STUDIES ON POT-BINDING OF GREENHOUSE PLANTS

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INTRODUCTION

For centuries, textbooks in horticulture have contained directions for the potting or shifting of plants based to a large extent upon customs and practices handed down from earlier generations of gardeners. Even in recent publications in floriculture, the degree of pot-binding is used as the criterion of when plants should be shifted to pots of a larger size. One would infer that it is impossible to maintain plants in a state of thrifty vegetative growth when massing of roots on the periphery of the soil has begun. Although it has not definitely been stated, it is implied that the massing of roots on the periphery of the soil is a condition which should be avoided, if possible, or at least delayed in its occurrence. It is possible that the sparse development of roots within the soil mass, relative to the concentration on the periphery, has given rise to the idea that soil moisture and plant nutrients are removed from a very thin layer of soil, and that most of the soil mass is of no use to the plant excepting as it serves as anchorage.

Plants with yellow leaves and stunted growth are commonly referred to by growers as pot-bound plants, apparently because the massing of roots at the soil-pot interface often occurs at approximately the same time as the checking of vegetative growth. A grower, on being asked to pick out a pot-bound plant, will usually select one which is lacking in vigor, and on removing the mass of soil from the pot, he will almost invariably be able to show the characteristic massing of roots on the periphery of the soil. Bailey (2) considers pot-binding to mean that stage in the development of the plant when roots on the periphery of the soil turn brown, and little new root growth occurs, and this view is held by many floriculturists. Hubbell (17), Jones and Haskins (20) and others, however, consider pot-binding to mean only the massing of roots on the periphery of the soil, regardless of whether these are white or brown, and with no implication of the presence of such symptoms as yellowing of the foliage or stunted growth. It is this latter view that is accepted in this investigation.

STATEMENT OF PROBLEM

In view of the fact that shifting of plants has been based largely upon well-established practice and custom, and because of the prevailing opinion that the pot-bound condition is detrimental to plant growth, there appeared to be a need to investigate further its causes and nature.

At the outset, pot-binding was assumed to be conditioned by certain soil factors. Soil moisture, soil aeration and nutrition were considered to be factors contributing to the development of the condition, both as they affect the concentration of roots in specific parts of the soil, and as they affect the absolute mass of roots produced by a plant.

REVIEW OF LITERATURE

Geotropism

It has long been observed that different plants have root systems which are more or less characteristic of the species or variety to which they belong. Hellriegel (15) reached the conclusion that "every plant builds up a root system to follow a definite architectural pattern, but that variations therefrom may take place if the plants in so doing are more able to satisfy their needs".

Weaver (33) states that "The general characters of the root systems of a species are often as marked and distinctive as are the above-ground vegetative characters. But the root systems of different species of the same genus, while often somewhat similar, may be of entirely different types." Weaver and Brunner (35) consider that the roots of many field crops are governed primarily by the hereditary growth characters of the species of variety. Some root systems are flexible and adapt themselves to different environmental conditions, while others are much less variable in different habitats.

Sachs (29) studied the influence of geotropism on the direction of root growth of _Vicia faba_. It was found that roots at first grew obliquely downwards, and on inverting the plants, roots continued to grow obliquely downwards; on returning to the normal position, roots grew at the same angle with the horizon as before the first inversion. It was found that rhizomes of many plants grew horizontally regardless of the position in which they were placed.

Brenchley and Jackson (5) showed that roots of wheat and barley grown in pots of 14 inches depth, penetrated downwards through the soil until they came in contact with the wall of the pot; these roots did not re-enter the soil, but rather continued to mass on the bottom of the pot.

Although it would appear that geotropism is responsible for the general root pattern of plants, there are some instances in which geotropism is apparently overcome by other stimuli. Coulter et al (8) note that horizontal adventitious roots of Philodendron melanochrysum are commonly found clasping the trunk of a tree, the bark, moisture or other stimulus being sufficient to overcome gravity and induce lateral growth. Further, Kerner and Oliver (22) report that roots of certain epiphytes direct their roots toward the axis of the branch of the tree in question, irrespective of whether this necessitates upward or downward growth, whereas land plants direct their roots toward the center of the earth.

Moisture and aeration

The opinion has been commonly held that the concentration of oxygen in the soil atmosphere is of importance in determining the distribution of roots in specific parts of the soil. Early investigators of the pot-bound condition believed that massing of roots on the periphery of the soil was to be attributed to passage of air through the wall of the pot.

Jost (21) believed that lack of oxygen in the soil was the condition responsible for aerotropic roots in Pandanaceae, Richardia, Cyperus, and Musa, and it was assumed that the formation of a layer of roots on the inside wall of the pot was likewise to be attributed to more favorable aeration in that part of the soil.

Hutchins (18) found that a considerable air space developed between the soil and the wall of the pot as drying occurred, and it was considered that the separation of the soil from the pot wall would allow comparatively free air movement in this region. That this actually occurred was proven by measurements of the oxygen-supplying power of the soil. No statement was made of the degree of dryness required to cause sufficient shrinkage of the soil to permit more favorable aeration conditions at the soil-pot interface than within the soil mass.

Jones (19) claimed to have disproved the popular idea that massing of roots at sides of pots is due to the stimulation of oxygen, since it was demonstrated that no significant movement of air occurs through the pot wall in the moist state. Breschke (6) reached the same conclusion, but found that in some porous pots flaws or fissures were present which allowed considerable passage of air, even though the pot wall was moist.

