A SAMPLING DESIGN FOR DETERMINING THE QUANTITATIVE DISTRIBUTION OF SOYBEAN ROOTS

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

INTRODUCTION

So far, very little work has been done on the study of root distribution in soybeans, and no reliable sampling schemes for such a study are available.

A greater knowledge of the quantitative distribution patterns of soybean roots under various soil tillage programs and at different growth stages of the plants, would enable better on-farm cultural practices such as better placement of fertilizers and more efficient irrigation programs. It is then the purpose of this investigation to determine the most efficient scheme for sampling soybean root distribution.

Sampling roots of any field crop requires a tremendous amount of labor and, consequently, increases the operational cost of the project. To increase the precision of the study, increasing the number of replications and treatments would mean an increase in the total number of sampling units, resulting in a higher cost. The main objective of this research is, therefore, to improvise a sampling scheme that would give dependable results and yet reduce costs to a reasonable value.

LITERATURE REVIEW

There have been many methods for taking root samples of field crops, some dating as far back as 1727 (Hales, cited by Pavlychenko, 1937). Generally, root sampling techniques can be categorized into three methodologies:

a) Excavation Sampling

b) Monolith and Pinboard Sampling

c) Core Sampling

Excavation Sampling.

This method of sampling involves the digging of trenches or cutting soil blocks from the field of interest, and the washing of the roots either directly in the field with water sprays or in specially constructed washtubs.

Monolith and Pinboard Method.

Monolith method of sampling involves the digging of a block of soil and supporting it with a frame. As the name implies, the pinboard method (which is actually a modification of the monolith method) requires the attachment of a spiked board to a vertical section of the soil monolith and digging up the whole monolith together with the pinboard. The spikes on the board hold the roots close to their original position in the ground. After careful washing, the root system displayed on the pinboard would give an approximate representation of the natural distribution pattern in the ground.

Core Sampling.

A cylinderical steel tube of selected diameter and length is forced into the ground, the cores extracted, and the soil samples washed and roots collected. This method is the most convenient of the three categories of sampling methods discussed. It is least laborious and at the same time facilitates replication. The main concern of this thesis is with this method of investigation.

There have also been other methods of studying undisturbed roots using electron scattering and radioactive isotopes, as well as root studies in rhizotron. However, these methods of root studies do not involve any actual sampling of the roots.

The earliest method for collecting roots is perhaps the direct washing method developed by Hales (1727, cited by Pavlychenko, 1937a). Excavation sampling methods soon developed. Also cited by Pavlychenko (1937a), Schubart (1855) improvised a trench-wash method. Sheppard (1905) had a quite similar trench method involving a pit and a jet of water to wash off the soil. Cited by Stoecheler and Kluender (1938), Weaver (1936) followed the excavation procedure by digging a trench around the plant and using an ice pick to remove the soil from the roots. Stoecheler and Kluender (1938) followed the similar trench-excavating technique but instead of using an ice pick to clean the roots, they used a hydraulic pump to wash the roots.

Another modification of the excavation method was the steel-frame method developed by Hays (1889, cited by Pavlychenko, 1937a). He constructed a cubical steel-frame with metal pipes, attaching wire netting to the frame at two- to three-inch intervals. The frame was set in the ground and filled with loose soil, creating an artificial field condition. Hays planted the seed in the center of the frame. At the desired stage of growth, the frame was lifted from the ground and the soil washed off exposing the root system. The wire netting fastened to the steel-frame helped maintain the approximate position of the roots in the ground after the soil was washed off.

The soil-block washing method was developed by Pavlychenko (1937a) for root collection under natural field conditions. Soil blocks were encased in wooden frames and soaked in specially constructed tanks for several hours before washing. Upchurch (1951) conducted studies on alfalfa roots using a soil-elution method and the regular trench-wash method. He dug a trench exposing two vertical walls on each side. On one side of the trench, he conducted his soil-elution method and on the other, he washed off the soil using the regular trench-wash procedures. For the soil-elution method, he removed and washed the soil separately by six-inch layers. The soil-elution method, so he concluded, was superior to the trench-wash method in that the former method gave more information on the amount of roots in the various soil horizons.

As mentioned by Pavlychenko (1937a), King (1893) also did his root collection under natural field conditions using the soil-prism washing method. Soil prisms or monoliths were excavated and reinforced with wooden or metal frames. Many thin rods were driven through the soil prisms to hold the roots in their original positions before washing off the soil. Modifications of this method were made, to develop the present pinboard method for sampling roots.

Nelson and Allmaras (1969) improved the monolith method of excavating roots using a modified pinboard. This method allowed quantitative studies on the plant roots as well as a study of rooting morphology, not only for single plants but also in field plots. As described by Schuurman and Goedewaagen (1971), the pinboard method gives a fairly complete picture of the structure and the shape of the root system, and also of the total amount of roots present. The main disadvantage of this method is that it gives a representation of the root distribution in only two dimensions instead of three. Gooderham (1969) developed a technique quite similar to the pinboard method but modified to present a real "in-situ" picture of roots and their distribution pattern in a three-dimensional configuration. Schuurman and Goedewaagen (1971) gave a rather complete resume of methods for examining the root systems of field crops. Their discussion covered developments from the excavation technique to the pinboard as well as the core sampling methods.

The cylinderical-steel (or coring) method was first introduced in 1883 by Hellriegel (cited by Pavlychenko, 1937a). This method is suitable for studying the depth of root penetration as well as the lateral spread of roots. Later, Thames and Reynolds (1961) developed a portable hydraulic soil sampler. With the increasing popularity in the coring method of root sampling, Riddler and Thomas (1966) designed a power-driven thin-walled core sampler. Core sampling and pinboard sampling methods rapidly became the two most popular methods for sampling roots. Bloodworth, Burleson and Cowley (1958) studied the root distribution of some irrigated crops using core sampling. Raper and Barber (1970) also used core sampling to study the rooting pattern of soybean varieties.

So far, no statistical studies on root sampling for soybeans or other field crops have been reported. This research is aimed toward showing some statistical aspects of root sampling and, thereby, improvising a sampling scheme for future root studies.

MATERIALS AND METHODS

Root data for this study were collected over a period of three years. The Upper Coastal Plain Research Station at Rocky Mount, North Carolina, was the collection site for 1974 and 1975. In 1976, the project was moved to another experimental site at the Central Crops Research Station, Clayton, North Carolina. This was done mainly because growing soybeans (or any crops for that matter) on the same locality for three successive years is generally not recommended for the reasons that disease outbreaks are more likely to occur, as is the buildup of pests. Also, the change of the experimental site could show differences in the root distribution pattern of soybeans in response to different soil-types. Soil analyses for the Rocky Mount and the Clayton experimental sites were run and the results showed very different soils for the two localities. The soil textural class at Rocky Mount was that of a sandy loam and followed the Norfolk series while Clayton had a sandy-textured soil of the Wagram series. The hardpan present at both the experimental sites also showed differences in thickness and density. The Clayton hardpan was more dense and thicker than the hardpan at Rocky Mount. The position of the hardpan at Clayton was slightly deeper (26 cm from the soil surface) than that of Rocky Mount (23 cm deep).

For this study, in an attempt to break up the hardpan present in the field and to work up the soil, five tillage treatments were used. The root distribution pattern for each treatment was then studied to determine the effectiveness of the tillage procedures. The five tillage methods used were as follows:

a) Normal-tillage

b) Chisel-plowed

c) Subsoiled and Bedded

d) Bedded

e) Limed

Normal-tillage.

This treatment consists of plowing the land in the conventional way and using a disk over the field several times working the soil to a depth of about 6 inches (15 cm).

Chisel-plowed.

The field was plowed to a depth of about 10 inches (25 cm) with chisels spaced approximately 12 inches (30 cm) apart.

Bedded.

The field was plowed and the soil gathered and piled up to a height of about 4 to 6 inches (10 to 15 cm) prior to sowing. The soybeans were than seeded on top of the bed.

Subsoiled and Bedded.

Subsoiling is rather similar to chisel plowing except that the subsoiler blades are equally spaced with the soybean rows (38 inches or 96 cm apart) and worked at a depth of approximately 16 inches (40 cm) followed by the bedding procedures. After the soil had settled, the soybeans were seeded directly over the slit formed by the subsoiler blades.

Limed.

The presence of the hardpan could be due to a chemical factor rather than a physical one. The application of lime was mainly to break up the chemically-induced hardpan. The field was then rototilled to incorporate the lime into the soil at a depth of about 10 inches (25 cm). This practice was used in 1974 only. Liming and rototilling caused the soil to "over-fluff," leaving deep tracks of machinery on the field. So, for 1975, no more lime was applied to the previously-limed plots, and instead of using a rotovator, the chisel plow was used.

For the 1976 study, only three of the treatments were used: the normal-tillage treatment, chisel-plowing and subsoiling.

Sampling.

Root collection for this study basically involved collection of core samples, washing of the soil cores to separate out the roots, and finally drying and weighing the roots. Sampling of the roots was carried out at the full-bloom stage of the soybeans, when the root dry matter accumulation is supposedly at or close to its maximum.

Soil core samples were taken by means of a hydraulic soil coring machine manufactured by the Giddings Machinery Company. Coring tubes of a nominal 2.5 inches (6.35 cm) diameter were used. Six depths were taken from the sampled cores, the first three depths or plugs, being 10 cm in length and the following three plugs, 15 cm. These plugs were the ultimate sampling units. Increasing the length of the last three depths from 10 cm to 15 cm would reduce the probability of getting zero readings in the dry-weight measurement of the roots, since root density decreases with depth. Admittedly, the use of unequal volumes poses some problems with variances, but they seem less worrisome than the problems associated with getting zero observations. In the analysis, however, the root dry-weights were adjusted for the volume of the soil cores sampled, giving the units of measurement in milligrams of secondary roots per liter of soil. The plugs or the sampling units were then placed in a cotton bag and kept separated from one another by tying a constriction, using a piece of cord, between them (comparable to sausage links).

Washing.

