance	Crown root abundance	Secondary root abundance
R[a]	3	0.70	0.96	5.24
E[b]	43	8.03**	8.17**	16.26**
R x E	129	0.42	0.46	0.99
L[c]	1	65.64**	75.48**	117.07**
R x L	3	0.86	0.89	1.65
E x L	43	1.27**	1.58**	2.98**
R x E x L	129	0.51	0.56	1.10
Total	351			

** Significant at the 1% level of probability.

[a] Replications (random)

[b] Entries (fixed)

[c] Location (fixed)

Table 11. Correlation coefficients between locations for three root ratings at Brookings (B) and Centerville (C), 1975.

	Total root abundance	Total root abundance	Crown root abundance	Crown root abundance	Secondary root abundance	Secondary root abundance
	B	C	B	C	B	C
Total root abundance - B		.54**	.85**	.72**	.51**	.64**
Total root abundance - C			.74**	.85**	.50**	.59**
Crown root abundance - B				.78**	.24	.31*
Crown root abundance - C					.26	.42**
Secondary root abundance - B						.68**

*, ** Significant at the 1 and 5% levels of probability, respectively.

The entries x locations mean squares for the three root abundance ratings as shown in Table 10 were highly significant. Those interaction mean squares, although significant, were much smaller than the entries mean square.

IV. Root Characteristics Associated with Pulling Resistance.

Abundance ratings for total, crown, and secondary roots were taken on pull 2 roots at Centerville and pull 3 roots at Brookings in 1975 to determine what root characteristics were associated with pulling resistance.

Table 12 shows the correlations between pulling resistance and various root measurements.

All the variables except secondary root abundance were positive and highly significant when correlated with pull 2. Root dry weight had the highest positive correlation with pull 2, while total and crown root abundance were next highest. Root spread also was highly significant and positively correlated with pulling resistance.

V. Loss in Pulling Resistance Between Pulls 2 and 3.

Another major objective pursued was to study the relationship of root rot to root-pulling resistance. Although root rot is usually not a part of the selection process for yield or rootworm tolerance, its neglect in inbred line development may lead to serious stalk and root lodging in the end-product. This problem is evident in a majority of the public

Table 12. Correlation coefficients between pull 2 and various root characteristics at Brookings and Centerville, 1975.

	Pull 2	Root dry wt.	Root spread	Total root abundance	Crown root abundance	Secondary root abundance
Pull 2		.77**	.58**	.62**	.62**	-.08
Root dry weight			.67**	.78**	.72**	.25
Root spread				.63**	.65**	.02
Total root abundance					.86**	.39*
Crown root abundance						.12

*, ** Significant at the 1 and 5% levels of probability, respectively.

lines released to date. The time of eight weeks after silking was chosen for a third pull at Brookings in 1975 to evaluate root deterioration because root and stalk rot usually appear near silking and become increasingly severe as maturity is approached. Table 13 shows the root rot ratings and loss in pulling resistance for 44 inbred lines of corn.

The mean squares among entries for pull 3, loss in pulling resistance, and root rot are shown in Table 14 and are highly significant. The loss in pulling resistance between pulls 2 and 3 ranged from 7.5 to 64.8 percent. If an entry had a loss of 20% or less it usually had a root rot rating of 5.0 or less. (A 1.0 rating denotes a root nearly free of rot). If an entry had a loss greater than 20%, it usually had a root rot rating of 5.3 or greater. For example, inbred A344 lost 64.2% of its pulling resistance between pulls 2 and 3, and had a rot rating of 8.8 which denoted a severely rotted root. Inbred A624 lost 17.9% and had a rot rating of 5.0 which denoted a moderately rotted root. Figures 13-15 compare root rot resistant with root rot susceptible lines of similar maturities.

Table 15 gives the correlation coefficients between variables listed in Table 13. The correlation between root rot and pull 3 was negative and highly significant. The correlation between pull 3 and days to silk was positive and highly significant.

Table 13. Loss in root-pulling resistance between pulls 2 and 3 of 44 inbred lines of corn at Brookings, 1975.

Entry	Pull 2[a] (kg)	Pull 3[a] (kg)	Loss Between Pulls (kg)	Loss Between Pulls (%)	Root Rot (1-10)[b]	Days to silk[c]
A238	154.0	77.8	76.2	49.2	8.5	35.3
A344	152.0	54.0	98.0	64.2	9.8	26.8
A427	149.5	61.0	88.5	58.9	7.5	38.8
A556	155.0	118.0	37.0	23.7	5.0	30.5
A619	164.5	115.3	49.2	27.7	6.3	36.5
A624	201.8	167.0	34.8	17.9	5.0	32.0
A629	153.0	97.5	55.5	36.3	7.5	32.5
A632	138.5	120.3	18.2	12.9	4.8	34.3
A634	192.3	157.5	34.8	17.7	4.8	34.5
A648	171.5	98.8	72.7	42.7	7.8	34.3
A657	205.5	156.0	49.5	24.4	5.3	35.0
A659	239.5	195.8	43.7	17.5	5.0	39.8
A660	154.0	109.8	44.2	28.7	5.8	36.3
A70-12	136.3	103.5	32.8	24.2	6.8	43.8
C123	166.3	110.0	56.3	32.8	4.3	34.8
MS214	199.8	143.5	56.3	28.6	6.5	35.3
NG72227	265.8	178.5	87.3	32.8	5.3	36.3
NG72232	225.5	153.0	72.5	32.1	5.8	34.0
NG72254	194.8	126.3	68.5	35.1	7.0	32.3
NG72303	225.5	81.0	144.5	64.0	7.8	36.0
NG72309	197.8	145.0	52.8	26.6	5.0	38.3
NG72312	268.8	216.5	52.3	19.4	4.5	39.3
NG72314	243.3	181.0	62.3	25.6	5.5	41.8
NG72317	250.0	170.8	79.2	31.6	6.5	38.8
NG72325	184.3	153.0	31.3	16.9	6.3	37.3
NG72335	274.0	183.5	90.5	33.0	5.0	37.0
NG72336	282.8	204.0	78.8	27.8	7.3	37.5
NG72353	198.0	136.8	61.2	30.9	4.5	37.8
NG72358	204.8	146.5	58.3	28.4	5.0	34.0
Oh545	155.8	119.5	36.3	23.0	5.5	38.0
SD1-1261	234.3	214.8	19.5	7.5	4.3	37.3
SD1-1412	173.8	148.0	25.8	14.2	3.0	38.0
SD1-1434	259.8	224.0	35.8	13.1	3.3	44.8
SD10	217.3	75.3	142.0	64.8	7.8	32.0
SD23	157.3	120.3	37.0	23.1	7.0	35.3
SD29	162.8	121.3	41.5	25.6	6.5	33.8
SD30	230.8	125.0	105.8	44.9	6.0	34.5
SDP2A	165.8	103.0	62.8	37.9	6.8	31.3
SDP309	193.8	177.5	16.3	8.3	3.0	39.8
SDP317W	199.5	130.5	69.0	34.9	6.5	36.3
W64A	183.0	87.0	96.0	52.3	6.8	32.3
W117	120.5	107.5	13.0	10.6	6.3	31.5
W182E	153.0	104.0	49.0	31.8	7.3	30.0
W202	263.0	213.8	49.2	18.4	4.8	37.3
mean	195.9	137.1	58.8	30.1	5.9	35.8

[a] August 25 and October 5 for pulls 2 and 3, respectively.

[b] 1 = resistant, 10 = susceptible

[c] Days after June 30 to 50% silk - 2 year mean at Brookings only.

Table 14. Means squares of four variables from the analyses of variance at Brookings, 1975.

Source of variation	Degrees of freedom	Pull 3	Root Rot	Loss (kg) between pulls 2 and 3	Loss (%) between pulls 2 and 3
R[a]	3	883.01	2.11	4752.93**	851.64**
E[b]	43	7579.88**	7.77**	3516.52**	847.71**
R x E	129	532.83	0.99	497.23	106.48
Total	175				

** Significant at the 1% level of probability.

a Replications (random)

b Entries (fixed)

Table 15. Correlation coefficients between pull 3 and five other root characteristics at Brookings, 1975.

	Pull 3	Root rot	Total root abundance	Crown root abundance	Secondary root abundance	Days to silk
Pull 3		-.55**	.67**	.62**	.36*	.48**
Root rot			-.41**	-.33*	-.34*	-.36*
Total root abundance				.85**	.51**	.43**
Crown root abundance					.24	.36*
Secondary root abundance						.43**

*, ** Significant at the 1 and 5% levels of probability, respectively.

There also seemed to be a trend for a significant, negative correlation between root rot and the three root abundance ratings.

The mean square among entries for percent loss in pulling resistance between pulls 2 and 3 as shown in Table 14 was highly significant. Root rot was suspected as being the main cause of these differences. The correlation between root rot and percent loss in pulling resistance was r = +0.61 which was highly significant.

Table 16 shows the means for all variables of 44 inbred lines of corn summarized over locations and years.