Hubbell (17) reported no determinable effect on root concentration on the inside walls of pots by creating a forced air movement through the soil. Dean (9) found that aeration of waterlogged horizons caused roots to develop in such soil even though the moisture level was well above the optimum for plant growth, and it was also observed that the densest root growth occurred in the neighborhood of the aerating coils. Likewise, the writer (23) found that aeration of soil cores which had been previously puddled resulted in considerable massing of alfalfa roots in the center of the cores, while in the unaerated cores no such development occurred.

There is a more extensive literature on the influence of air capacity of the soil upon total mass of roots produced than on the influence of specific constituents of the soil atmosphere upon massing of roots in different parts of the soil. It is difficult, however, to distinguish between the separate effect of soil aeration and the direct effect of level of soil moisture upon plant growth. Instances have probably occurred in which small root systems in relation to shoot growth have been attributed to the influence of high level of soil moisture, whereas it is probable that insufficient soil aeration was responsible for the relatively small root development. Likewise, the development of relatively large root systems has been frequently attributed directly to low soil moisture, but the possibility of an aeration influence is tenable in such instances, especially before soil moisture becomes limiting to shoot growth.

The influence of artificial aeration in stimulating the development of roots in water cultures has been demonstrated by Hall, Benchley and Underwood (13), Knight (24), and others. Hubbell (17) reported that root growth is greatly inferior in sealed pots as compared to pots in which the surface is uncovered, the reduction in shoot growth being attributed to deficient aeration in the sealed pots. The occurrence of smaller root systems in glazed pots as compared to porous pots may have resulted from differences in aeration between the two kinds of pots or from the direct influence of level of soil moisture.

Harris (14) reported that plants produced a proportionately smaller root weight in comparison with the weight of shoot in soil with the higher moisture level, and that the shoot/root ratio was affected more by a change in the moisture level of the soil than by a change in the amount of nutrients. Similar results were obtained by Tucker and vonSeelhorst (31) and by Weaver and Himmel (36) who report that root growth increases with decreasing water content of the soil until soil moisture becomes the limiting factor.

Henderson (16) believed that maintaining the soil in a wet condition was responsible for poorly developed root systems in potted plants with a large amount of foliage. When geraniums or other large-leaved plants were placed close together, there resulted weak and poorly developed root systems, presumably because of prolonged state of high soil moisture or because of unfavorable conditions for photosynthesis. Moving the plants farther apart resulted in the development of more extensive root systems. Jones and Haskins (20) found larger root systems in porous pots than in glazed pots in the case of tomatoes. It was believed that the higher moisture level in glazed pots was responsible for the smaller mass of roots. Breschke (6) found that the matting of chrysanthemum roots was considerably thicker on the permeable than on the lacquered side of half-coated pots, and actual dry weights confirmed this observation. No difference in root development was observed, however, in the matting of tomato roots on the two sides of half-coated pots, and this was also true in the case of geranium (Pelargonium zonale). Whether there was actually a significant movement of oxygen through the uncoated pot wall or whether the greater massing of roots on the porous pot wall was merely a response to lower soil moisture in the one half of the soil mass seems uncertain, especially in view of the fact that different responses were obtained with different plants.

Nutrients

Many investigators have studied the influence of localized concentrations of nutrients upon the development of roots in specific parts of the soil. Thiel (30) found profuse branching of roots in fertile soil when alternated with poor sand. Nobbe (27) reported that regardless of where nutrient salts were concentrated in the soil, the form of root system was practically the same in all cases, but the degree of branching was much greater in fertilized than in unfertilized soil. Frank (11) found with individual plants grown with divided root systems in two separate vessels that roots were only slightly branched in the nitrogen-free vessel, while in the vessel receiving nitrogen there was a profuse branching of roots.

Jones and Haskins (20) attributed the massing of roots at the soil-pot interface to the influence of localized concentration of nutrients since there were relatively few roots on the outside of the soil mass when plants were grown in glazed pots. The theory was advanced that "distribution of roots in plant containers is tied up directly with plant nutrients and is indirectly related to soil moisture movements." Non-porous pots were found to have a relatively uniform distribution of plant nutrients throughout the mass of soil, while in clay pots there was a decreasing gradient from the center to the outside. Since porous pots were shown to absorb nutrients from the soil, it was considered that "roots develop at the point where the relatively large amount of available nitrogen is concentrated by movement of water through the soil by the force of evaporation." It was concluded that the pot-bound condition was characteristic only of plants in clay pots.

There is an extensive literature on the influence of the nitrogen level of the rooting medium upon the total mass of roots produced (Harris (14), Turner (32) and others). In general, it has been found that increasing the level of available nitrogen increases both shoot and root growth, but that shoot growth is increased proportionately more than root growth. Likewise, decreasing the level of available nitrogen leads to a checking of shoot growth with a simultaneous stimulation of root growth.

From the survey of the literature presented, it becomes evident that, with the exception of the systematic investigations of Jones (19), Jones and Haskins (20), and Hubbell (17), there has been only a limited amount of study devoted specifically to the pot-bound condition of greenhouse plants. There is, however, a wealth of information concerning such factors as the influence of geotropism, soil moisture and nutrition upon root behaviour.

With respect to the influence of geotropism upon this condition, it seemed that the general principle that roots of plants spread laterally, obliquely and directly downwards, regardless of the influence of other factors, was of importance in the present investigation. Further, it appeared that soil aeration, soil moisture and nutrition were also concerned in this problem, both insofar as they affect localization of root development and the shoot/root ratio of plants.