Each sample plug (representing a specific depth) was washed with water on a 16-mesh sieve with 1 mm openings (U.S.A. Standard Testing Sieve Number 18). Roots were picked from the sieve with tweezers and placed in numbered paper (Dixie) cups. During the process of root picking, the secondary roots were shaved from the primary roots and were weighed separately. For the purpose of this study, only the secondary roots were analyzed. Compared to the weight of the secondary roots, the primary root weights were so tremendous that when the primary and secondary roots were analyzed together, all the effects upon the secondary roots were erased. The primary root weights, which were not significantly affected by the tillage treatments when analyzed alone, did not show interesting results.

Drying and Weighing.

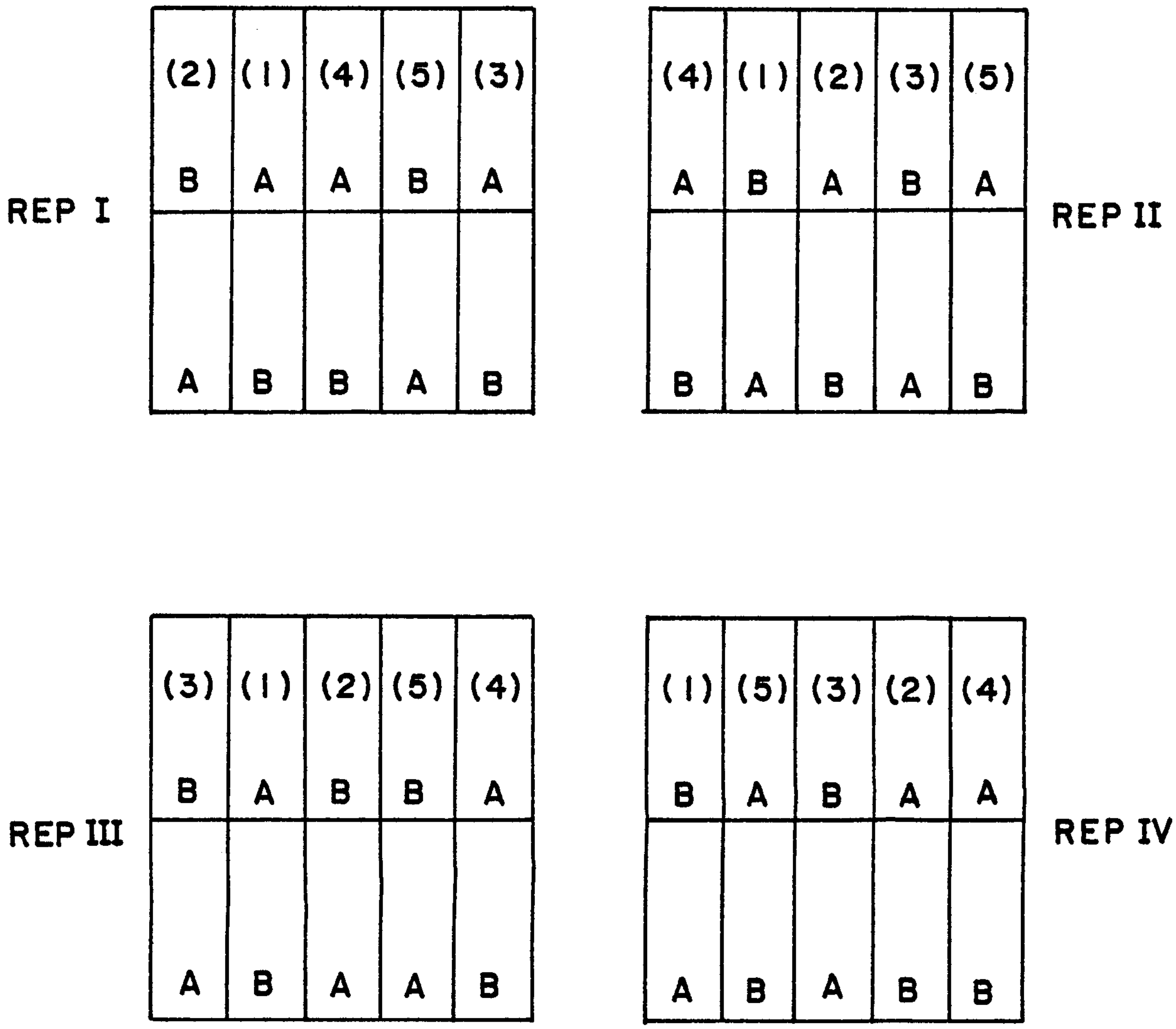
The paper cups containing the roots were then placed in an oven at 45°C for about 24 hours to dry. The secondary roots from each plug (depth) were weighed on an analytical balance and the weights recorded.

The general field layout for the 1974 and 1975 studies is shown in Figure 1, while Figure 4 shows the field plan for the 1976 study. Figure 2 shows the positions and locations of the sampling points along and between the soybean rows for the 1974 and 1975 studies. A detailed diagram showing the positions and locations as well as the depths of the sampling scheme used for the 1974 and 1975 studies is given in Figure 3. For the 1976 study, the scheme used is shown in Figure 5.

In 1974 and 1975, 5 treatments (tillage methods) were run over 4 replications; 4 positions and 4 locations were sampled within each plot. The positions represented the sampling points along the soybean rows while the distances from the rows to the midrows were represented by locations. A total of 6 depths were taken at each position and location. For the study, 2 varieties of soybeans were used, Ransom (a late-maturing variety) and Forrest (an early- maturing variety).

For the 1976 data, only 3 treatments were imposed on one variety (Ransom) with 6 replications; 2 positions, 5 locations, and 6 depths were sampled in each plot. This allocation of replications, positions, locations, treatments, depths and variety was thought to be a good and economical sampling scheme based on analysis of the 1974 and 1975 data.

In the analysis, since the sampling units (depths) consisted of different volumes (the last three depths were 50 percent greater in volume than the first three depths), the root weight (in milligrams) from each sampling unit was adjusted to a per liter of soil basis.



TREATMENTS

(1) Normal-tillage

(2) Chisel-plowed

(3) Subsoiled and Bedded

(4) Bedded

(5) Limed

VARIETIES

A : Ransom

B : Forrest

Figure 1. The field layout for the 1974 and 1975 studies.

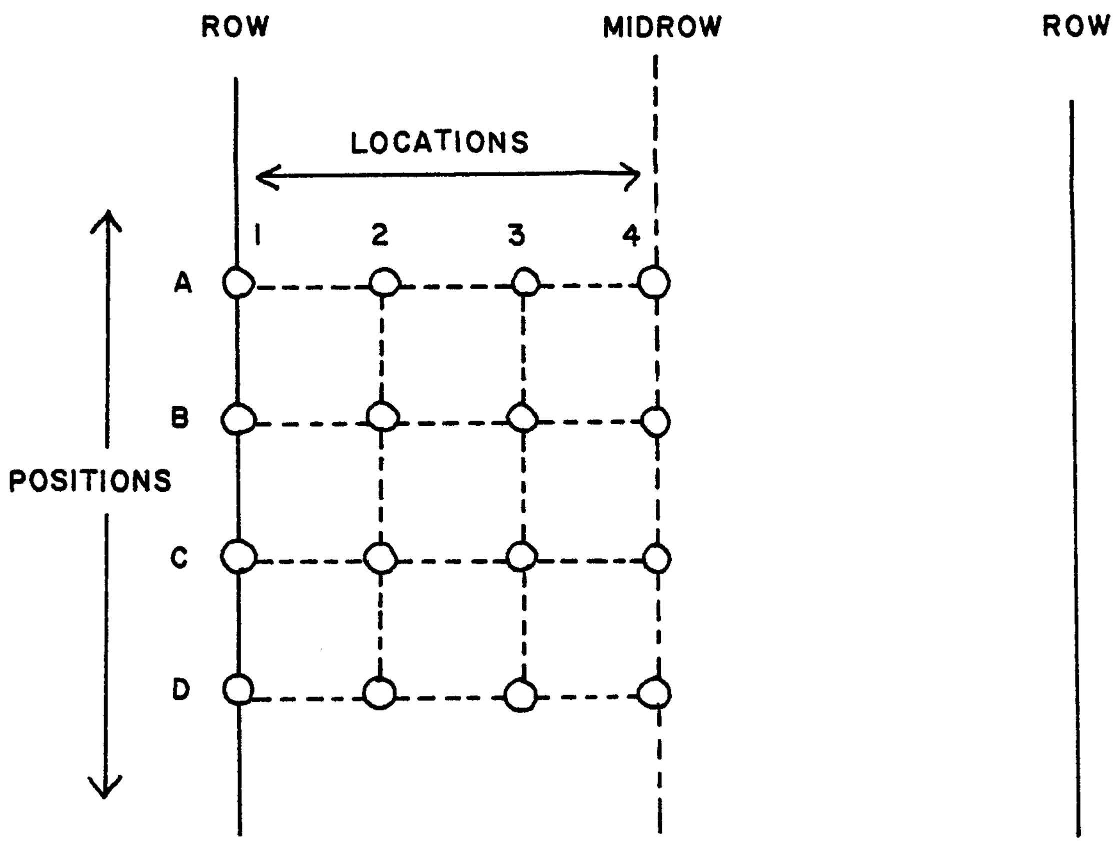


Figure 2. The positions and locations of sampling points along and between the soybean rows for 1974 and 1975.