Those lines with high pulling resistance at pull 1 may offer potential tolerance to rootworm feeding. Inbreds NG72227, NG72232, NG72303, NG72312, NG72317, NG72336, SD1-1261, SD1-1434, SD10, SD30, and W202 were among those lines with high pulling resistance at the pre-tassel stage. Several of these lines, such as NG72312 and NG72336 continued extensive root development between pulls 1 and 2. This is apparent when one compares pulling resistance at pulls 1 and 2 for each of the lines. Inbreds such as NG72303, NG72353, NG72358 and SD10 apparently did not continue to develop an extensive root system after pull 1. Inbreds A344, A427, A619, W117, and W182E that were quite low in pulling resistance might be considered to have less potential for rootworm tolerance than those listed above.

Table 16. Means of all variables of 44 inbred lines of corn summarized over years and locations.

Entry	Pull 1[a] (kg)	Pull 2[a] (kg)	Pull 3c (kg)	Root dry weight (g)	Root spread[a] (cm)	Root rot[c]	Total root abun.[b] (1-10)	Crown root abun.[b] (1-10)	Secondary root abun.[b] (1-10)	Days to silk[d]
A238	101.9	123.3	77.8	7.86	16.4	8.5	3.1	3.2	3.1	35.3
A344	102.1	112.2	54.0	5.61	14.4	8.8	3.0	3.1	1.1	26.8
A427	97.2	118.9	61.0	9.36	16.0	7.5	3.8	3.6	4.3	38.8
A556	110.7	127.3	118.0	14.57	12.1	5.0	4.1	3.9	4.8	30.5
A619	97.4	128.1	115.3	8.19	15.5	6.3	4.0	4.1	4.3	36.5
A624	107.6	147.5	167.0	11.30	15.0	5.0	4.5	4.0	2.8	32.0
A629	97.8	115.8	97.5	9.37	15.1	7.5	3.3	3.6	1.4	32.5
A632	104.6	117.0	120.3	12.28	17.7	4.8	4.3	4.4	3.3	34.3
A634	128.7	158.4	157.5	15.06	20.1	4.8	5.1	5.1	3.6	34.5
A648	120.5	136.2	98.8	15.52	16.0	7.8	4.9	4.5	5.6	34.3
A657	128.3	157.2	156.0	12.87	15.0	5.3	5.0	4.9	3.4	35.0
A659	111.1	171.7	195.8	16.18	15.5	5.0	4.8	4.1	4.5	39.8
A660	87.8	110.2	109.8	11.99	13.9	5.8	4.1	3.6	5.5	36.3
A70-12	80.7	113.6	103.5	10.17	15.7	6.8	4.1	3.5	5.4	43.8
C123	107.0	136.1	110.0	8.59	13.2	4.3	3.4	3.9	1.8	34.8
MS214	103.1	154.9	143.5	11.47	14.7	6.5	4.3	3.8	5.4	35.3
NG72227	159.8	195.0	178.5	20.88	20.2	5.3	6.9	6.8	5.3	36.3
NG72232	152.2	174.0	153.0	14.10	13.8	5.8	5.0	5.1	4.0	34.0
NG72254	129.4	150.9	126.3	11.53	14.2	7.0	4.3	4.1	3.6	32.3
NG72303	151.6	161.3	81.0	18.62	18.2	7.8	5.3	5.3	5.1	36.0
NG72309	125.7	153.1	145.0	16.95	17.1	5.0	5.5	5.5	5.0	38.3
NG72312	150.0	202.6	216.5	23.30	19.3	4.5	6.6	6.3	5.8	39.3
NG72314	142.1	185.1	181.0	18.67	19.6	5.5	5.6	6.1	4.3	41.8
NG72317	148.3	195.4	170.8	20.04	18.7	6.5	5.6	5.5	5.0	38.8
NG72325	120.0	138.6	153.0	9.75	12.5	6.3	3.8	3.6	2.8	37.3
NG72335	138.7	209.7	183.5	20.21	20.6	5.0	6.4	6.8	4.5	37.0
NG72336	147.9	206.6	204.0	19.68	20.4	7.3	5.9	6.1	4.4	37.5
NG72353	124.8	149.7	136.8	17.38	15.7	4.5	5.3	4.8	5.9	37.8
NG72358	139.4	159.7	146.5	14.42	13.7	5.0	4.8	4.9	3.9	34.0
Oh545	96.7	115.8	119.5	10.73	18.7	5.5	4.0	3.8	4.4	38.0
SD1-1261	152.8	184.9	214.8	18.46	18.4	4.3	6.5	5.8	6.5	37.3
SD1-1412	124.4	145.7	148.0	10.93	17.6	3.0	4.6	4.9	2.6	38.0
SD1-1434	148.8	190.5	224.0	18.45	19.0	3.3	6.6	6.6	5.3	44.8
SD10	146.2	157.2	75.3	16.54	17.6	7.8	4.9	5.1	3.1	32.0
SD23	101.2	119.8	120.3	9.28	15.0	7.0	4.2	3.8	4.1	35.3
SD29	112.2	123.4	121.3	13.95	17.3	6.5	4.4	4.6	3.3	33.8
SD30	149.5	179.9	125.0	17.62	21.1	6.0	6.1	6.5	4.8	34.5
SDP2A	103.4	122.7	103.0	10.76	18.4	6.8	4.3	4.5	3.0	31.3
SDP309	110.1	148.0	177.5	12.16	12.6	3.0	4.5	4.0	5.5	39.8
SDP317W	115.7	143.4	130.5	9.53	16.3	6.5	4.6	4.1	5.5	36.3
W64A	114.2	143.6	87.0	11.70	17.5	6.8	5.0	4.9	2.1	32.3
W117	84.0	98.3	107.5	8.85	16.4	6.3	3.9	4.1	2.4	31.5
W182E	80.7	101.5	104.0	5.67	13.8	7.3	3.4	3.9	2.1	30.0
W202	142.1	193.0	213.8	19.54	15.4	4.8	6.1	5.6	7.6	37.3
mean	120.7	149.6	137.1	13.63	16.5	5.9	4.8	4.7	4.1	35.8

[a] Brookings and Centerville, 1974 and 1975

[b] Brookings and Centerville, 1975

[c] Brookings, 1975

[d] Brookings, 1974 and 1975

Only a few of the inbreds retained their pulling resistance through maturity, and this usually corresponded to a healthy root system. Inbreds A556, A624, A632, A634, A659, NG72312, SD1-1261, SDP309, and W202 were examples of this type.

Inbred W202 was a rather unusual line in that it produced a very extensive secondary root system as can be noted by the secondary root abundance rating in Table 16.

CONCLUSIONS

An estimated 88% of the upper root system was recovered by pulling as compared to digging. This estimate will probably vary among environments, but under normal conditions it seems attainable. Whether pulling or digging equipment is used depends on one's objectives, however, a mechanical method of digging roots such as described by Nagel (13), rather than pulling, will probably yield a more symmetrical and complete upper root system.

The highly significant mean squares among entries for root-pulling resistance supports the findings of other researchers when studying root-pulling resistance. It should be noted that to insure maximum differences among genotypes for possible rootworm tolerance selection, one should pull plants at least 1-2 weeks before tasseling. This would allow sufficient time, in the case of S_1 lines, for selection and recombination in the same generation as part of a recurrent selection program leading to the development of corn rootworm tolerant germplasm. Early, extensive root development as measured by pulling resistance near tasseling may not, in itself, lead to rootworm tolerance (16). It may, however, be one of the most important traits involved in rootworm tolerance, and therefore should be pursued extensively (11, 16).

Severe drought at Centerville in both years undoubtedly contributed to the significant main effects and first order interactions as apparent in Table 3 for pulls 1 and 2, root dry weight, and root spread. The variation due to the main factor of differences among entries was much greater than any of the interactions. The highly significant, first order interactions indicate that some of the lines did not perform similarly between locations or years. All correlation coefficients, however, between locations and years for pulls 1 and 2 were positive and highly significant. This indicates that effective selection for high root-pulling resistance is possible, but that significant interactions may occur under certain conditions. Further root studies are needed to establish the extent of these interactions under more normal conditions.

The entries x locations mean squares for all root abundance ratings were highly significant. These interactions were expected as drought conditions seriously affected plant growth and root development at Centerville in both years. All correlations between locations, however, for root ratings (except secondary root abundance), root spread, and root dry weight were highly significant. Root abundance ratings seemed to present a reasonably accurate estimation of root mass as the correlations between total root abundance, ($r = +0.78$), and crown root abundance, ($r = +0.72$), with root dry weight were highly significant. The positive and highly significant correlation, (r = +0.86), between total and crown root abundance over both locations suggests that either one or the other, but not necessarily both, be used in future investigations of this nature.

Root dry weight had the highest positive correlation with root-pulling resistance at the milk stage, while crown root abundance was next highest. The correlation between root spread and pull 2 was positive and highly significant. The specific time of pull 2 in regard to plant growth may be one of the critical factors in determining such a significant relationship. If the root system is completely developed at the time of pull 2, then a significant correlation may result, whereas it may not if pull 2 were to come at a time of incomplete root development. Root spread was not significantly correlated, (r = +0.22), with days to silk which disagrees with the positive significant correlation found by Weiking (23) in his root study.