EXPERIMENTAL METHODS AND RESULTS

I. Relation of Pot-binding to Development of Roots within the Soil Mass

As was mentioned previously, statements have appeared in the literature to the effect that root systems of pot-bound plants are restricted largely to the periphery of the soil, and this is in agreement with the generally-held opinion of gardeners. A systematic inquiry seemed appropriate to determine the extent to which this view is borne out by the facts.

Plants of the following species were used in this study: column stocks (Matthiola incana), primula (Primula malacoides), cineraria (Cineraria hybrida), coleus (Coleus Blumei), and schizanthus (Schizanthus wisetonensis). Column stocks were grown in 2½-inch pots from the time of first transplanting; all other plants were shifted to porous pots of larger sizes according to commercial practice, and at the time of observation, plants of primula and coleus were in 5-inch pots, and cineraria and schizanthus in 6's. Plants showing the pot-bound condition to different degrees were selected for study.

The procedure used in examining the concentration of roots within the soil mass consisted of sectioning the soil masses vertically through the center, and then, by means of a gentle stream of water, exposing the cut ends of the roots. By this means it was found possible to compare the massing of roots on the periphery with the concentration within the soil mass in a large number of plants in a short period of time. A photographic record was considered the most satisfactory means of recording the observations.

There was a direct and consistent relationship between pot-binding and the concentration of roots within the soil mass in the case of all plants studied. This is at once evident from an inspection of Figs. 1 to 3. Pot-bound plants had always a greater number of roots within the soil mass than did those which were not pot-bound. This relationship was more noticeable in the case of schizanthus (Figs. 2 and 3) than in stocks (Fig. 1)

In comparing the development of roots within the soil masses in Figs. 1 and 3, it must be remembered that the schizanthus were grown in pots of a smaller size before the final shift to 6's, while the stocks were grown only in 2½-inch pots. Such previous treatment would result in a greater massing of roots within the soil mass than would have occurred had the plants been grown in 6-inch pots from the seedling stage.

Fig. 1. Relationship between degree of pot-binding and root development within the soil in column stocks.

1. Vertical section and periphery, respectively of a pot-bound plant.

2. Vertical section and periphery of a plant which is not pot-bound.

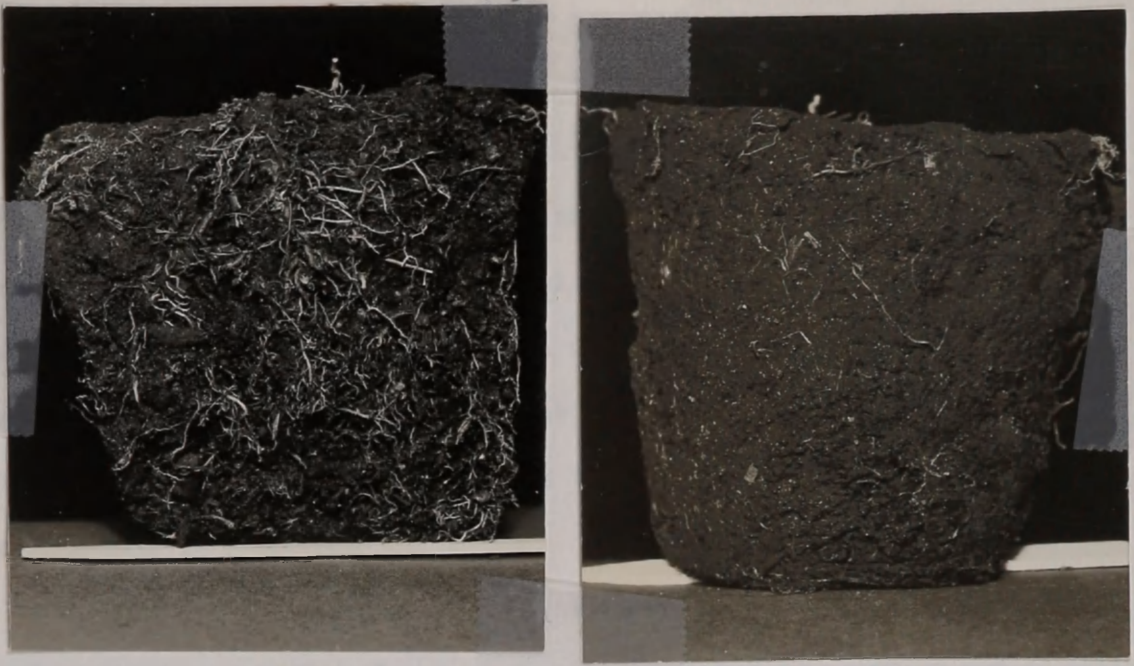

Fig. 2. Schizanthus root system showing relatively small root development within the soil mass and few roots on periphery.

Left: vertical section Right: periphery

Fig. 3. Schizanthus root system showing relatively greater massing of roots within the soil and considerable development on periphery.

Left: vertical Right: periphery

II. Relation between Weight of Shoot and of Root, the Shoot/root Ratio and Pot-binding.

Hubbell(17), and Jones and Haskins(20) reported that the mass of roots in clay pots was always greater than in glazed pots, and that there was also a higher shoot/root ratio when plants were grown in glazed pots. At the beginning of this study, it seemed important to study the relationship between degree of pot-binding and the shoot/root ratio, since it was assumed that any soil condition which tends to promote root development might substantially alter this ratio.