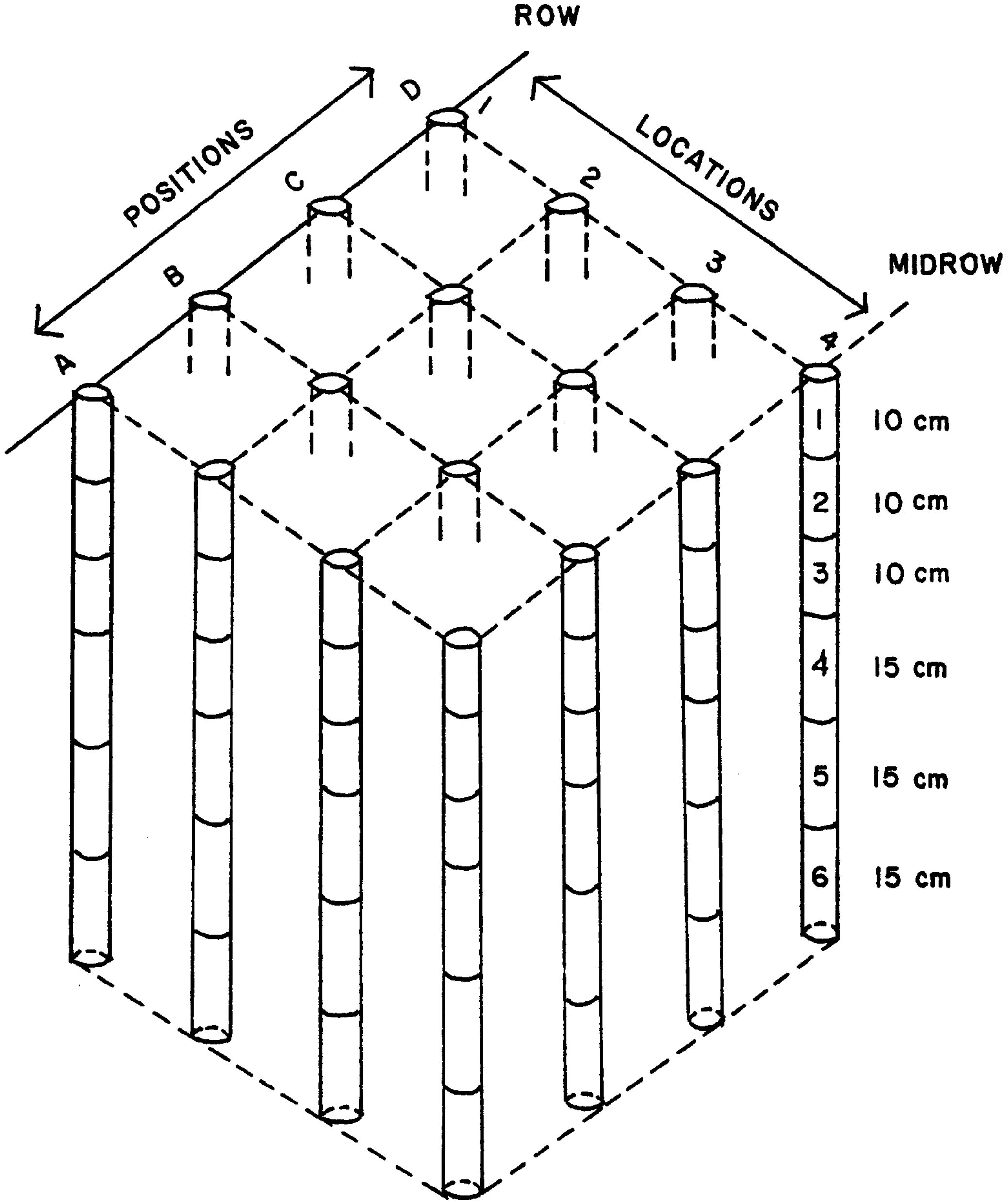
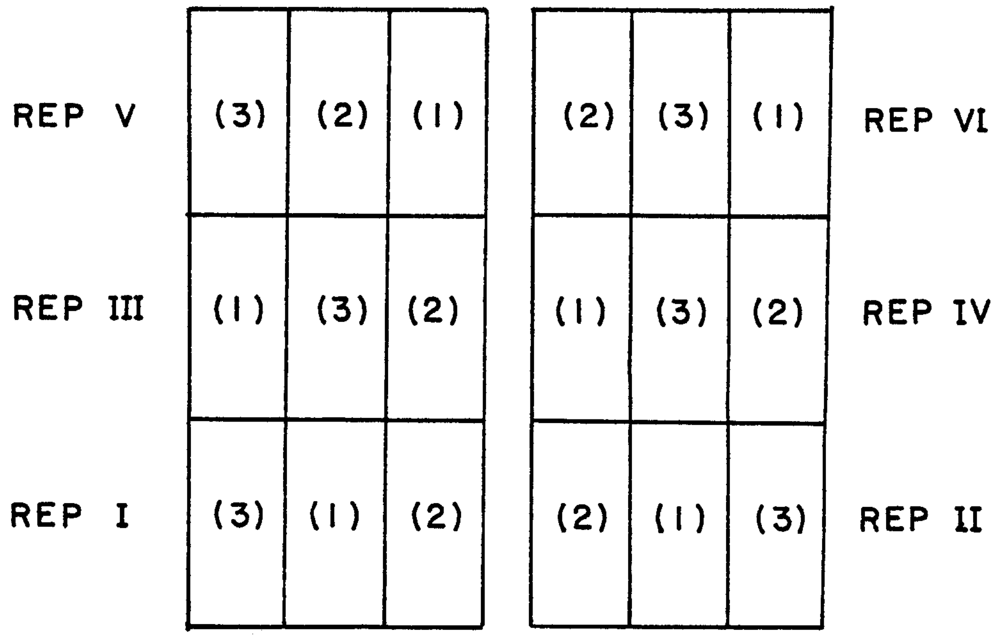


Figure 3. The positions, locations and depths of the sampling scheme used in 1974 and 1975.



TREATMENTS

(1) Normal-tillage

(2) Chisel-plowed

(3) Subsoiled and Bedded

Figure 4. The field plan for the 1976 study.

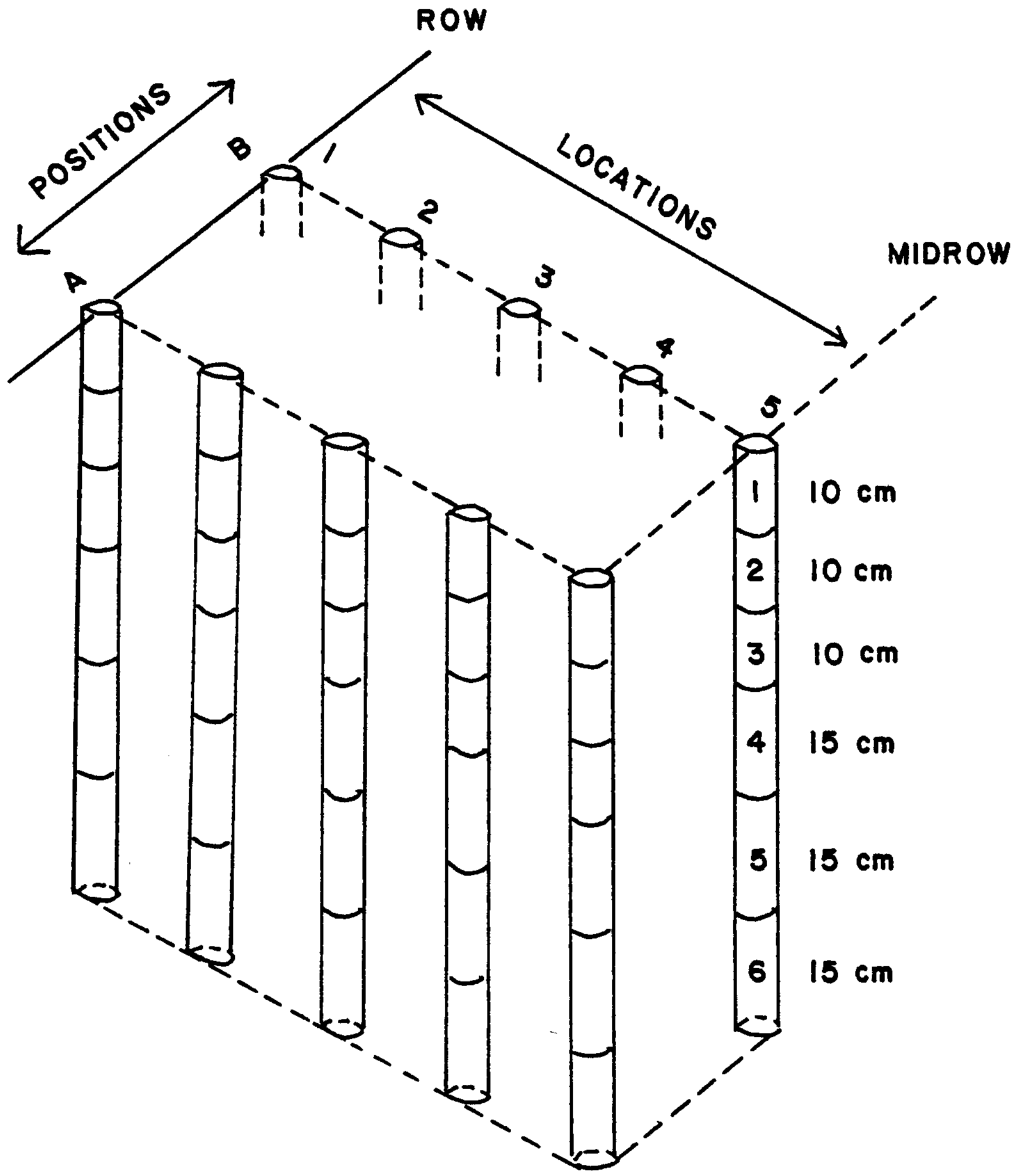


Figure 5. The positions, locations and depths of the sampling scheme for the 1976 study.

Logarithmic transformation of the data sets was suggested because of the skewness of the data, which is to be expected based on knowledge of root distribution. By doing so, the coefficients of variation for the three years of study was greatly reduced relative to the untransformed data, as shown in Table 1.

Years	Coefficients of Variation	
	Untransformed	Transformed
1974	120.73%	32.53%
1975	129.46%	27.25%
1976	119.79%	42.98%

Table 1. Coefficients of variation of the transformed and untransformed data for the three years of root study.

The sources of variation and the degrees of freedom for the analysis of variance are given in Table 2 (for 1974 and 1975 data sets) and Table 3 (for 1976 data set). The average values of the mean squares were obtained following the rules given by Schultz (1955). These expected mean squares are presented in Table 4 (for 1974 and 1975 data sets) and in Table 5 (for 1976 data set).

Calculations of the degrees of freedom for the synthesized error terms for testing of significance was done following Satterthwaite's principles (1946). The level of significance for each interaction is shown in Tables 8 and 9.