The mean square for percent loss in pulling resistance between pulls 2 and 3 was highly significant. The correlation, (r = -0.55), between root rot severity and pull 3 was highly significant. The correlation, (r = +0.48), between pull 3 and days to silk also was highly significant. The correlation, (r = -0.36), between root rot severity and days to silk was significant. Several reasons may exist for this significant, negative correlation. Most of the lines chosen as entries in this study were developed in breeding programs where very little, if any, selection pressure for root rot resistance was practiced. The chance was slight, therefore, of having early silking, root rot resistant lines in this study. In addition, the set of lines selected were to be of similar maturity, however, silking date differences did exist. One would expect less root rot to be present in those later silking lines simply because the roots probably were developed later in the growing season and were exposed to rot-causing organisms for a shorter period of time than the roots of early silking lines. The selection pressure used for the past 15 years in the South Dakota State University corn project has been for root rot resistance in early maturing, corn germplasm. Several early maturing lines with good root rot resistance have been developed through such a selection procedure. It seems logical, therefore, to suggest that the significant, negative correlation between root rot severity and days to silk may be probable but such that it could be overcome by breeding.

There was a definite trend, as shown in Table 14, for a significant, negative correlation between root rot severity and root abundance. This suggests that lines with low root masses generally have more root rot. Holbert and Koehler (6) and Semeniuk (18) also found that root rot susceptible lines seemed to have root volume deficiencies.

By taking the time to make an additional plant pull or a visual observation of the roots at or near maturity, plant breeders should be able to refine any previous selections made, and at the same time reassure themselves that root and stalk rot susceptibility would not be a limiting factor in the development of superior inbred lines of corn.

The results of this study indicate that there are large differences in root development among inbred lines of corn. Root-pulling resistance seems to be an accurate method for measuring these differences. It is apparent that, by selecting those genotypes with high pulling resistance at either pull 1 or 2, one could develop lines or improve S_0 populations that would possess profuse root systems. This information is likely to be of value to corn breeders whose objectives are to develop rootworm tolerant germplasm. Further investigation is necessary, however, to determine what effect profuse root systems have in drought tolerance and high plant population response. Sullivan and Blum (21) speculated,

> "Under moderate drought or short, severe drought, the profuse root system may continue to provide for the shoot, but in a protracted, severe drought, it may exhaust the available moisture and succumb to the drought. The desirability of root size and development may depend on the climatic region and expected frequency and duration of the drought. If the plant has a greater heat and

dessication tolerance, a smaller root system may be more desirable during a long drought than a more profuse root system."

Burström (1) suggests that there is no voluntary partnership between root and top growth, but a case of "hard competition" for the necessary compounds. Tryptophane, which roots may not be able to synthesize, is one of those compounds that is of special interest not only for protein synthesis, but also as a mother substance of the indole acetic auxins which are directly attributed to flower development. Thus, in times of stress extensive root proliferation may be consuming a large share of the tryptophane, as well as other essential compounds, making them less available for ear development.

Most of the relationships suggested above present valid questions that need to be answered if plant breeders are to increase production of agricultural crops in general. One can compare the root system of a corn plant to the foundation of a house; without reasonably strong foundations the house and the corn plant may collapse. Plant breeders need to expend more effort toward studying the root systems of corn as well as other crops to determine what root characteristics are important in crop production.

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Table A1. Line numbers and parentages of the 44 inbred lines of corn used in the 1974-75 root study.

Inbred	Parentage
A238	(A347 x A73)
A344	U.S. 153 (Iowa)
A427	(A405 x CC36)
A556	(B164 x 886)A237
A619	(A171 x Ch43)Oh43
A624	(A629 x ND203)A295
A629	(CV3 x WF9)WF9
A632	(Mt42 x B14)$B14_3$
A634	(Mt42 x B14)B14 x $B14_2$
A648	Minn. Syn 3
A654	Iowa Stiff Stalk Synthetic
A659	Minn. Syn 3
A660	Minn. Syn 3
A70-12	unknown
C123	C102 x C103
MS214	Iowa Stiff Stalk Synthetic
NG72227	(B57 x SD10)
NG72232	(SD10 x B69)
NG72254	(MO12 x A251)
NG72303	(SD10 x B69)
NG72309	(SD10 x B69)
NG72312	(B57 x SD10)
NG72314	(B57 x SD10)
NG72317	(B57 x SD10)
NG72325	(P246 x MY8)
NG72335	(Zap 15 x B57)
NG72336	(Zap 15 x B57)
NG72353	(B69 x A251)
NG72358	(B69 x MS107)
Oh545	(M14 x CI187-2)$Oh45_2$ x (Oh45 cms_4 x Cash O.P) x (M14 x CI187-2) x $Oh45_2$) x Oh45A
SD1-1261	Poelstra O.P.
SD1-1412	Poelstra O.P.
SD1-1434	Poelstra O.P.
SD10	(Oh56A x B8)
SD23	(Oh43 x Ellis O.P.)
SD29	(SD14 x S.C. 28) (Released in 1976)
SD30	Pioneer 3558 (Released in 1976)
SDP2A	Fulton's Yellow Dent
SDP309	(K63 x SDP236)
SDP317W	(K63 x SDP236)
W64A	(WF9 x 187-2)
W117	(643 x O.P. Minn. 13)
W182E	(WD x W22)
W202	Corn Borer Synthetic (Iowa)

Figure 1. Root-pulling apparatus and root spread measuring technique used in this study.

A. Cast-iron clamp which hooks on ring attached to scale of root-pulling apparatus.

B. Complete root-pulling apparatus

C. Root spread measurement taken at the widest portion of the upper root system.

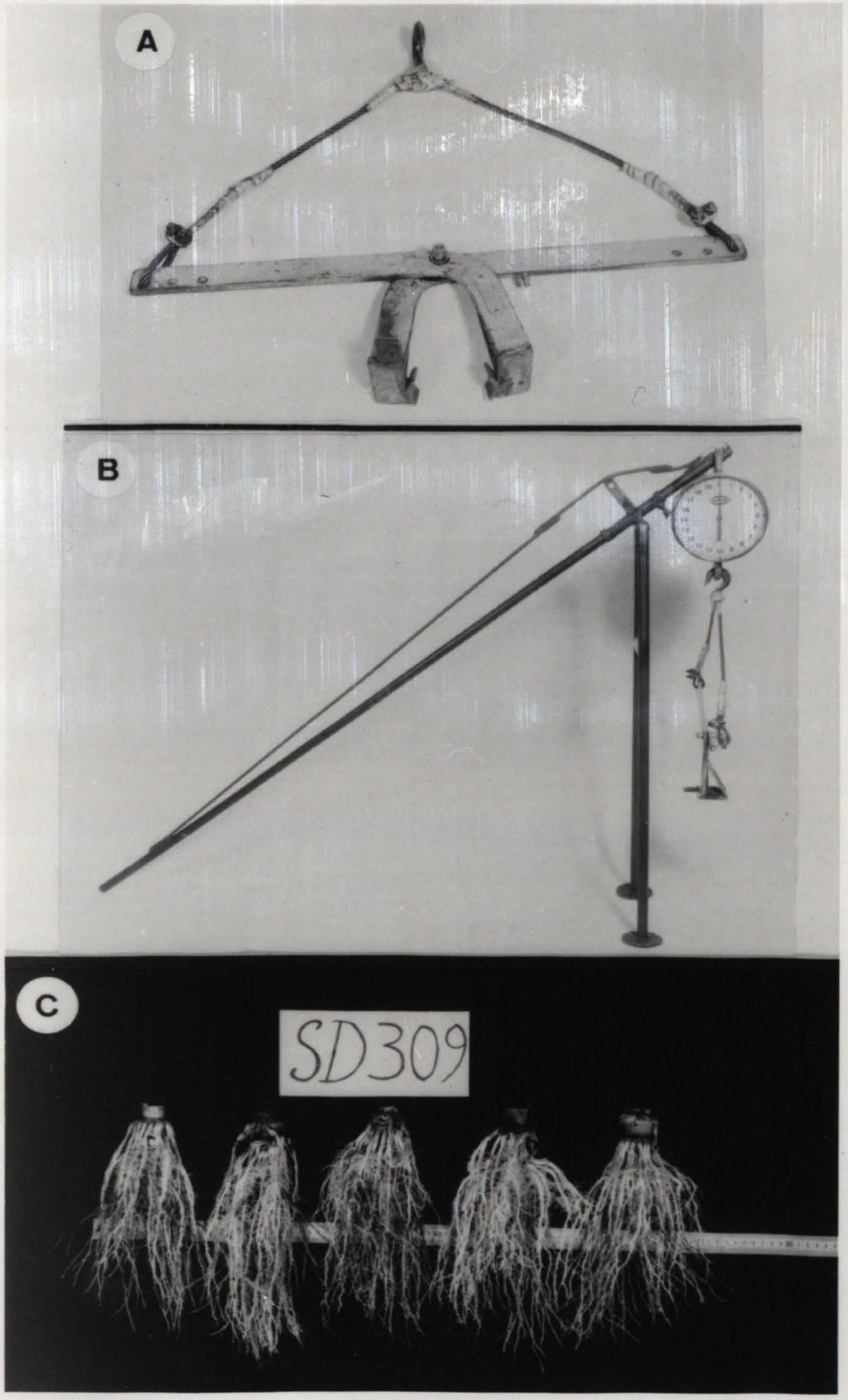

A
B
C
SD309

Figure 2. Root development comparisons at pull 1 among various inbred lines grown at Brookings, 1975.