Root systems of mature plants of schizanthus, cineraria and primula which had been grown for the purpose of studying the effect of localized nutrient concentrations upon the development of roots within the soil mass were examined. Considerable variability was found among individual plants of each kind at the beginning of the study, especially in the case of schizanthus. Watering was performed in such a way that leaching was reduced to a minimum, applications being made whenever the lighter color of the surface soil indicated its need.

Plants of primula, schizanthus and cineraria were divided into two classes: those which showed considerable pot-binding, and those which showed only a slight massing of roots on the periphery. Plants showing an intermediate degree of pot-binding were omitted from this study. Plants of the two classes were of the same age, and can be selected from any group of plants where differences in vegetative growth are exhibited.

All soil and foreign material was washed from the roots, and plants were then oven-dried at 90°C. for 24 hours, at which time the dry weights of shoots and roots of individual plants were determined.

Table 1. Relationship within the same age group between weight of shoot and of root, the shoot/root ratio and degree of pot-binding.

Plants with no pot-binding			Plants with pot-binding		
Shoot wt. gm	Root wt. gm	Shoot/root ratio	Shoot wt. gm	Root wt. gm	Shoot/root ratio
Schizanthus 13.5±4.4	.83±.19	16.2±2.5	17.0±1.7	*** 2.24±.62	*** 7.9±1.5
Cineraria 14.0±3.0	1.6±.6	9.8±3.5	*** 20.3±3.2	*** 3.0±.41	* 6.9±1.7
Primula 11.8±1.7	.53±.16	23.2±7.0	* 15.0±2.9	*** 1.1±.28	** 13.8±1.7

*** significance at 1% point between means of pot-bound plants and those showing no pot-binding.

** significance at the 5% point.

* near significance at the 5% point.

Although the number of plants involved in the above study was limited to from four to six individuals in each group, there were some consistent and significant differences in mass of shoot and root between plants with few roots on the periphery and those which were pot-bound. From data presented in Table 1, it can be seen that there was a consistent relationship between weight of shoot and the tendency to become pot-bound, but this was significant only in the case of cineraria. When average root weight is considered, however, it is evident that pot-bound plants had significantly larger root systems than those which were not pot-bound, and this held true in the case of all plants studied. The relation between shoot/root ratio and degree of pot-binding was highly significant in schizanthus, only slightly so in primula, and in cineraria the difference approached significance at the 5 per cent point.

Corroborative evidence of the above-mentioned relationships between mass of shoot and root and degree of pot-binding is afforded from data presented by Hubbell (17) to show the difference in amount of shoot and root growth produced in plant containers of different kinds by geranium (*Pelargonium hortorum*). Calculation of the rank correlation coefficient between average dry weight of shoot and root, and degree of pot-binding presented in Table IV of Hubbell's report shows a very high relationship between both shoot and root weight and degree of pot-binding. The rank correlation coefficient between weight of root and degree of pot-binding is + 0.877, that between weight of shoot and degree of pot-binding is + 0.795, while the correlation between shoot/root ratio and degree of pot-binding is – 0.886. These relationships are similar to those established by the writer.

The interpretation to be placed upon Hubbell's data and that obtained in this study is that pot-binding is an expression of the total mass of plant, and particularly of the mass of root. The application of this conclusion is of importance in this study, since the problem of what causes pot-binding resolves itself, in part, into a study of those factors which influence the mass of shoot and of root and the shoot/root ratio of plants.

In view of the above discussion, it seemed logical to assume that plants of different kinds might exhibit varying degrees of pot-binding, depending upon their relative masses of shoot and root and their shoot/root ratios. Although no definite conclusions have been drawn, it has been suggested that a relationship exists between mass of the root system of different plants and degree of pot-binding, and especially when this is determined on a fresh weight basis. Likewise, there appears to be a relationship between the shoot/root ratio of different plants and degree of pot-binding when weights are determined on the fresh weight basis.

III. Influence of Moisture and Aeration upon Pot-binding.

At the beginning of this study, it was assumed that pot-binding was related to the difference in soil moisture level, and consequently in soil aeration, in different parts of the soil mass, since the air capacity of a soil decreases as a state of saturation with water is approached. It was believed that the massing of roots on the periphery of the soil mass and the relatively smaller development within the soil was to be attributed, at least in part, to the more favorable aeration conditions that might exist at the interface between the soil and the pot wall than within the mass of the soil. Conversely, the sparse development of roots within the soil was believed to be due to the relatively high state of soil moisture which presumably prevented effective aeration.

Methods of Study

Variation in moisture content within the soil mass in porous pots

Twelve 6-inch pots were filled with a greenhouse compost and water was added until drainage occurred. After 18 hours, samples of soil were taken from four pots, the samples being taken from the following regions: (1) from the periphery of the soil (2) at a distance of 2 to 3 cm from the periphery, and(3) from the center of the soil mass. Scrapings were taken from the entire exposed surface of each sampling region. The second set of samples was taken at the time that the surface of the soil became slightly gray, and the third set at the time that a gray crust had formed, and shrinkage of the soil mass from the pot wall had occurred. Samples were oven-dried, and the moisture content calculated on the dry weight basis.

A second study was conducted, similar to the above in all respects excepting that the pots contained well-established root systems of coleus. Fifteen plants were used in this study, five plants being sampled at each of the three periods.