Sources of Variation	Degrees of Freedom
Replication	3
Treatment	4
Error (a)	12
Variety	1
Variety x Treatment	4
Error (b)	15
Location	3
Position (Location)	12
Location x Treatment	12
Treatment x Position (Location)	48
Location x Variety	3
Variety x Position (Location)	12
Location x Variety x Treatment	12
Treatment x Variety x Position (Location)	48
Error (c)	450
Depth	5
Depth x Treatment	20
Depth x Variety	5
Depth x Variety x Treatment	20
Depth x Location	15
Depth x Position (Location)	60
Depth x Location x Treatment	60
Depth x Treatment x Position (Location)	240
Depth x Location x Variety	15
Depth x Variety x Position (Location)	60
Depth x Location x Variety x Treatment	60
Depth x Variety x Treatment x Position (Location)	240
Residual or Error (d)	2400
Total	3839

Table 2. Key-out for the Analysis of Variance for 1974 and 1975 data sets.

Sources of Variation	Degrees of Freedom
Replication	5
Treatment	2
Error (a)	10
Location	4
Position (Location)	5
Location x Treatment	8
Treatment x Position (Location)	10
Error (b)	135
Depth	5
Depth x Treatment	10
Depth x Location	20
Depth x Position (Location)	25
Depth x Location x Treatment	40
Depth x Treatment x Position (Location)	50
Residual or Error (c)	750
Total	1079

Table 3. Key-out for the Analysis of Variance for 1976 data.

	$\sigma^2_{Residual}$	$r\sigma^2_{DVTP(L)}$	$rp\sigma^2_{DLVT}$	$rt\sigma^2_{DVP(L)}$	$rtp\sigma^2_{DLV}$	$rv\sigma^2_{DTP(L)}$	$rvp\sigma^2_{DLT}$	$rtv\sigma^2_{DP(L)}$	$rtvp\sigma^2_{DL}$	$rpl\sigma^2_{DVT}$	$rplt\sigma^2_{DV}$	$rplv\sigma^2_{DT}$	$rplvt\sigma^2_{D}$	$d\sigma^2_{c}$	$dr\sigma^2_{TVP(L)}$	$drp\sigma^2_{LVT}$	$drt\sigma^2_{VP(L)}$	$drtp\sigma^2_{LV}$	$drv\sigma^2_{TP(L)}$	$drvp\sigma^2_{LT}$	$drvt\sigma^2_{P(L)}$	$drvtp\sigma^2_{L}$	$dpl\sigma^2_{b}$	$dplr\theta^2_{VT}$	$dplrt\theta^2_{V}$	$dplv\sigma^2_{a}$	$dplvr\theta^2_{T}$	$dplvt\sigma^2_{R}$
R	x													x									x			x		x
T	x	o	o			x	x			o		x		x	o	o			x	x			x	o		x	x	
Error (a)	x													x									x			x		
V	x	o	o	x	x					o	x			x	o	o	x	x					x	o	x			
VT	x	x	x							x				x	x	x							x	x				
Error (b)	x													x									x					
L	x	o	o	o	o	o	o	x	x					x	o	o	o	o	o	o	x	x						
P(L)	x	o		o		o		x						x	o		o		o		x							
LT	x	o	o			x	x							x	o	o			x	x								
TP(L)	x	o				x								x	o				x									
LV	x	o	o	x	x									x	o	o	x	x										
VP(L)	x	o		x										x	o		x											
LVT	x	x	x											x	x	x												
TVP(L)	x	x												x	x													
Error (c)	x													x														
D	x	o	o	o	o	o	o	x	x	o	o	o	x															
DT	x	o	o			x	x			o		x																
DV	x	o	o	x	x					o	x																	
DVT	x	x	x							x																		
DL	x	o	o	o	o	o	o	x	x																			
DP(L)	x	o		o		o		x																				
DLT	x	o	o			x	x																					
DTP(L)	x	o				x																						
DLV	x	o	o	x	x																							
DVP(L)	x	o		x																								
DLVT	x	x	x																									
DVTP(L)	x	x																										
Residual	x																											

x Present in random effects model.

o Deleted from model with treatments and varieties fixed, otherwise present.

Table 4. Expected Mean Squares for 1974 and 1975 data sets.

	$\sigma^2_{Residual}$	$r\sigma^2_{DTP(L)}$	$rp\sigma^2_{DLT}$	$rt\sigma^2_{DP(L)}$	$rtp\sigma^2_{DL}$	$rpl\sigma^2_{DT}$	$rplt\sigma^2_{D}$	$d\sigma^2_{b}$	$rd\sigma^2_{TP(L)}$	$rdp\sigma^2_{LT}$	$rdt\sigma^2_{P(L)}$	$rdtp\sigma^2_{L}$	$dpl\sigma^2_{a}$	$rdpl\theta^2_{T}$	$dplt\sigma^2_{R}$
R	x							x					x		x
T	x	x	x			x		x	x	x			x	x	
Error (a)	x							x					x		
L	x	o	o	x	x			x	o	o	x	x			
P(L)	x	o		x				x	o		x				
LT	x	x	x					x	x	x					
TP(L)	x	x						x	x						
Error (b)	x							x							
D	x	o	o	x	x	o	x								
DT	x	x	x			x									
DL	x	o	o	x	x										
DP(L)	x	o		x											
DLT	x	x	x												
DTP(L)	x	x													
Residual	x														

x Present in rondom effects model.

o Deleted from model with treatments and varieties fixed, otherwise present.

Table 5. Expected Mean Squares for the 1976 data set.

RESULTS AND DISCUSSION

Soybeans were seeded around mid-May and root sampling was done at the full-bloom stage which was in the latter part of July for 1974 and 1975, and in early August for 1976. The rainfall figures as shown in Table 6 were compiled starting one week prior to seeding through the date of root sampling. Considering May and June to be the early-growth period of soybeans and from July through the sampling dates as the later-growth period, we can see from the rainfall data (Table 6) that 1974 and 1976 had plenty of moisture during the early-growth period of soybeans while 1975 was relatively drier. Looking at the distribution of the root dry-weight means at the various depths studied, the maximum curvature of the plots occur at points corresponding to depths from about 15 cm through 40 cm as seen in Figures 6, 7 and 8. It would then seem appropriate to increase the sampling points between these depths (15 cm to 40 cm). A recommendation of five depths appears to be adequately sufficient for the sampling of root distribution since the changes in the root dry matter for the greater depths were small as well as linear. The five depth intervals suggested are 0-15 cm for the first depths, 15-25 cm for the second depth, 25-35 cm for the third depth, 35-45 cm for the fourth depth and 45-60 cm for the final depth, as indicated on the right side of Figures 6, 7 and 8.

The turning points on the curves (Figures 6, 7 and 8) were very much affected by the position of the hardpan as well as the weather (moisture) conditions. Differences in soil characteristics for the two experimental sites are presented in Table 7. The hardpan at Rocky Mount (1974 and 1975 studies) was located at a depth of about 23 cm and at

Year	Rainfall (in inches)		Total Rainfall
	May and June (Early-Growth Period)	July Until Sampling	
1974	7.94	8.28	16.22
1975	5.85	7.56	13.41
1976	8.26	2.78	11.04

Table 6. Rainfall data for the three years of study (starting from one week prior to seeding until sampling dates).

Soil Characteristics	Rocky Mount	Clayton
Soil textural class	Sandy loam	Sand
Soil series	Norfolk	Wagram
Depth to hardpan	9 inches (23 cm)	10 inches (26 cm)
Thickness of hardpan	2 inches (5 cm)	2.5 inches (6 cm)

Table 7. Differences in soil characteristics for the two experimental sites.

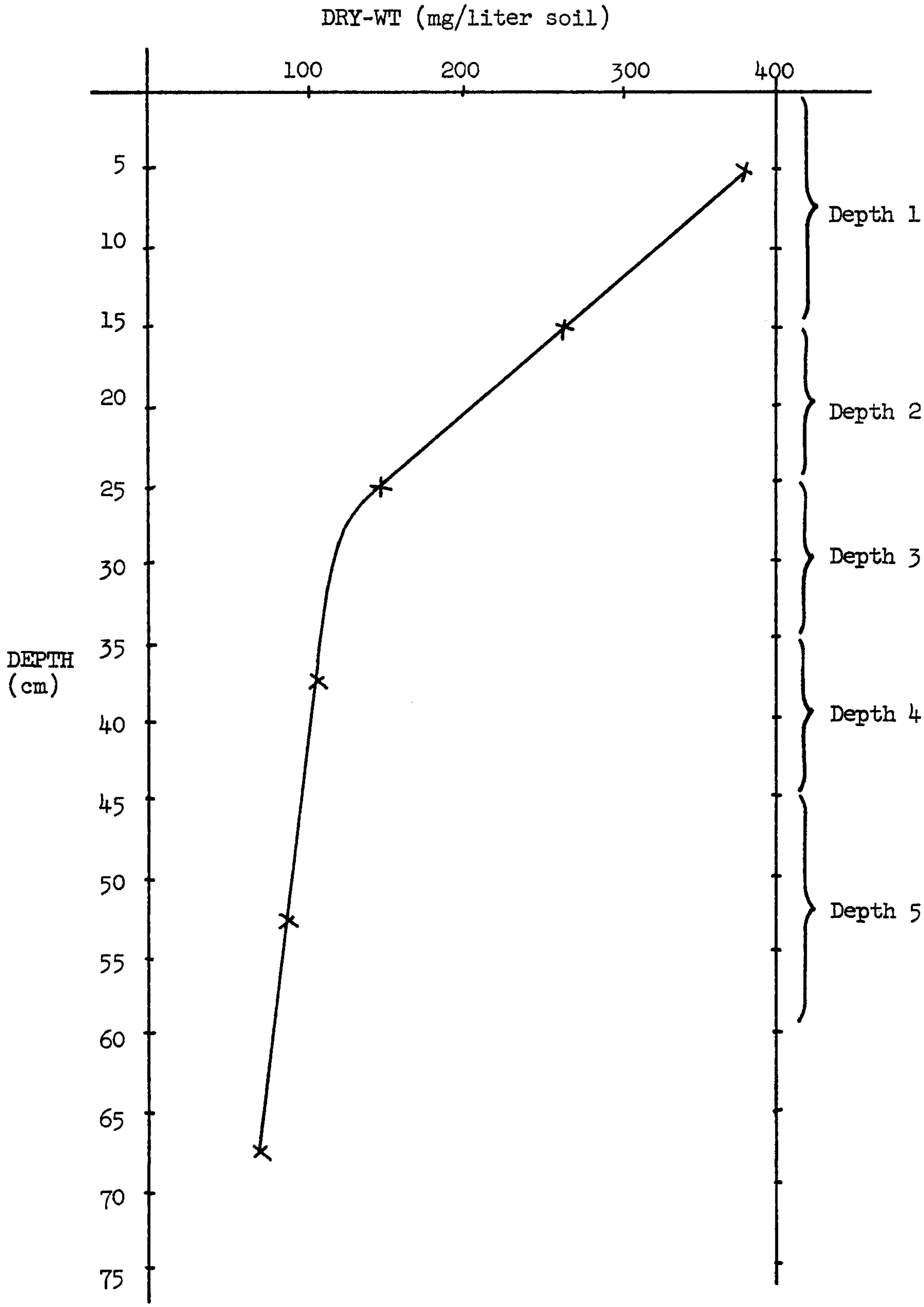


Figure 6. The distribution of root dry-weight means at different depths for the 1974 study. (The depth-interval recommended is indicated on the right.)