A. SD10 (E) (top) vs. W117 (E) (bottom)

B. NG72227 (L) (top) vs. A659 (L) (bottom)

C. SD10 (E) (top) vs. NG72227 (L) (bottom)

(E = early silking, L = late silking)

Silking dates were used in this study as a measure of maturity.

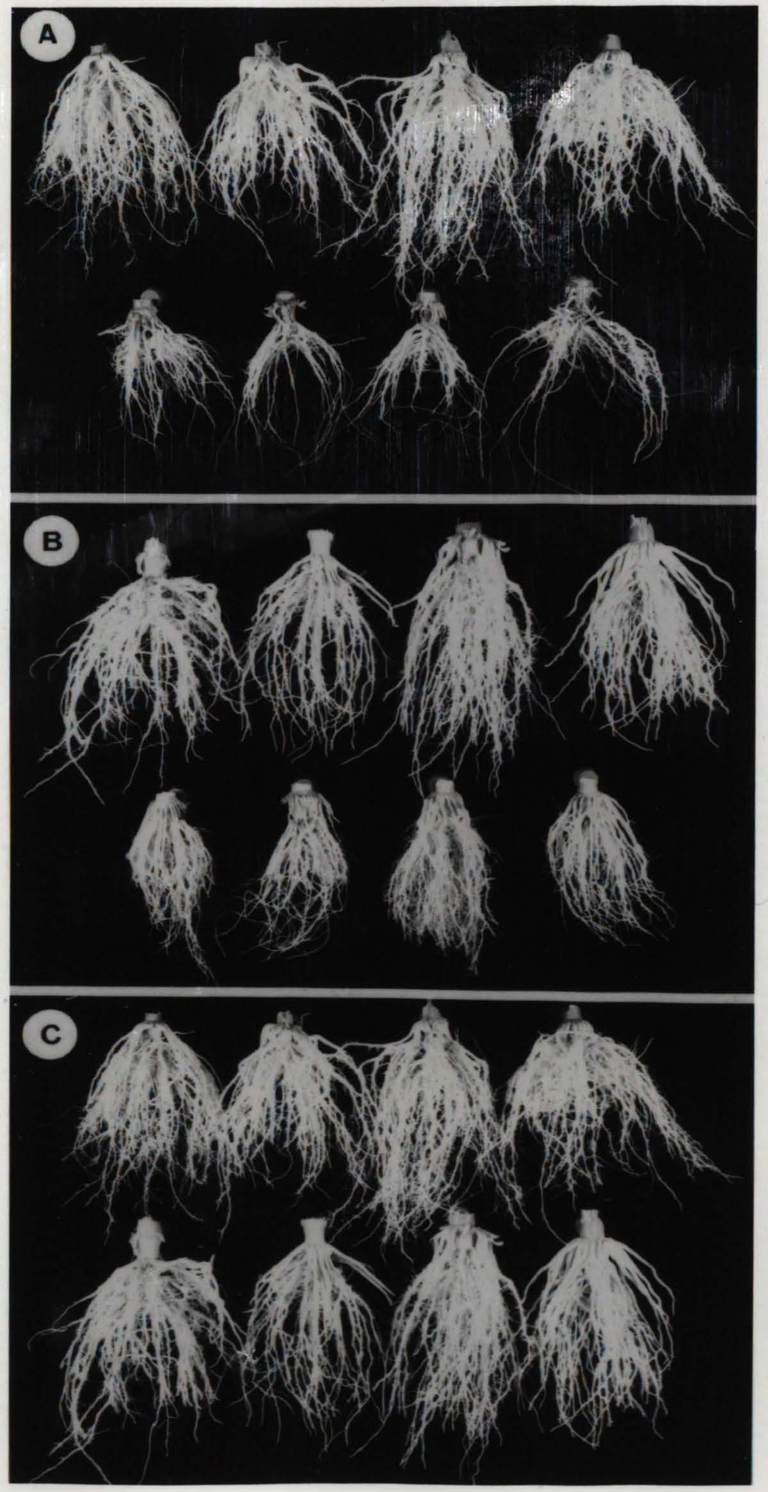

A
B
C

Figure 3. Root development between pulls 1 (top) and 2 (bottom) of two inbred lines grown at Brookings, 1975.

A. W117 (E)

B. SDP309 (L)

(E = early silking, L = late silking)

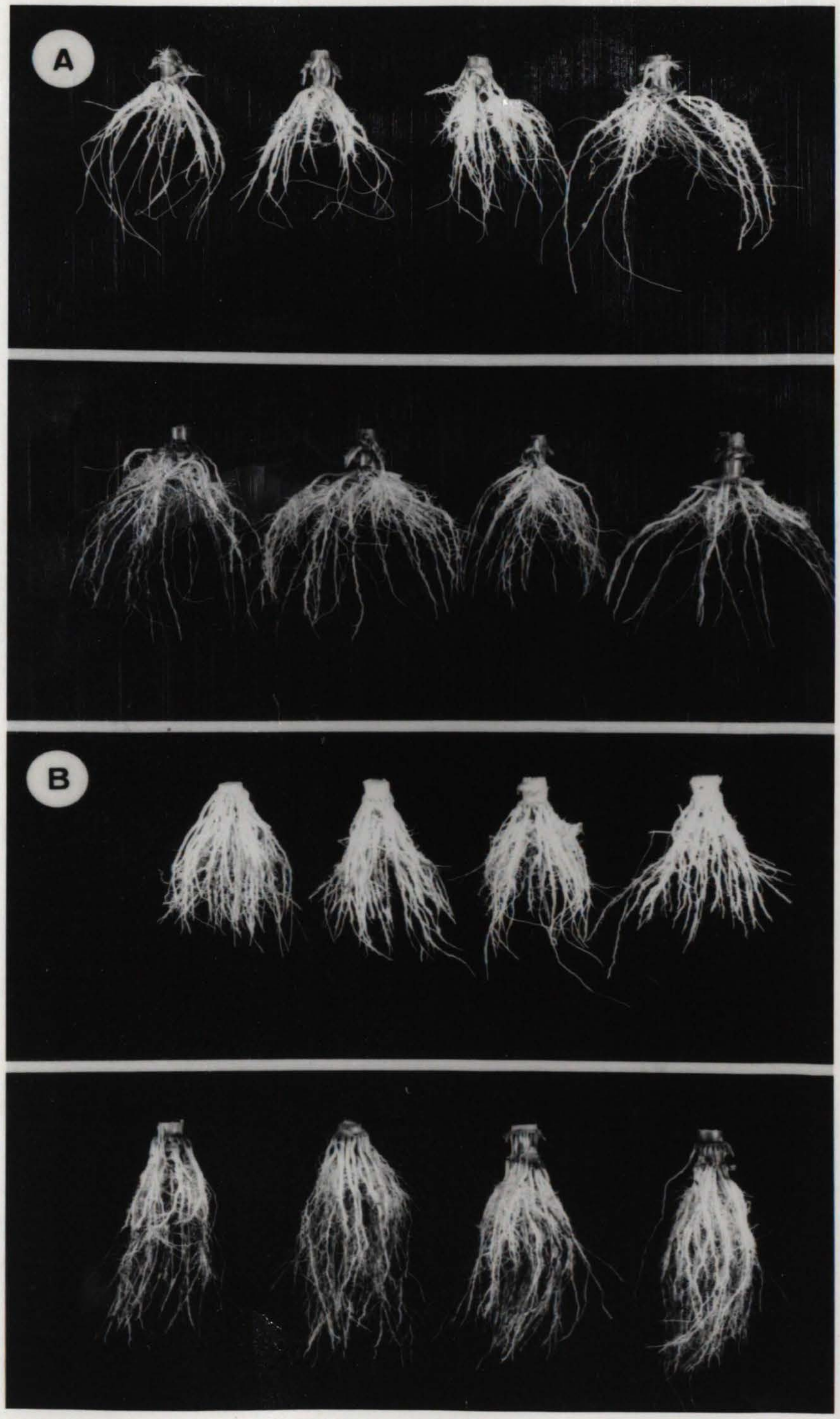

A
B

Figure 4. Root development between pulls 1 (top) and 2 (bottom) of two inbred lines grown at Brookings, 1975.