A further test of the difference in soil moisture in different parts of the soil mass was made by measuring the soil moisture tension by means of tensiometers placed at varying distances from the periphery. Tensiometers were constructed by using a small block of plaster of Paris to allow the attainment of rapid equilibrium between tensions in the soil and in the instruments. A glass tube filled with air-free distilled water was sealed into the permeable blocks by means of ferrule cement. The mercury manometers on the end of the tubes allowed the reading of soil moisture tensions with considerable accuracy and rapidity. Tensiometers were checked for uniformity by exerting definite tensions on them by means of suction. These instruments were placed over a porous plate of plaster of Paris, surrounded with soil in a buchner funnel, and a tension was exerted upon the soil. Tensiometers giving deviations in reading of more than 0.1 cm of mercury from the mean were discarded.

Plaster of Paris resistance blocks, similar to those designed by Bouyoucos, were found to be unsatisfactory for measuring the range in soil moisture which is of significance in aeration, since there is no change in resistance readings of these blocks until pF 2.0 is reached. According to Baver (3), it is the range of soil moisture tensions from zero to pF 1.6 which is of significance in soil aeration. Tensiometers are well suited to the measurement of this range of tensions.

Effect of artificial aeration on distribution of roots

As a further test of the influence of soil aeration on the development of roots in different parts of the soil, a study was made of the influence of artificial streaming of air through the center of the soil mass upon root distribution. This study was designed to test the hypothesis that a deficiency of oxygen or an accumulation of carbon-dioxide in the center of the soil mass is in part responsible for the relatively sparse development of roots in this area.

In a preliminary test, four small plants each of primula and cineraria were set in 5 and 6-inch pots, respectively, two plants of each kind being used as checks while two received artificial aeration. The primula plants were set in 5-inch pots and the cineraria in 6's, small plants and large pots being used to reduce the rate of water loss to a minimum, and hence aggravate the aeration deficiency if this existed. A glass tube was inserted into the pot through the drainage hole in the bottom and with the upper end opening into the center of the soil; the lower end was connected to a water aspirator which gave a low vacuum. A volume of 225 cc of air was pulled through the soil daily at a rate such that artificial streaming of the soil atmosphere occurred for a period of approximately 12 hours. This method of aerating masses of soil had been found to be entirely satisfactory in aerating cores of soil in a previous experiment (23). A volume of 225 cc was decided upon in this study, since it had been found that a volume of 300 cc was equally as satisfactory as 900 cc in aerating the much larger masses of soil used in the previous study.

Soil moisture was maintained in the moist end of the available range by frequent but light irrigations; at no time during the experiment did a state of saturation or a drying out of the surface soil occur.

An examination of the root systems after three months showed no detectable difference in root distribution in different parts of the soil mass between those plants receiving artificial aeration and those which received only natural aeration. On account of the large pots used in proportion to the size of plants, there was little tendency for roots to mass on the periphery of the soil under either natural or artificial aeration. It was conceived that natural aeration was entirely effective in maintaining a vigorous root development under the conditions of soil moisture maintained in this study, and that any further exchange of soil gases was of no importance as far as root growth was concerned.

A second aeration trial was conducted using column stocks in $2\frac{1}{2}$-inch pots, the small pots being employed because of the shorter length of time required for a considerable mass of roots to be produced. Stocks were especially satisfactory for this purpose because these plants have been found by the writer to be particularly susceptible to deficient soil aeration. Any deficiency in soil aeration within the soil mass would be indicated by this plant. In seven pots, an air tube entered the center of the soil mass as in the preliminary trial, and in three pots, the tubes opened into a layer of coarse sand in the bottom of the pots, thus aerating the periphery of the soil in the event of cleavage occuring between the periphery of the soil and the wall of the pot.

At the end of three weeks, it was necessary to add 10 ml of a solution containing 0.05 per cent of nitrogen in solution to each pot to correct a deficiency of nitrogen. Daily aeration and frequent but light irrigation was practiced as in the previous trial. An equal number of plants in pots of the same size received similar treatment as far as watering and addition of nutrients are concerned, but no artificial aeration was provided. An examination of the development of roots within the soil mass and on the periphery was made after 5½ weeks by sectioning the soil masses vertically through the center and exposing the cut ends by gentle washing.

Results of Study

Study of soil moisture levels in porous pots

Determinations of level of soil moisture in different parts of soil masses maintained fallow and with plants, from a state of soil moisture approaching saturation until a gray crust formed on the surface, showed no significant differences until the surface layer of soil became gray (Table 2). At saturation, there was no significant difference between the level of soil moisture at the periphery and within the soil mass, either when the pots were maintained fallow or when coleus were grown in the pots. When plants were growing in the pots, there was in all individual pots sampled at the "near saturation" point a slightly higher level of soil moisture at the periphery than within the soil mass. This difference is attributed to the larger proportion of roots in samples from the periphery than in those taken at 2 to 3 cm from the periphery or from near the center of the soil mass.

Table 2. Soil moisture levels at varying distances from the periphery in porous pots maintained fallow and with plants from saturation to the wilting point.

Location of Sampling	State of soil moisture*		
	Near saturation	Surface becoming gray	Surface gray
	(per cent by wt.)		
Fallow			
Periphery	55.2	24.6	15.8
2 to 3 cm from periphery	54.8	25.5	18.4
Center	55.8	26.2	19.1
With Plants			
Periphery	49.3	28.0	16.3
2 to 3 cm from periphery	48.2	29.2	17.0
Center	48.8	29.3	18.5

* Data presented are for representative individual pots.