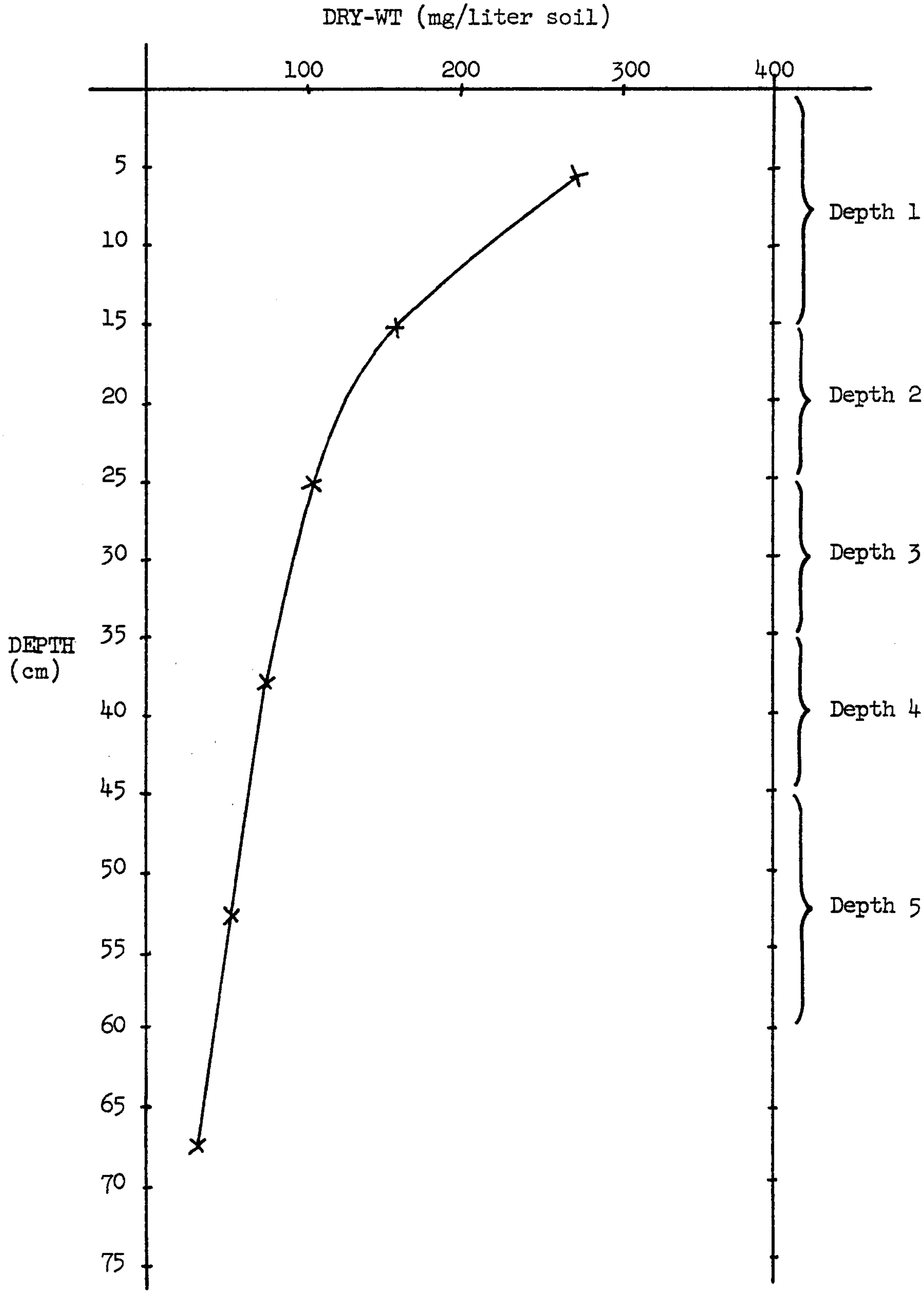


Figure 7. The distribution of root dry-weight means at different depths for the 1975 study. (The depth-interval recommended is indicated on the right.)

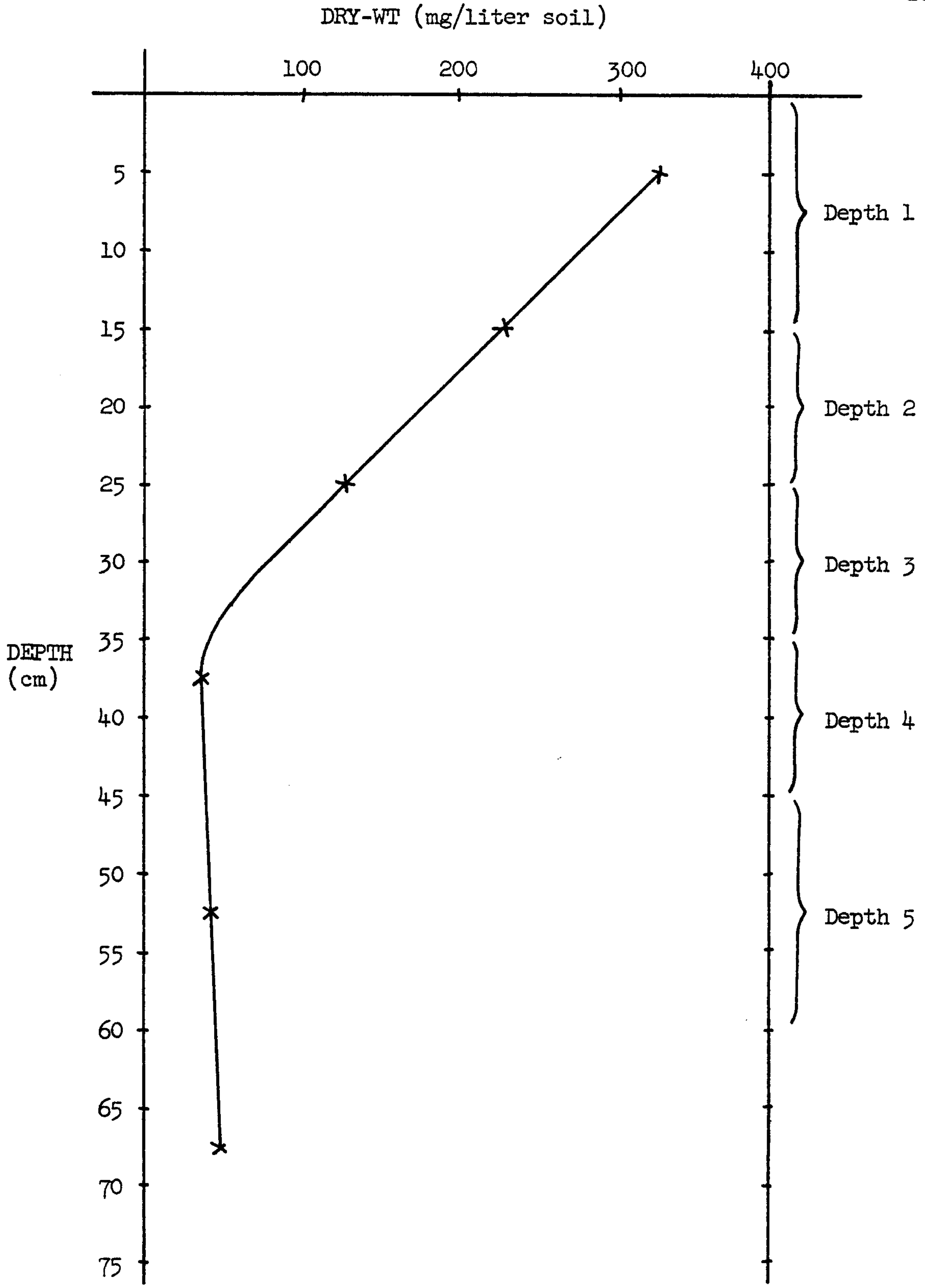


Figure 8. The distribution of root dry-weight means at different depths for the 1976 study. (The depth-interval recommended is indicated on the right.)

Clayton (1976 study) it was located at about 26 cm deep. If the hardpan were located at a greater depth, below the soil surface, the depth intervals recommended could have been different.

Figure 9 shows the root dry-weight means for each depth for Ransom (variety common for the three years of study). The 1974 study showed greater root biomass for all the depths studied, as compared to the 1975 and 1976 studies. This was probably because of the high amount of rainfall throughout the growth period of soybeans for that year (Table 6). The 1976 study showed rather a curve similar to that of 1974; both years having a wet early growth period. The differences between these two years could be due to the soil-type differences (different experimental sites) as well as the weather factor; the later-growth period for the 1976 study was drier than that of 1974 although there was a plentiful supply of moisture during the early-growth period for both years.

The 1974 and 1975 studies, as recalled, were conducted on the same experimental site (at Rocky Mount). The 1975 graph showed a gradually decreasing root biomass while the 1974 data showed a more abrupt reduction in the shallower depths. The differences in these two sets of graphs are attributable mainly to the weather factor.