A. SD10 (E)

B. NG72227 (L)

(E = early silking, L = late silking)

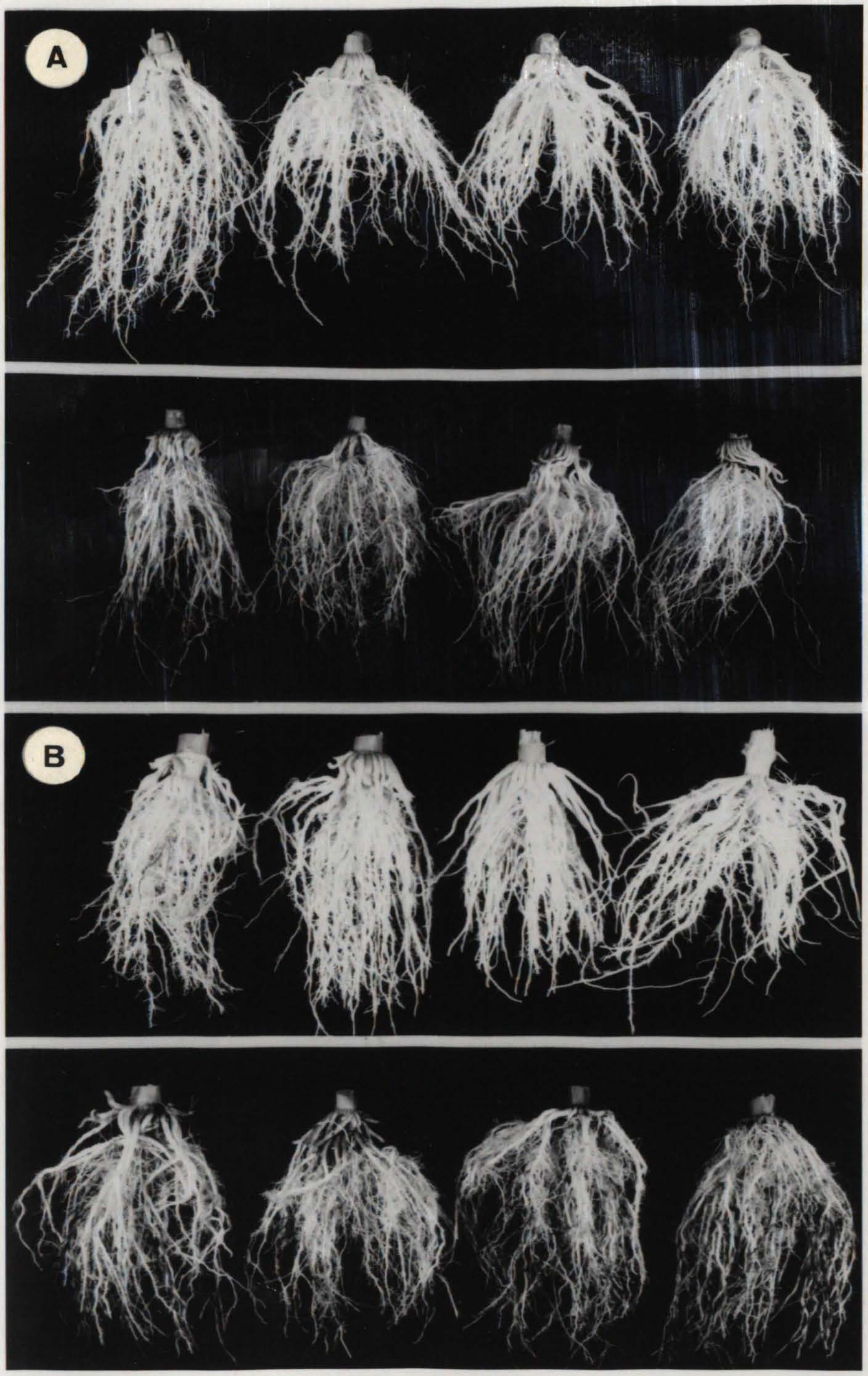

A
B

Figure 5. Root development between pulls 1 (top) and 2 (bottom) of two inbred lines grown at Brookings, 1975.

A. A659 (L)

B. SD1-1261 (L)

(L = late silking)

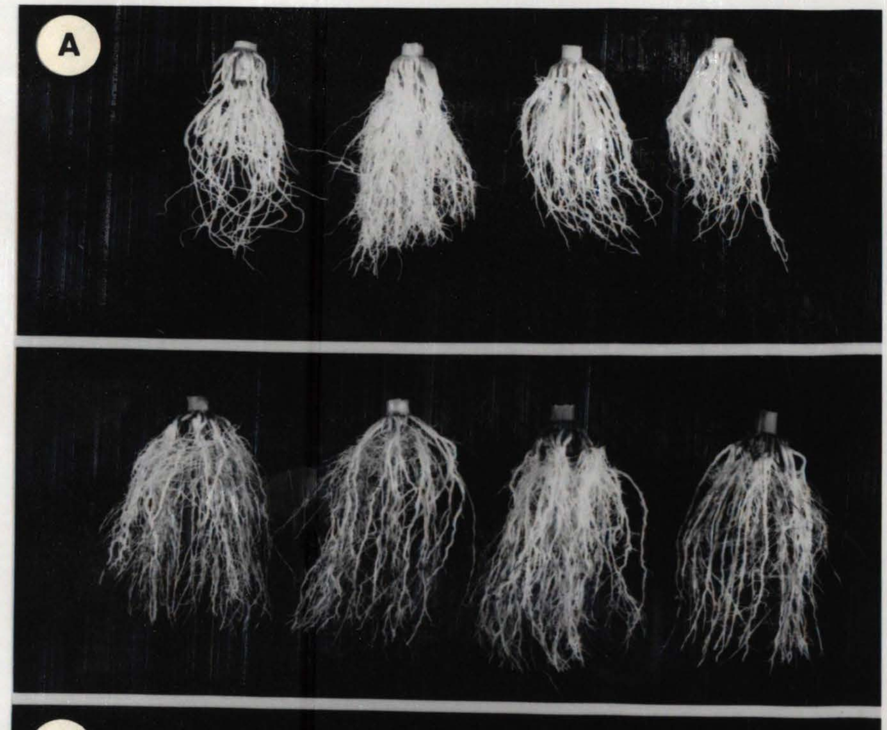

A
B

Figure 6. Root spread consistency of two inbred lines within and between locations in 1975.

SDP309 (left half by replications 1-4) vs. W64A (right half by replications 1-4) at Brookings, 1975.

(Each root is a typical representative of the line for that specific replication.)

SDP309 (left half by replications 1-4) vs. W64A (right half by replications 1-4) at Centerville, 1975.

(Each root is a typical representative of the line for that specific replication.)

SDP309 (left half) vs. W64A (right half) at Brookings (A) and Centerville (B), 1975.

(Each root is a typical representative of the line for that specific location.)

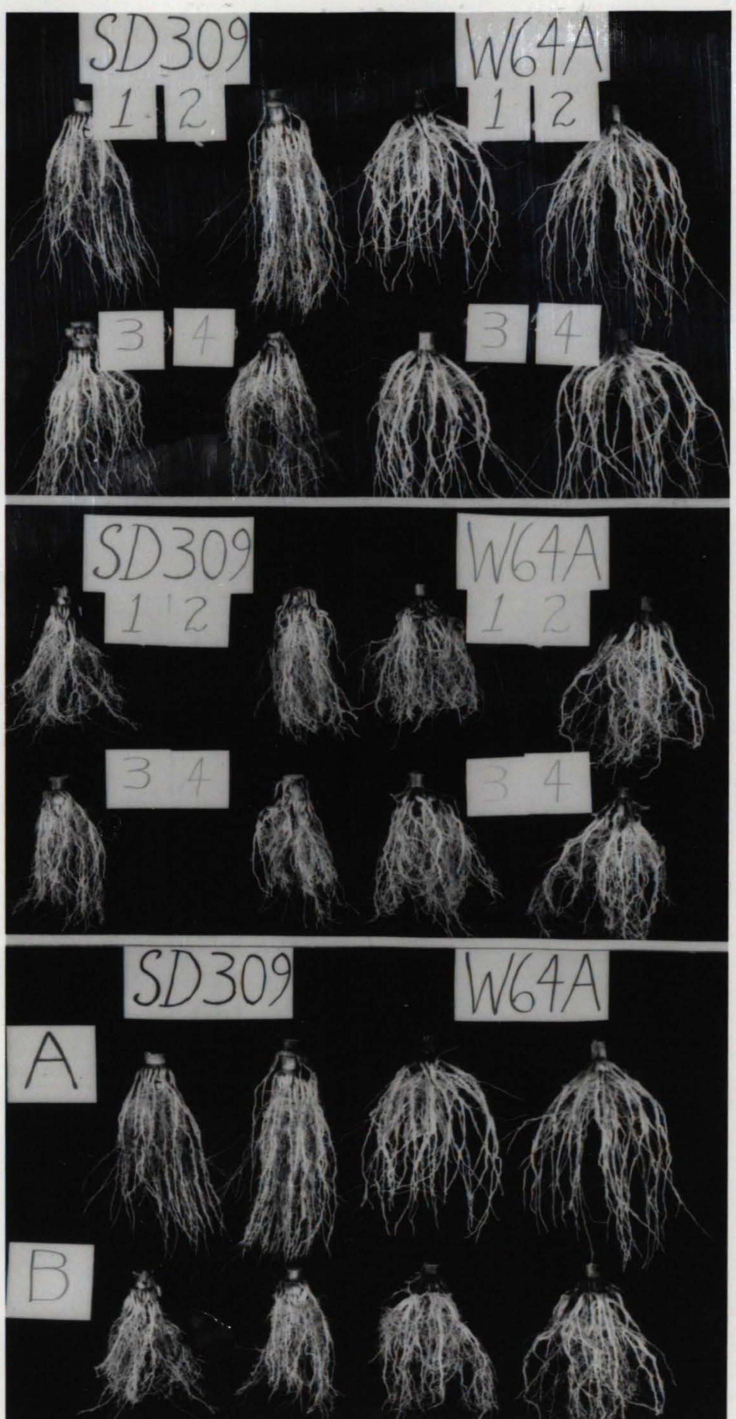
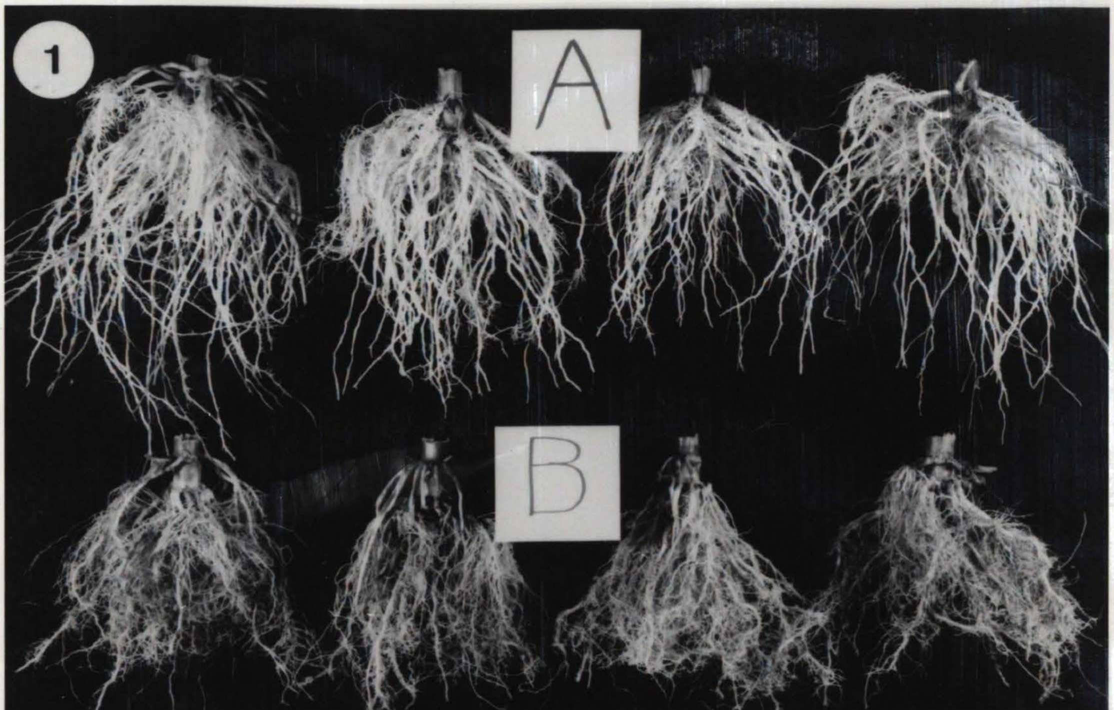