It is unlikely that a difference of 1.7 per cent in soil moisture between the periphery and center of the soil mass at the time that the surface soil becomes gray is of any significance insofar as aeration is concerned. If such a difference occurred at saturation or at any stage from saturation until pF 1.6 is reached, it is entirely conceivable that significant differences in aeration might exist. When aeration of the soil is already favorable, however, it is improbable that root growth is affected by a slightly higher air capacity in one part of the soil than in another. As the wilting point of the soil is approached, the difference between soil moisture levels at the periphery and within the soil becomes greater, but with most soils encountered in greenhouse practice, aeration is not likely to be restricted within this range of soil moisture.

At the time that the surface of the soil is becoming gray, the layer of soil immediately below has a moisture content equal to that of the moisture equivalent, according to Woodruff (37). Determination of the moisture content of the entire soil mass at the time of the graying of the surface has given values of 23 to 27 per cent moisture on a volume basis, which is 5 to 9 per cent higher than the moisture equivalent. It is the range of soil moisture from saturation to the time of the graying of the surface that is of most importance in greenhouse studies, since it seldom happens in ordinary plant culture that the soil moisture level is allowed to go below the moisture equivalent.

Since it has been demonstrated that no significant difference in moisture content occurs in any part of the soil mass in pots on the same horizontal plane between a state or saturation and the point when the surface becomes gray, it is improbable that significant differences in aeration exist in pots receiving ordinary watering treatment. Any differences in soil moisture level occurring after the surface becomes gray is of no significance in aeration in compost soils of the type used generally.

Similar results were obtained by measuring the differences in soil moisture tension by means of tensiometers placed in different parts of the soil mass. From a state of saturation until drying of the surface of the soil began, there was a marked uniformity in soil moisture tensions in all parts of the soil on the same horizontal plane. Tensions were measured at the periphery, at the center and at intermediate locations. In no instance did the difference in soil moisture tension exceed 0.2 cm of mercury, and this was true in pots containing well-established root systems of chrysanthemums, as in those in which no plants were growing. These measurements were made under the conditions of slow rate of evaporation which occur in cool greenhouses in winter, and it is possible that somewhat greater differences would have occurred had the study been conducted under conditions of rapid evaporation and transpiration. There was usually a difference of 0.6 cm of mercury between the tensions at the top and bottom of the soil mass owing to the influence of gravity upon moisture distribution.

These observations further support the conclusion that massing of roots on the inner surface of porous pots is not associated with differences in soil aeration resulting from unequal distribution of soil moisture. Furthermore, from the results of investigations of the permeability of moist pots to air by Jones(19) and by Breschke(6), it seems highly improbable that sufficient passage of air occurs through walls of porous pots to have any significant effect upon the accumulation of roots at the soil-pot interface.

Effect of artificial aeration upon distribution of roots of column stocks

Examination of aerated root systems of stocks was conducted after five weeks. There was no difference in concentration of roots within the soil mass as a result of the artificial streaming of air through the soil as is shown in Fig. 4. Likewise, there was no stimulation of root development on the periphery as a result of aerating the layer of sand in the bottom of some pots. As is shown in Figs. 1 and 4, the concentration of roots within the soil mass was similar to that obtained when only natural aeration occurred.

With the compost soil and the range in soil moisture used in this investigation, it is concluded (1) that no significant difference in

Fig. 4. Cross-section of soil mass aerated at the center showing absence of stimulation from artificial aeration (stocks potted 5 weeks) Left: vertical section. Right: periphery

capacity occurs between different parts of the soil mass in porous pots, (2) that exchange of soil gases, and consequently the composition of the soil atmosphere, is favorable under aeration conditions prevailing naturally, and (3) that the sparse development of roots within the soil mass relative to that on the periphery is not the result of a deficiency of oxygen, or of an accumulation of carbon-dioxide.

IV. Relation of Nitrate Level to Pot-binding.

Methods of Study

Plants in single pots

It has been well-established by Egorov (10), Turner (32), and others that raising the available nitrogen level of the soil results in a higher shoot/root ratio, that is, a plant growing at a high level of nitrogen and with a large mass of shoot may have a root system whose mass is little greater than that of a much smaller plant growing at a lower nitrogen level. It seemed that the application of this principle to the development of pot-binding should be studied, and especially so since previous studies showed that massing of roots on the periphery of the soil was directly related, both to the concentration of roots within the soil mass and to the absolute weight of root produced.

Only stocks were used in studies involving the shoot/root ratio, but in experiments designed particularly to show the relationship between nitrate level and the tendency to become pot-bound, both stocks and coleus were used. Plants were grown in pots of different sizes and with varying nitrate levels in the soil, the level of nitrate concentration being controlled by the degree of leaching and by the addition of nutrients in solution. Group I received heavy leaching with no supplementary nitrogen, group 2 received no leaching and no nitrogen, and group 3 received no leaching but supplementary nitrogen as required. Thus the nitrate level in group 1 was reduced rapidly and maintained at a very low level throughout the experiment, that in group 2 was reduced much more slowly, and that in group 3 was maintained at a relatively high level.

An attempt was made to maintain a uniform moisture level in all groups. Plants in the first group received water at the same time as those in the other groups, the only difference in watering being that these plants received more water at each irrigation. Careful attention was required to prevent drying out of the soil. Water was applied only when the surface of the soil began to turn gray, since it has been found by the writer that stocks are particularly susceptible to deficient aeration in the soil. Woodruff(37) reports that when the change in color of the surface soil occurs, the layer of soil immediately below the dry crust has a moisture content equal to that of the moisture equivalent, and by making a few trials with pots of different sizes, it was found possible to add water to pots of a given size without having leaching occur. It was therefore possible to work with as many as 30 plants in each group without requiring the great expenditure of labor that would have been involved had individual pots been brought to constant weight two or three times daily.