In all the three years of study, moisture showed great influence over the root penetrative ability as well as the lateral distribution. For the 1974 and 1976 studies which, as mentioned earlier, had plentiful supply of moisture during the early-growth period, showed some root penetration beyond the hardpan as indicated, in Figure 9, by the turning points occurring below the location of the hardpan (26 cm deep for the 1976 data and 23 cm for the 1974 data). The other case, for 1975

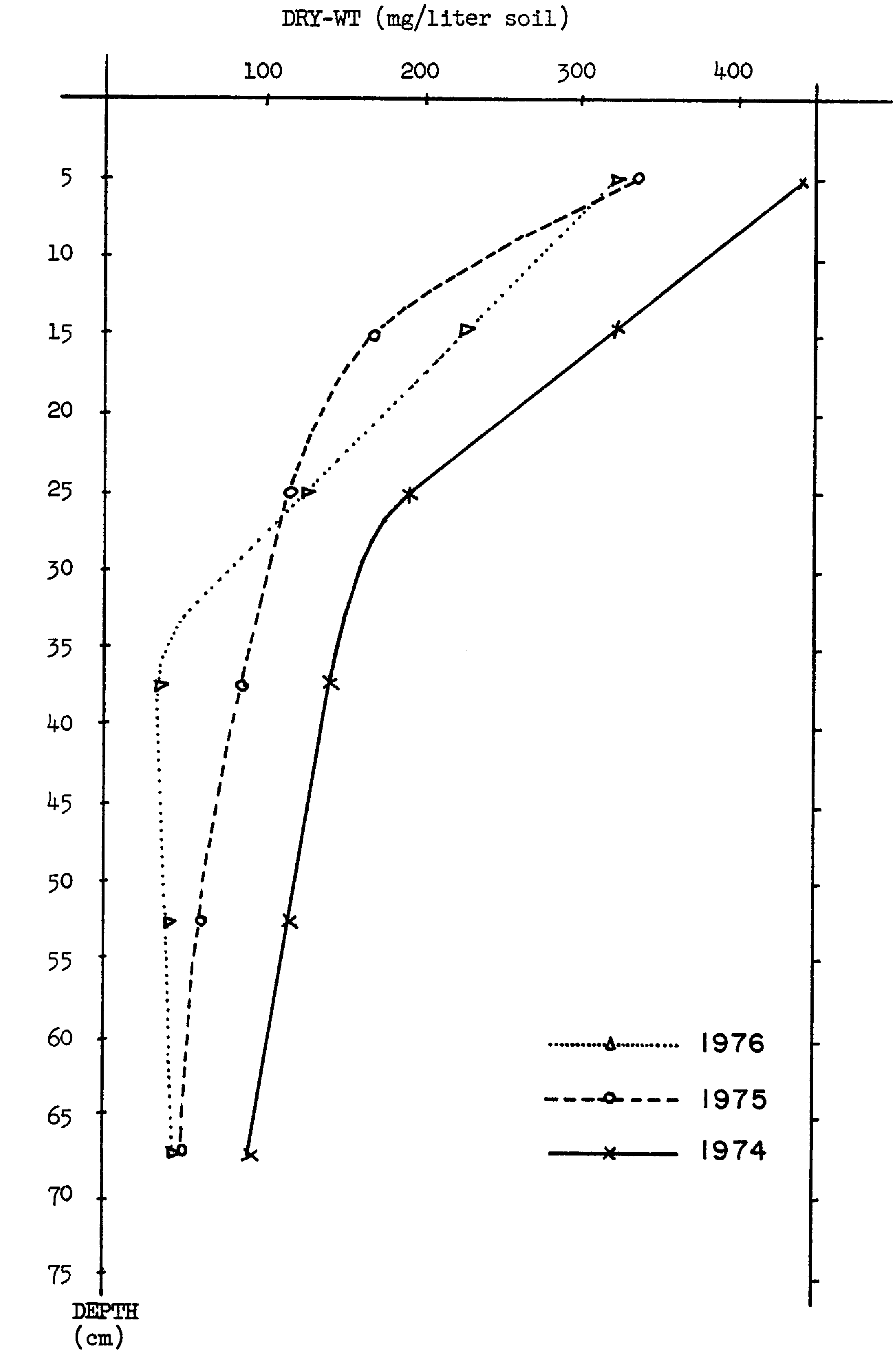


Figure 9. The distribution of root dry-weight means at different depths for the variety Ransom for the three years of study.

which was a relatively dry year, showed less root penetration beyond the hardpan (the turning point occurred above the hardpan region, i.e. at 23 cm deep).

Isoquants were plotted for each treatment to show the root densities by depth and location as presented in Figures 10, 11 and 12. By the F-test, differences in response to varieties were highly significant, as can be noticed from the isoquant plots in Figures 10 and 11 but, oddly enough, the treatment effects turned out to be not significant for all the three years of study.

Generally, Forrest (an early-maturing variety) tended to have more outspreading of the roots in the first 45 cm of the soil, in contrast to Ransom (a late-maturing variety) which exhibited a tendency for deeper root penetration. However, in 1976, Ransom showed a slightly different pattern. As mentioned several times before, 1976 started off with plenty of moisture for the early-growth period of soybeans but drought eventually followed the wet spell (Table 6). The weather conditions and possibly the different soils (1976 sampling was done at Clayton on a Wagram sand) were the probably causes of the peculiar behavior of Ransom in 1976. Nevertheless, in the subsoiled and bedded treatment for that same year, again there was a penetrating effort seen (Figure 12). It is known that the hardpan at Clayton was more dense that that at Rocky Mount (Table 7). This then easily accounts for the non-penetrating pattern of Ransom in the 1976 study for the chiselled and the normal-tillage treatments. However, with the subsoiled and bedded treatment (Figure 12), the penetrative barrier of the hardpan was apparently removed.

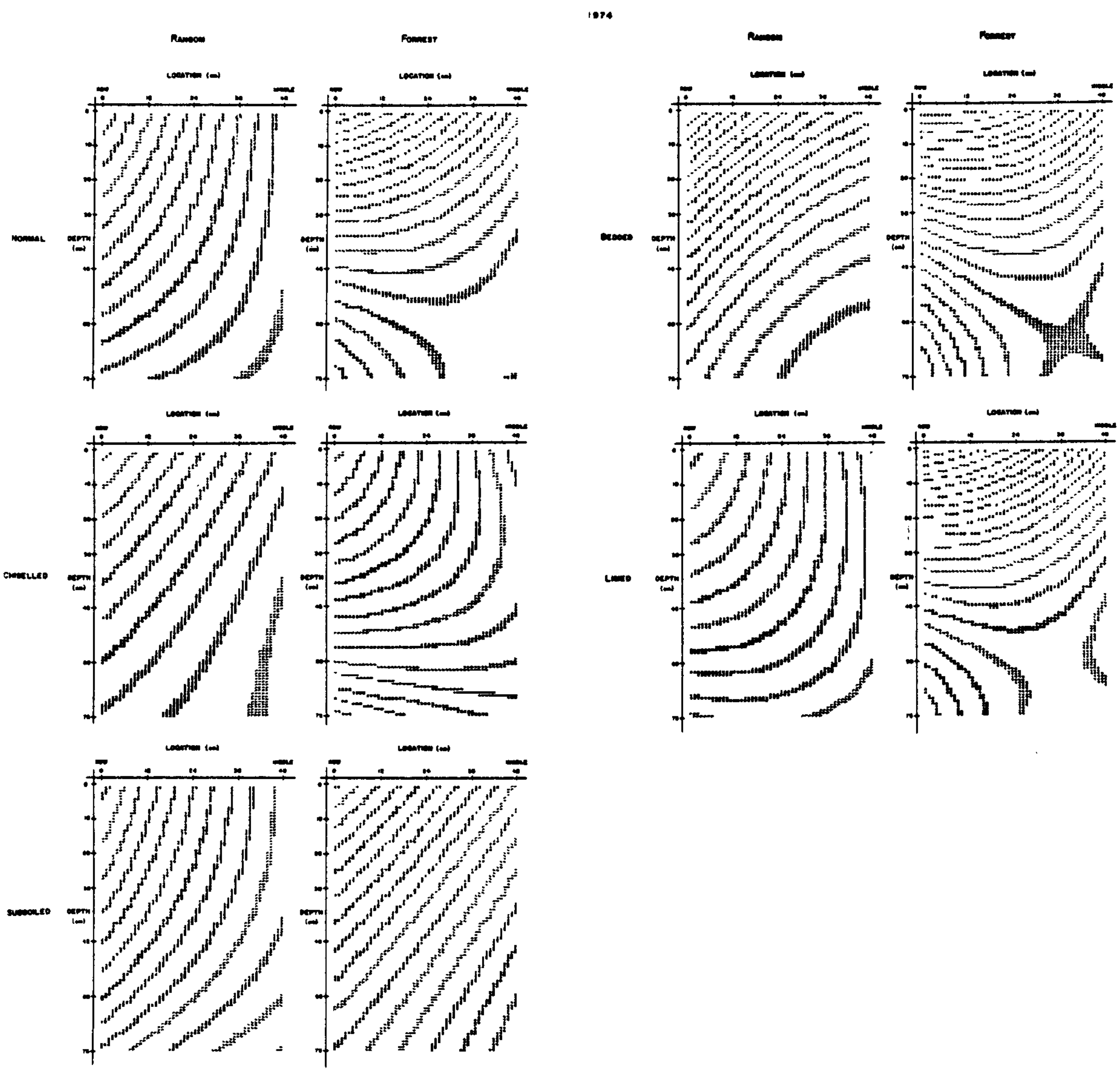


Figure 10. Isoquant plottings of depth by location for each treatment and variety for the 1974 root study.