SD309
W64A
1
2
1
2
3
4
3
4
SD309
W64A
1
2
1
2
3
4
3
4
SD309
W64A
A
B

Figure 7. Second pull roots of two inbred lines grown at Brookings (A) and Centerville (B), 1975.

1. SD30

2. SD1-1261


1
A
B

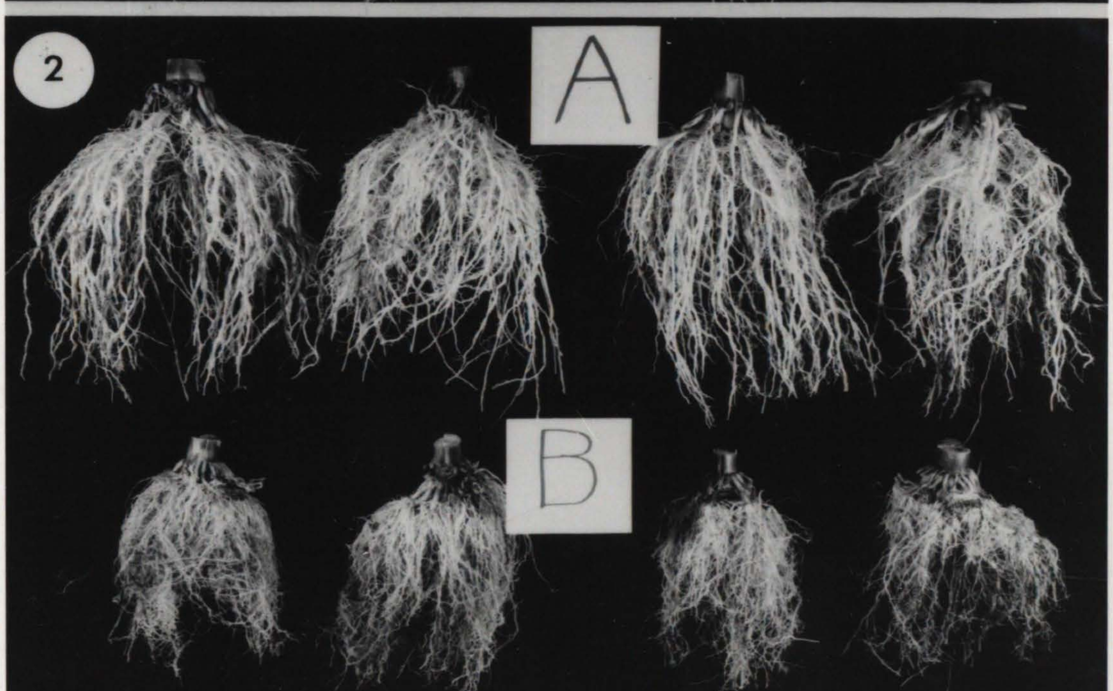

2
A
B

Figure 8. Second pull roots of two inbred lines grown at Brookings (A) and Centerville (B), 1975.

1. W64A

2. NG72227

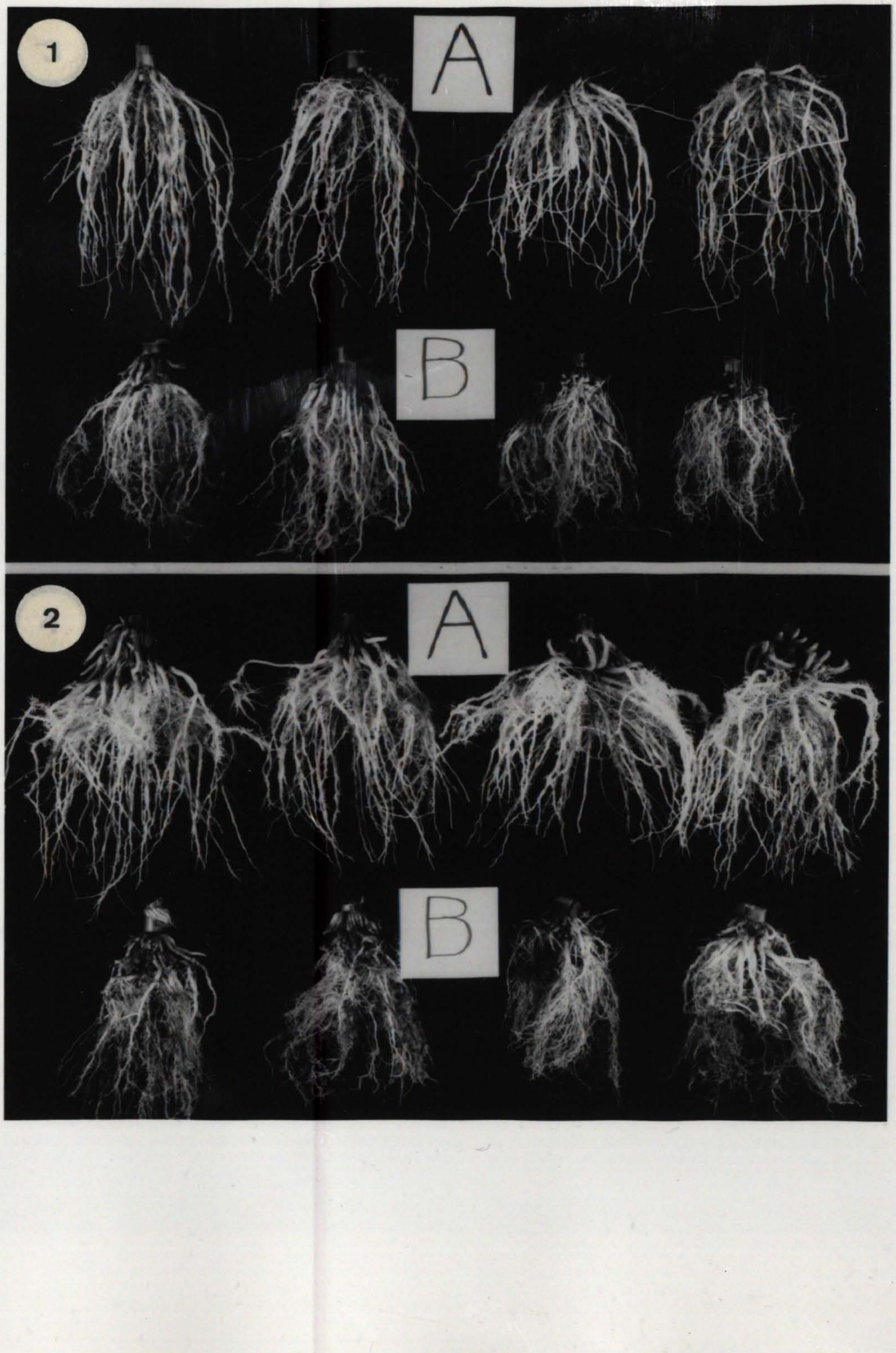
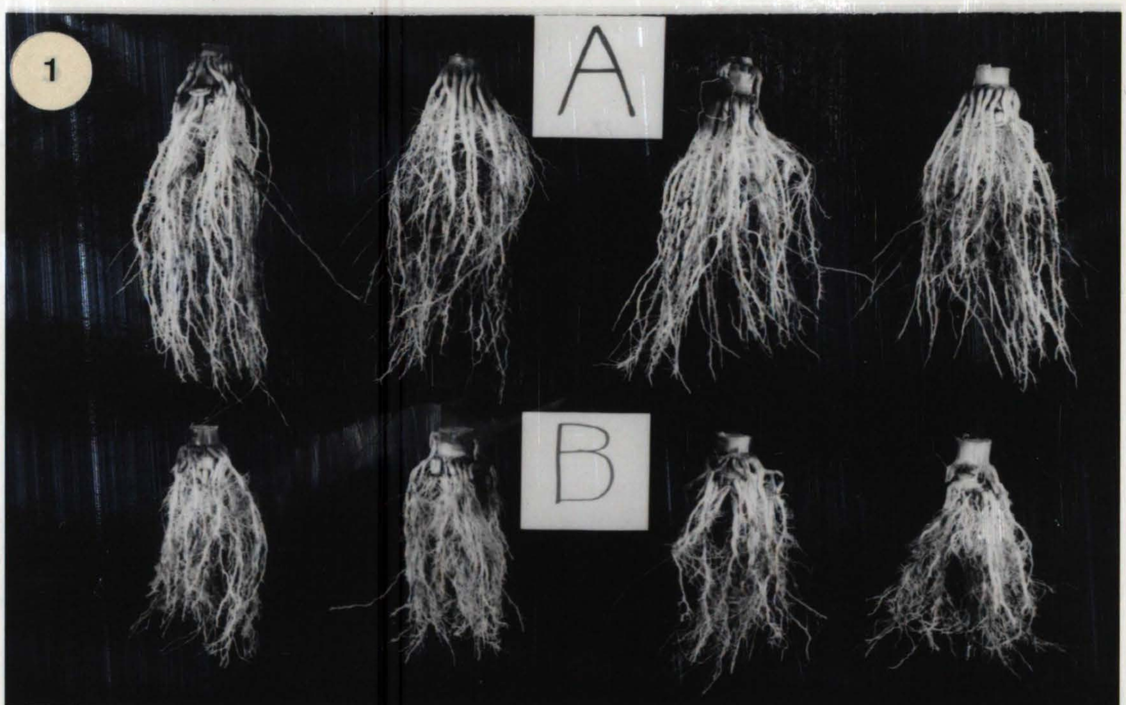