Nitrogen was added in the form of potassium nitrate, using it to give a concentration of 0.075 per cent nitrogen in solution. A volume of five cc was added to each pot of group 3 at each application. A careful check was made of the nutrient level of plants in each group throughout the period of study. This was possible by making an analysis of approximately six cc of leachate from four individual pots in each group at regular intervals. It was assumed that the small volume of leachate removed would not reduce the nitrate level of the soil to any appreciable degree. "Rapid" tests were made for nitrate at every sampling, and an occasional test was also made for potassium in order to prevent the occurrence of an excess of this ion. Correlation between soil and leachate analysis from 35 pots showed that the value for nitrate in the leachate could be divided by 60 to give the approximate nitrate level in the soil, the error being less than three parts per million when the nitrate level of the soil was within the limits of 3 and 20 parts per million. The corresponding division factor for potassium was 8, the lower value in this case being due to the potassium being present largely in the adsorbed state. These division factors hold only for the greenhouse compost and for the degree of packing used in this investigation, since different soils will hold different percentages of water at saturation.

Stocks were transplanted from flats when the first two true leaves had developed, and were then set in 2½-inch pots. In the first trial, 24 plants were employed in each group, but in all later trials, 30 plants were used in each. The three varieties used were Exquisite, Puritan Pure White, and Priscilla Silvery Lavender.

Plants of Coleus Blumei were set in 2½-inch and 4-inch pots of standard shape, and in 3½-inch "rose" pots, the smaller plants being set in the smaller pots. Plants to be set in each size of pot were selected for uniformity. Twelve plants were used in each group for each of the three pot sizes.

All soil and foreign material was washed from the roots of the stocks, and the oven-dry weights of shoot and root of individual plants determined.

Plants with divided root systems.

Owing to the fact that all plants in single pots receiving the same treatment did not show a uniform degree of pot-binding, it was thought that the relation between nitrate level of the soil and degree of pot-binding could be clearly demonstrated by splitting the root system and the lower part of the stem and growing single plants in two separate rooting media of different nitrate levels. Coleus was used extensively in this study owing to the fact that the stem and root system can be divided without retarding the growth of the plant. Geraniums were found to be unsatisfactory owing to separation of the bark from the woody tissue. Column stocks were satisfactory providing that division of the stem was made before hardening of tissue had begun.

The base of the stem was split longitudinally in two parts, as is shown in Fig. 14, and the root system then concentrated on the inside wall of pots. The development of roots on the sides of pots opposite the place where the roots were originally massed was used as the criterion of influence of nitrate level upon pot-binding.

In studying the influence of varying concentrations of nitrate in the soil upon pot-binding, it was only necessary to leach one pot to the required degree and leave the other unleached or add supplementary nitrogen, depending upon the nitrate level desired. Analysis of six ml. of leachate from each pot at regular intervals throughout the period of study allowed a precise and rapid determination of available nitrate and potassium in the soil.

Results of Study

Plants in single pots.

In the preliminary trial, using 24 plants of the Exquisite variety of column stocks in each group, there was evidence of nitrogen deficiency in those plants receiving leaching at the end of three weeks. Plants receiving supplementary nitrogen rapidly surpassed the other two groups in shoot growth, so that at the end of seven weeks, they had approximately four times the weight of shoot as plants in group 1. The differences in vigor of growth between the three groups are shown in Fig. 5. Plants in groups 2 and 3 showed the pot-bound condition to about the same degree, while those in group 1 were only slightly pot-bound. Many of the older root tips turned brown after prolonged nitrogen deficiency.

The effect of different nitrate levels in the soil on the weight of shoot and root and on the shoot/root ratio is presented in Table 3. There was a consistent increase in the weight of shoot and root, and in the shoot/root ratio with higher nitrate levels. It appeared that the tendency to become pot-bound was always less marked in plants growing at a low level of nitrogen nutrition than at higher levels. It is certain that at the state of development of the stocks represented in Fig. 5, the pot-bound

Table 3. Effect of different nitrate levels upon the weight of shoot and root and upon the shoot/root ratio of stocks (dry wt. basis).

Treatment	Shoot wt. gm.	Root wt. gm.	Shoot/root ratio
Low nitrate (group 1)-6 weeks	.22 ± .09 ***	.07 ± .02	3.7 ± .96
Medium nitrate (group 2)-6 weeks	.37 ± .13 ***	.09 ± .02 ***	4.1 ± .80 ***
High nitrate (group 3)-6 weeks	.84 ± .17 ***	.13 ± .03 ***	6.75± .92 ***
8 weeks	1.20 ± .25	.17 ± .03	7.1 ± .46

*** indicates significance between means at the 1% point using low nitrate as the basis for comparison

Fig. 5. Relation of nitrate level to shoot growth and degree of pot-binding in column stocks (7 weeks).

1. Low nitrate (heavy watering)	2. Medium nitrate (light watering)	3. High nitrate (light watering plus nitrogen)

condition was exhibited to a much greater degree in those plants receiving light watering and supplementary nitrogen than in those which had been leached during the course of the experiment.

In succeeding trials of the influence of nitrogen nutrition upon pot-binding, careful observations of the development of roots on the periphery of soil masses of different groups were made at weekly intervals from the time of potting until the conclusion of the experiments at eight weeks. The sizes of plant produced and the associated development of roots on the periphery of the soil are illustrated in Figs. 6 to 8, showing the stage of shoot and root development at 3½ weeks, 5 weeks, and 8 weeks respectively. Each plant was selected to represent the 30 plants in each group.