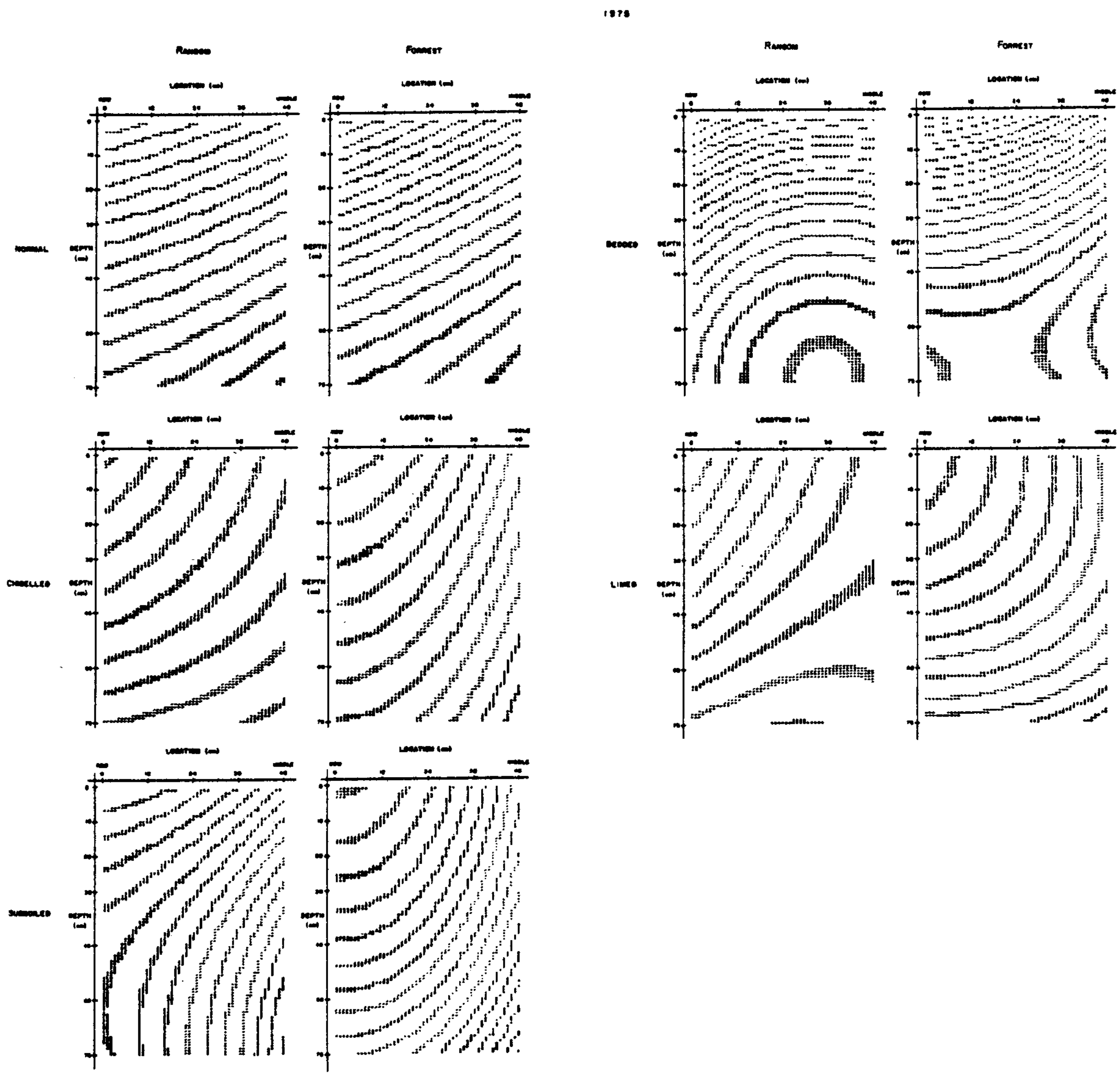


Figure 11. Isoquant plottings of depth by location for each treatment and variety for the 1975 root study.

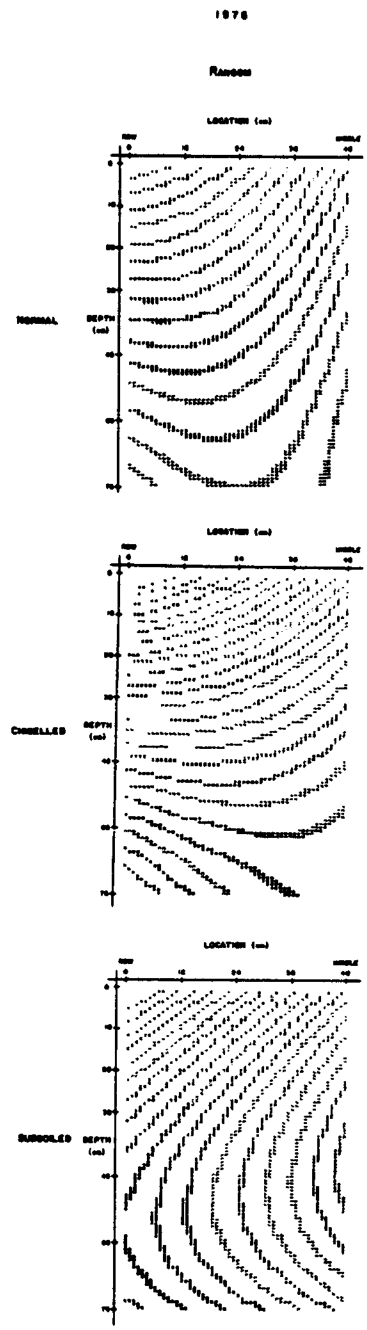


Figure 12. Isoquant plottings of depth by location for each treatment for the 1976 root study.

As mentioned earlier, increasing the total number of sampling units would result in an increase in the overall cost of the project. Washing of the sampling units (plugs) to separate the roots was very time-consuming and, consequently, constituted the major part of the research cost. Collection of the soil cores also contributed, to some degree, to the overall operational cost.

Increasing either the number of varieties, treatments, replications, positions, locations or depths in the sampling scheme would correspondingly increase the total sampling units. However, increasing the number of varieties, treatments and replications would require a larger number of field plots. Following the system of sampling used for this study, having more field plots would mean having to move the truck (soil coring device attached to the rear of the truck) more often. Once the truck is positioned in a field plot, it is just a matter of adjusting the soil coring device to the position and location wanted. Taking more depths would mean that extra force (hydraulically powered in this case) is required to push the coring tube deeper; however, the additional cost involved would be small.

When two sampling schemes have the same total number of sampling units, the one with more field plots will have a slightly higher cost over the other sampling scheme. For example, a sampling scheme A has 3 treatments, 2 varieties, 4 replications, 3 positions, 4 locations and 5 depths, and a sampling scheme B has 2 treatments, 2 varieties, 3 replications, 4 positions, 5 locations and 6 depths. Although both sampling schemes have a total of 1440 sampling units, scheme B requires only 12 field plots (2 treatments x 2 varieties x 4 replications) whereas scheme A requires 24 plots (3 treatments x 2 varieties x 4 replications), which is twice that of scheme B. The cost of scheme A would be higher than that of sampling with scheme B, but not necessarily doubled.

The two major elements of the overall cost of the study, as discussed earlier, are the sampling cost and the washing cost. In order to present a more realistic cost involvement, the expenses could be considered in terms of manhours. From the amount of work put in during the three years of data collection, the cost of sampling a field plot is estimated to be 3.5 manhours. With our field set-up, increasing the number of soil cores taken within a plot cost proportionally less than increasing the number of plots, because of the time consumed in moving and positioning the coring rig. Washing of the soil samples, and all the associated tasks, took 0.42 manhours per soil plug (sampling unit).

Coming back to the two sampling schemes A and B discussed earlier, scheme A having 24 field plots would require a sampling cost of 84 manhours (24 plots x 3.5 manhours per plot) and a washing cost of 605 manhours (1440 sampling units x 0.42 manhour per sampling unit) making a total of 689 manhours. Washing cost for scheme B (with 1440 sampling units from 12 field plots) would be the same as that of scheme B (605 manhours) since both schemes had a total of 1440 sampling units. Scheme B, having only 12 field plots, would cost 42 manhours (12 plots x 3.5 manhours per plot). The total cost for scheme B would add up to only 647 manhours, compared to 689 manhours with scheme A.

In summary on the economics of the sampling scheme, the cheapest scheme would be one which has the smallest number of sampling units and requires the minimum number of field plots. However, the relative cost of each expense factor of the sampling scheme will have to be considered at the local basis where the sampling is to be done.

For the purpose of this study, we were interested in the pattern of root distribution relative to locations and increasing depths for the given treatment and variety. We then chose to look at the depth by location by treatment by variety (DLVT) interaction which was significant as indicated in Table 8. The variance of the means for the DLVT interaction is given below in Equation 1.

$$V(\bar{y}_{DLVT}) = \frac{\hat{\sigma}^2_{Residual}}{(r)(p)} + \frac{\hat{\sigma}^2_{DTVPL}}{p} \qquad [1]$$

where r is the number of replications used and p is the number of positions. The values of $\hat{\sigma}^2_{Residual}$ and $\hat{\sigma}^2_{DTVPL}$ are given in Table 8.

Since the 1976 data set dealt with only one variety, there was no DLVT interaction. The depth by location by treatment (DLT) interaction was studied instead. The variance of the means for the DLT interaction is given in Equation 2.

$$V(\bar{y}_{DLT}) = \frac{\hat{\sigma}^2_{Residual}}{(r)(p)} + \frac{\hat{\sigma}^2_{DTPL}}{p} \qquad [2]$$

The values of $\hat{\sigma}^2_{Residual}$ and $\hat{\sigma}^2_{DTPL}$ for the 1976 study are given in Table 9.