1
A
B
2
A
B

Figure 9. Second pull roots of two inbred lines grown at Brookings (A) and Centerville (B), 1975.

1. SDP309

2. W117


1
A
B

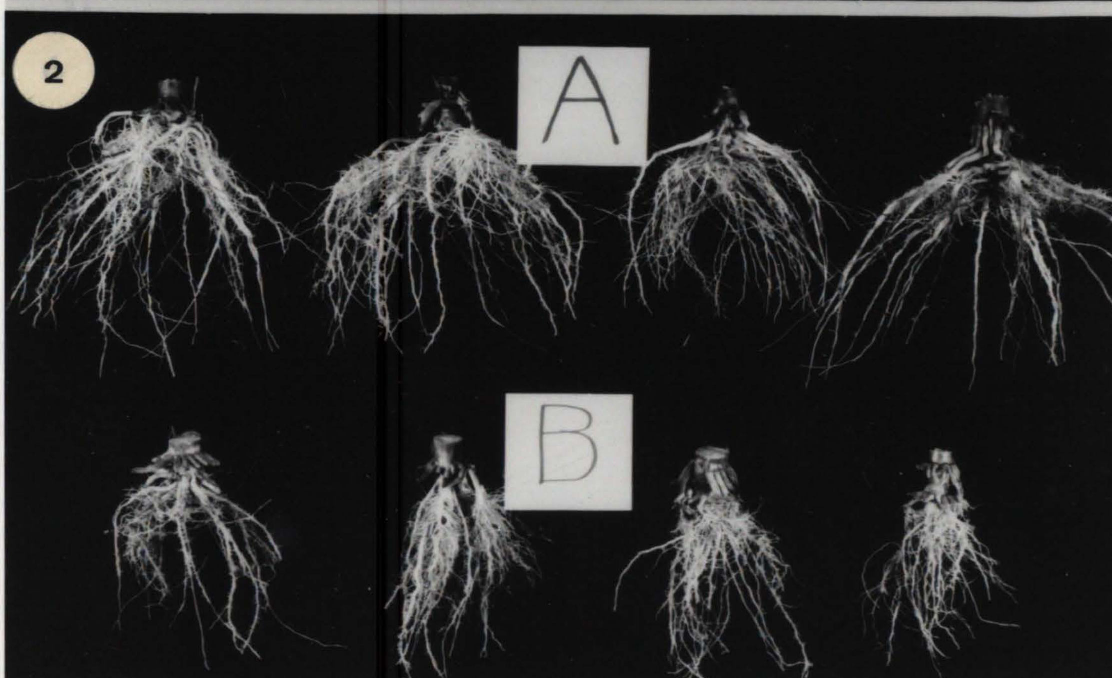

2
A
B

Figure 10. Range of root spread at pull 2 among various inbred lines grown at Brookings, 1975.

A. SD10 (top) vs. W117 (bottom)

B. SD10 (top) vs. NG72227 (bottom)

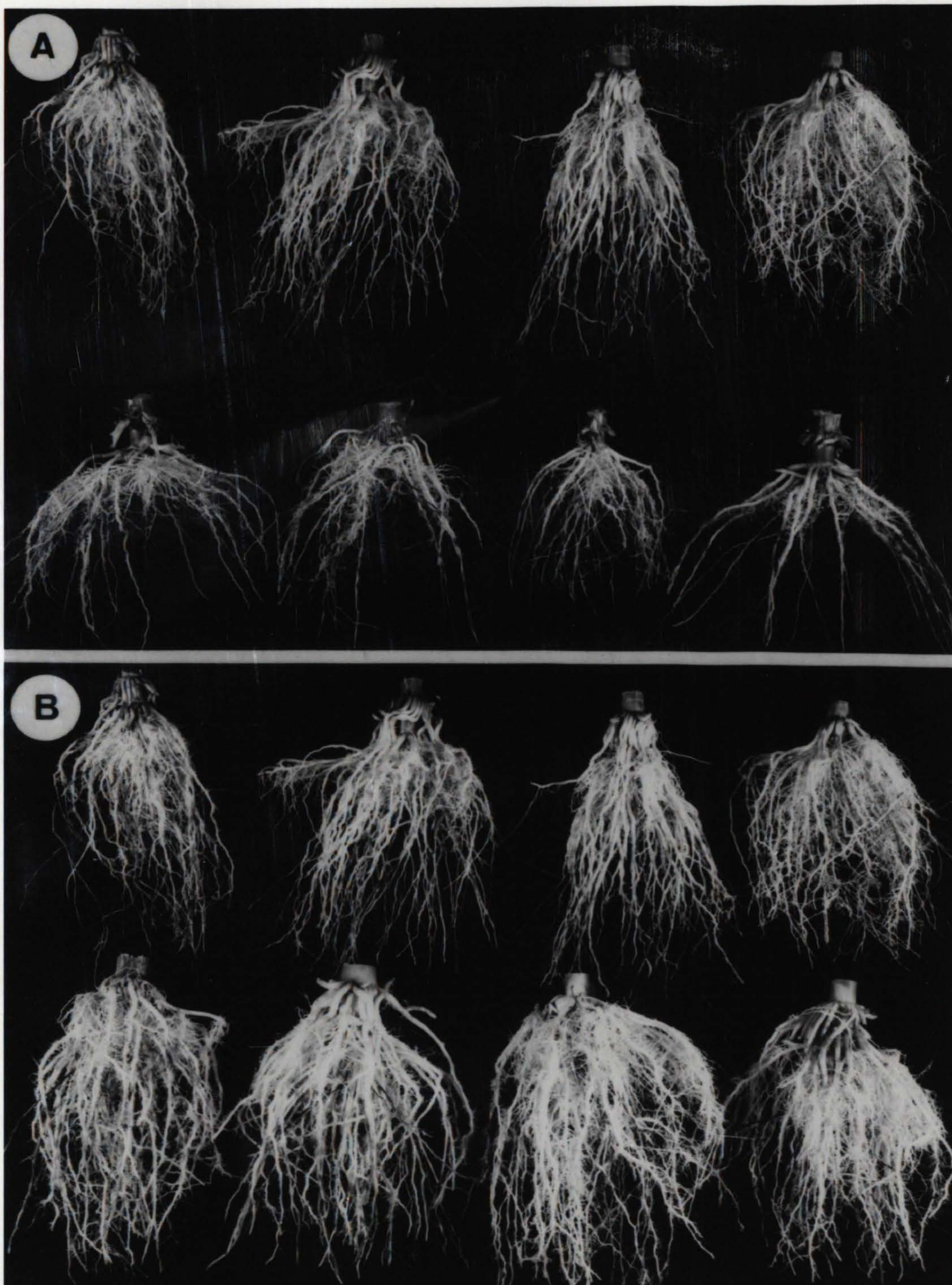


Figure 11. Range of root spread at pull 2 among various inbred lines of corn grown at Brookings, 1975.

A. NG72227 (top) vs. SDP309 (bottom)

B. SD30 (top) vs. C123 (bottom)

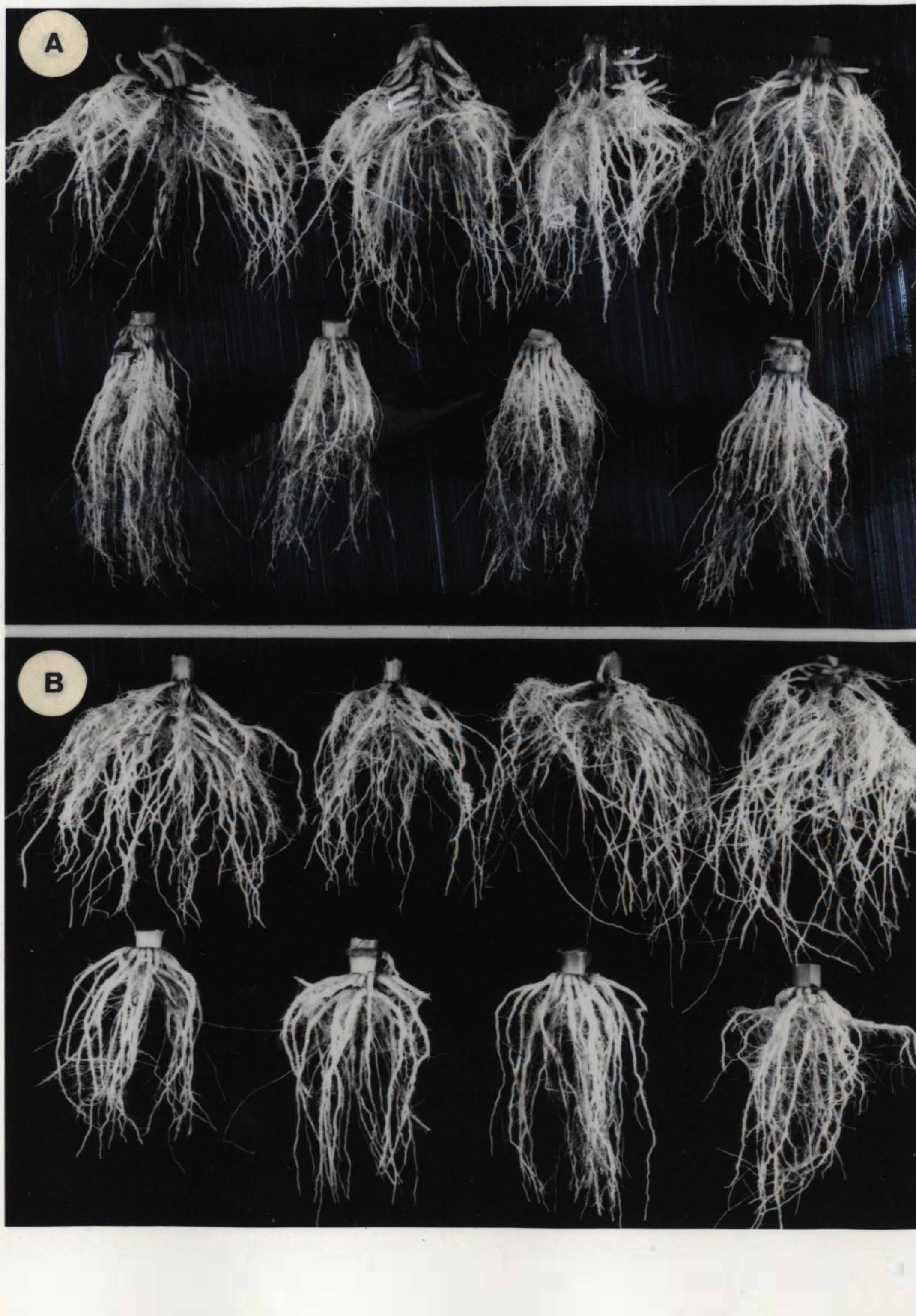

A
B

Figure 12. Range of root spread at pull 2 among various inbred lines of corn grown at Centerville, 1975.

A. MS214 (top) vs. C123 (bottom)

B. SD30 (top) vs. SDP309 (bottom)

C. SD10 (top) vs. W117 (bottom)

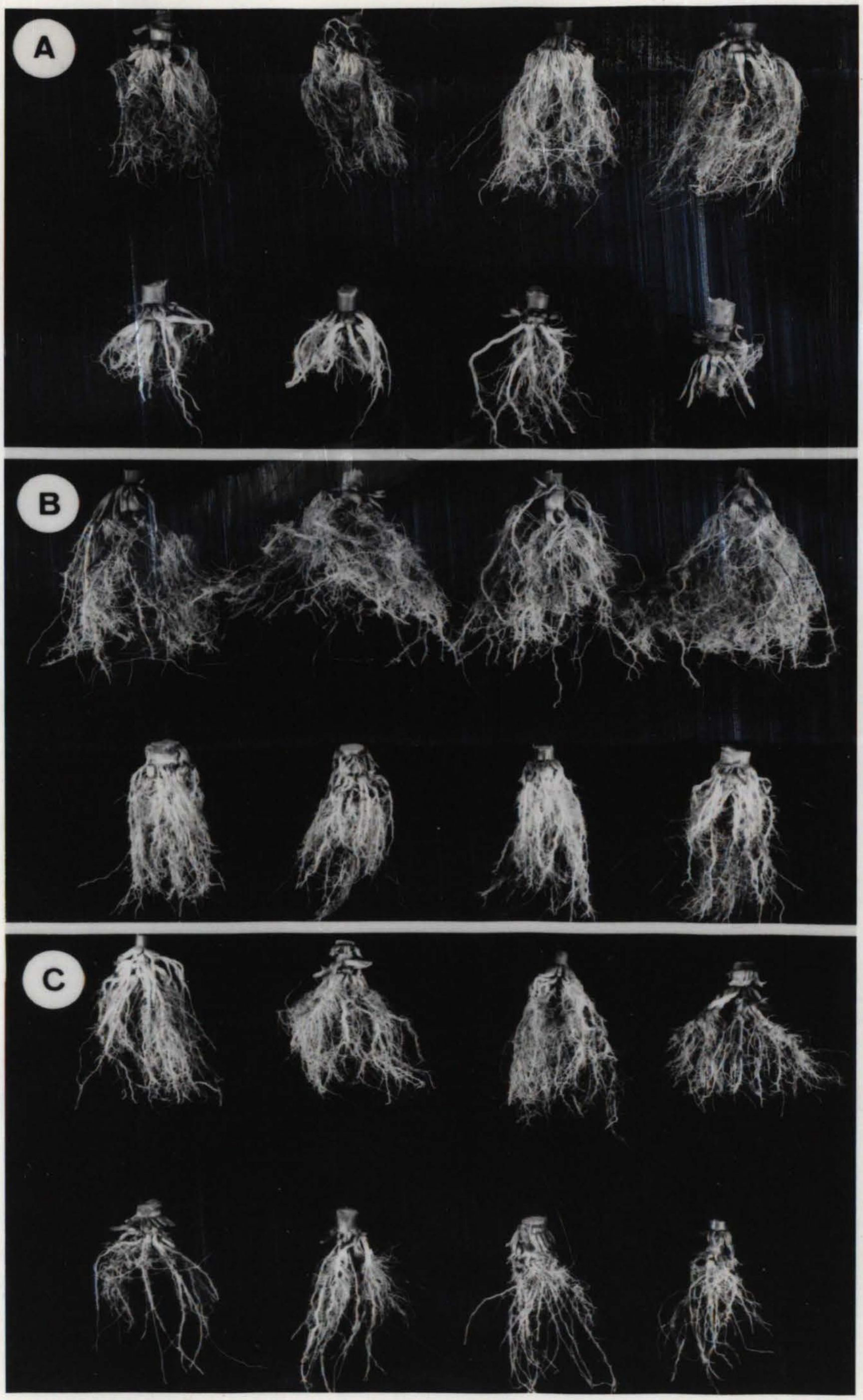

A
B
C

Figure 13. Comparison of root rot resistant (R) with root rot susceptible (S) lines grown at Brookings, 1975.

A. NG72353 (R) (L) vs. NG72336 (S) (L)

B. NG72336 (S) (L) vs. SDP309 (R) (L)

(L = late silking)


A
B

Figure 14. Comparison of root rot resistant (R) with root rot susceptible (S) lines grown at Brookings, 1975.

A. NG72312 (R) (L) vs. SDP309 (R) (L)

B. A624 (R) (E) vs. W182E (S) (E)

(E = early silking, L = late silking)


A
B

Figure 15. Comparison of root rot resistant (R) with root rot susceptible (S) lines grown at Brookings, 1975.

A. A624 (R) (E) vs. A344 (S) (E)

B. A624 (R) (E) vs. SDP309 (R) (L)

(E = early silking, L = late silking)


A
B