For the 1974 and 1975 studies, we were also interested in the DLT interaction. The variance of the means for the DLT interaction for these two data sets as shown in Equation 3, has a variety factor involved in the denominator.

$$V(\bar{y}_{DLT}) = \frac{\hat{\sigma}^2_{Residual}}{(r)(v)(p)} + \frac{\hat{\sigma}^2_{DTPL}}{p} \qquad [3]$$

$\hat{\sigma}^2$-subscript	$\hat{\sigma}^2_i$ 1974	$\hat{\sigma}^2_i$ 1975
R	0.0791 *	0.0208 ns
T	0.0134 ns	0.0655 ns
Error (a)	0.0879	0
V	0.5668 **	0.0868 *
VT	0.0504 ns	0 ns
Error (b)	0.1633	0.1315
L	0.2645 **	0.3382 **
P(L)	0.0579 *	0.0084 *
LT	0.0229 ns	0.0500 **
TP(L)	0 ns	0.0074 ns
LV	0.0523 *	0.0214 **
VP(L)	0.0186 ns	0 ns
LVT	0.0425 *	0 ns
TVP(L)	0 ns	0 ns
Error (c)	0.4676	0.1380
D	0.6601 **	0.7705 **
DT	0.0323 **	0.1341 **
DV	0.0837 **	0.0202 **
DVT	0.0425 **	0.0219 *
DL	0.2032 **	0.0419 **
DP(L)	0.0287 **	0.0001 ns
DLT	0.0569 **	0.0227 **
DTP(L)	0 ns	0 ns
DLV	0.0448	0 ns
DVP(L)	0 ns	0.0062 ns
DLVT	0.0639 **	0.0234 *
DVTP(L)	0 ns	0 ns
Residual or Error (d)	1.5735	1.0783

Table 8. Variance component estimates for 1974 and 1975 data sets.
ns indicates non-significance at 5% level
* indicates significance at 5% level
** indicates significance at 1% level

In this case, from the 1974 and 1975 data, increasing the number of varieties for such a study would result in a reduction of $V(\bar{y}_{DLT})$. The recommendation derived would then be too specific concerning the number of varieties to be used for future root studies. In order to work with a more generalized case so as to approach the more flexible recommendation of a sampling scheme that would be independent of the variety factor, the treatments and varieties were combined for the analysis of variance as a factorial as compared to the earlier case where the data were analyzed as a split-plot. This new approach must be considered to be only an approximation of the true situation. However, it seems not unreasonable to do so since the new $\hat{\sigma}^2_{DLC}$ is now an average of $\hat{\sigma}^2_{DLT}$, $\hat{\sigma}^2_{DLV}$ and $\hat{\sigma}^2_{DLVT}$. The depth by location by treatment-variety combination (DLC) interaction, which also happened to be highly significant was studied. The variance of the means for the DLC interaction is given in Equation 4.

$$V(\bar{y}_{DLC}) = \frac{\hat{\sigma}^2_{Residual}}{(r)(p)} + \frac{\hat{\sigma}^2_{DCPL}}{p} \qquad [4]$$

The values of $\hat{\sigma}^2_{Residual}$ and $\hat{\sigma}^2_{DLC}$ are given in Table 10. Comparing Equations 1 and 4, it is apparent that both yield the same numerical value for $V(\bar{y}_{DLVT})$ and $V(\bar{y}_{DLC})$ for the same number of replications and positions; the $\hat{\sigma}^2_{Residual}$ for both equations are the same and $\hat{\sigma}^2_{DTVPL}$ and $\hat{\sigma}^2_{DCPL}$ both happened to have zero values.

By allocating different numbers of treatments, varieties, positions, locations, replications and depths in Equations 1, 2 and 4, different values for the variances of the means, $V(\bar{y})$, may be obtained. The optimum combination or sampling scheme is one with a reasonably small $V(\bar{y})$ as well as one having a relatively low cost.

$\hat{\sigma}^2$-subscript	$\hat{\sigma}^2_i$		
	1974	1975	1976
R	0 ns	0 ns	0.0481 ns
T	0.0102 ns	0.0384 ns	0.1525 ns
Error (a)	0.0703	0.0950	0.0603
L	0.5181 **	0.3487 **	0.1275 **
P(L)	0.0623 **	0.0104 ns	0.0081 ns
LT	0 ns	0.0865 **	0.2020 **
TP(L)	0.0145 ns	0 ns	0.0090 ns
Error (b)	0.1800	0.1695	0.0860
D	0.2451 **	0.5754 **	0.7542 **
DT	0.0205 *	0.0839 **	0.5392 **
DL	0.1003 **	0.0566 **	0.4475 **
DP(L)	0.0098 ns	0 ns	0 ns
DLT	0.0043 ns	0.0551 **	0.1820 **
DTP(L)	0 ns	0 ns	0 ns
Residual	1.2588	0.9629	2.0163

Table 9. Variance component estimates for 1974, 1975 and 1976 data sets.
ns indicates non-significance at 5% level
* indicates significance at 5% level
** indicates significance at 1% level

From Equations 1, 2 and 4, we know that increasing the number of replications and positions would reduce $V(\bar{y})$. However, increasing replications would result in a slightly greater cost relative to increasing the number of positions, because increasing the number of replications demands a larger number of field plots.

Depths, as mentioned earlier, could be reduced from six to five without affecting $V(\bar{y})$ and at the same time would reduce the cost by 15%. Increasing the number of locations would also have no effect on $V(\bar{y})$ but would result only in an increase of the total sampling units and, hence, the cost of the project. Four locations (as used in the 1974 and 1975 root collection) seem appropriate enough to sample for root distribution. Besides, the space from the soybean row to midrow places a limit on the number of locations that can be taken depending upon the diameter of the coring tube used.

The costs (in terms of manhours) and $V(\bar{y})$ for some sampling schemes are presented in Table 11. The original sampling scheme of 10 treatment-variety combinations (C), 6 depths (D), 4 locations (L), 4 positions (P) and 4 replications (R) used in the 1974 and 1975 studies is presented in Case 1. Case 5, with 3 treatments and 1 variety (3C), 6D, 5L, 2P and 6R, was the sampling scheme followed in 1976. Case 2 (10C, 5D, 4L, 4P and 4R) gives a 15% cheaper scheme over Case 1 and yet achieves the same precision. Case 3 (10C, 5D, 4L, 6P and 3R) compared to Case 2, requires only a 9% increase in cost and yet at the same time reduces $V(\bar{y})$ by 11%. Case 4 (10C, 5D, 4L, 5P and 4R) compares to Case 2, gives a 20% reduction in $V(\bar{y})$ but requires a substantial increase of 23% in cost. Case 3, then, would be preferred over Case 4 because in the latter case, the increase in cost is greater than the reduction in $V(\bar{y})$ while in the former

$\hat{\sigma}^2$- subscript	$\hat{\sigma}_i^2$ 1974	$\hat{\sigma}_i^2$ 1975
R	0.1069 **	0.0178 ns
C	0.3492 **	0.0925 *
Error (a)	0.2414	0.1072
L	0.2645 **	0.3382 **
P(L)	0.0579 **	0.0084 *
LC	0.0683 **	0.0561 **
CP(L)	0 ns	0.0017 ns
Error (b)	0.4676	0.1380
D	0.6601 **	0.7705 **
DC	0.0941 **	0.1401 **
DL	0.2032 **	0.0419 **
DP(L)	0.0287 **	0.0001 ns
DLC	0.1061 **	0.0284 **
DCP(L)	0 ns	0 ns
Residual	1.5735	1.0783

Table 10. Variance component estimates for 1974 and 1975 studies with treatments and varieties combined.

C denotes Treatment-Variety Combination
ns indicates non-significance at 5% level
* indicates significance at 5% level
** indicates significance at 1% level

case, the gain in precision is greater than the cost increase. Compared to the original sampling scheme (Case 1), Case 3 gave a greater relative advantage than Case 4. By changing from Case 1 to Case 3, the cost is reduced by 8% and at the same time, $V(\bar{y})$ is reduced by 11%. Using Case 4 instead of Case 1 would result in a reduction of $V(\bar{y})$ by 20%, but there is a cost increase of 4%. If cost is not a critical limitation on the experiment, then Case 4 would be preferred; otherwise Case 3 would be a reasonable scheme to use.

Cases	C	D	L	P	R	Total Sampling Units	Number of Plots (CxR)	Cost (Manhours)	$V(\bar{y})$		
									1974	1975	1976
1	10	6	4	4	4	3840	40	1752	9.83	6.74	12.60
2	10	5	4	4	4	3200	40	1484	9.83	6.74	12.60
3	10	5	4	6	3	3600	30	1617	8.74	5.99	11.20
4	10	5	4	5	4	4000	40	1820	7.87	5.39	10.08
5	3	6	5	2	6	1080	18	517	13.11	8.99	16.80
6	3	5	4	4	4	960	12	445	9.83	6.74	12.60
7	3	5	4	6	3	1080	9	485	8.74	5.99	11.20
8	3	5	4	5	4	1200	12	546	7.87	5.39	10.08

Table 11. Some sampling schemes, their costs and the variance of the means for the three years of study.

Note: Case 1 was the scheme followed in the 1974 and 1975 samplings.
Case 5 was the scheme followed in the 1976 sampling.
C denotes treatment-variety combination.
D denotes depth.
L denotes location.
P denotes position.
R denotes replications.

CONCLUSION

In 1974 and 1975, a total of 10 treatment-variety combinations (2 varieties and 5 tillage treatments) were used while in 1976, we had only 3 treatment-variety combinations (1 variety and 3 tillage treatments). The number of treatment-variety combinations to be used with the sampling scheme would depend upon the interests of the researcher, as well as the budget and facilities available for the project. Varying the number of treatment-variety combinations apparently will not affect the variances of the means (viz. Cases 3 and 7).

In summary, for future studies on root distribution of soybeans, a sampling scheme of 5 depths, 4 locations, 6 positions and 3 replications is recommended. The suggested depth interval for the sampling scheme is 0-15 cm for the first depth, 15-25 cm for the second depth, 25-35 cm for the third depth, 35-45 cm for the fourth depth and 45-60 cm for the final depth.

This recommendation is based on obtaining a small $V(\bar{y})$ value and a low cost involvement for the project. Since the values of $V(\bar{y})$ depend on the number of replications and positions, the larger the replication-position combination, the smaller the value of $V(\bar{y})$ would be (theoretically) but the costs would increase proportionally. Our recommended sampling scheme of 3 replications and 6 positions (18 replication-position combinations) showed much improvement over the sampling schemes used in 1974 and 1975 (with 16 replication-position combinations) and that in 1976 (with 12 replication-position combinations). Using a sampling scheme with 20 replication-position combinations, as in Cases 4 and 8, would reduce the $V(\bar{y})$ by 10% (compared to a sampling scheme with 18 replication-position combinations) but the cost is increased by 13%. So our recommended sampling scheme with 18 replication-position combinations appears to be a reasonable compromise.

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