At the end of 3½ weeks, there were no appreciable differences in either shoot or root growth between any of the three groups (see Fig. 6). At five weeks, the upright character of the upper leaves indicated the beginning of symptoms of nitrogen deficiency, but insofar as amount of shoot growth is concerned, there was little difference between the three groups. Those plants receiving heavy watering showed a considerable massing of roots on the periphery (see Fig. 7); the degree of pot-binding was somewhat less in those plants receiving light watering, and still less in those plants receiving supplementary nitrogen. In some instances, the degree of pot-binding was greater in group 2 than in group 1, but there was always a definite and consistent difference between pot-binding of groups 1 and 3, and of groups 2 and 3. At eight weeks, the symptoms of nitrogen deficiency had become readily discernible in those plants receiving heavy watering, and to a lesser degree in those receiving light watering (Fig. 8). Defoliation of the lower parts of the stems had occurred, there was a definite stunting of the plants, and the characteristic upright habit of growth of the upper leaves indicated an advanced stage of nitrogen deficiency.

Fig. 6. Relation of nitrate level to shoot growth and degree of pot-binding in column stocks at 3½ weeks(Silvery Lavender variety).

1. Low nitrate (heavy watering)

2. Medium nitrate (light watering)

3. High nitrate (light watering plus nitrogen)

Fig. 7. Relation of nitrate level to shoot growth and degree of pot-binding in column stocks at 5 weeks (Silvery Lavender variety).

1. Low nitrate (heavy watering)	2. Medium nitrate (light watering)	3. High nitrate (light watering plus nitrogen)

Fig. 8. Relation of nitrate level to shoot growth and degree of pot-binding in column stocks at 8 weeks (Silvery Lavendar variety).

1. Low nitrate (heavy watering)

2. Medium nitrate (light watering)

3. High nitrate (light watering plus nitrogen)

Comparing group 1 in Figs. 7 and 8, it would appear that the degree of pot-binding was less at eight weeks than at five weeks. A close examination of the periphery of the 8-week plants showed that the roots had become brown and only a sparse development of new roots had occurred. According to the definition of pot-binding accepted in this study, there was actually a reduction in degree of pot-binding as the symptoms of nitrogen deficiency became more pronounced; in accordance with the usage of the term by gardeners, however, namely that plants lacked vigor and roots were brown in color, there was a definite increase in degree of pot-binding. In group 3 of the 8-week plants, the massing of roots on the periphery was quite pronounced, and there was no evidence of browning of the roots such as occurred under deficiency of nitrogen. In fact, there was no evidence of browning of roots at the periphery of plants in group 3 after 12 weeks. All primary and secondary roots remained white in all three groups.

Whether toxic conditions developed at the periphery in plants receiving heavy leaching was not definitely determined, but the fact that roots of plants receiving supplementary nitrogen remained white, and that white roots were again produced on addition of nitrogen to leached pots, would suggest that merely a deficiency of nitrogen and the resulting increased maturity of root tissues was the cause of the browning of the roots, This explanation of the cause for roots becoming brown is of significance to those who consider pot-binding to be that stage in plant development when vegetative growth is restricted and roots on the periphery of the soil lose their characteristic white color. It is not to be inferred, of course, that deficiency of available nitrogen is the only condition which can bring about browning of the roots, since any factor which increases the maturity of tissue, or which has a toxic effect upon root tissue, might be responsible; in this case, however, nitrogen deficiency is most likely to be the primary cause.

The difference in development of shoot and root under the different levels of nutrition were carefully checked in two succeeding plantings of stocks. There was in both repetitions a smaller amount of shoot growth in those plants receiving heavy watering than in the first trial. A change in the seasonal conditions during the early period of development, or a more severe leaching was probably responsible for this difference.

A repetition of the test to determine the influence of nitrogen level upon the shoot/root ratio was conducted using plants of the three groups at eight weeks. The results were similar to those presented in Table 4. As the size of plants increased, and praticularly the mass of the root, there was a tendency for plants to exhibit a greater degree of pot-binding.

All of the previous experiments designed to show the influence of nitrogen level upon degree of pot-binding were conducted with the Silvery Lavender variety of column stocks. Application of the same treatment to the Puritan Pure White variety produced an extremely dwarfed shoot growth in the leached group (see Fig. 9). There was no detectable difference, however, either in amount of shoot growth or in degree of pot-binding between groups 2 and 3. At five weeks, plants receiving supplementary nitrogen were larger, and exhibited a greater degree of pot-binding than did those plants receiving no additional nitrogen. In view of the fact that plants were grown in a uniform soil and received the same degree of leaching, it appears that the Puritan Pure White variety requires a higher concentration of available nitrogen in the soil in order to produce a thrifty growth than does the Silvery Lavender variety.

Fig. 9. Relation of nitrate level to shoot growth and degree of pot-binding in stocks at 3½ weeks (Puritan Pure White variety).

1. Low nitrate (Heavy watering)	2. Medium nitrate (light watering)	3. High nitrate (light watering plus nitrogen)

A determination was made of the shoot/root ratio of groups of stocks of the variety Silvery Lavender grown in pots for three weeks. The results are presented in Table 4, and supply evidence to indicate the stage at which differences in pot-binding occur under the different nitrate levels. It is evident that at this stage of growth, there was no significant difference in weight of shoot, weight of root, or in the shoot/root ratio between the two groups.

Table 4. Relationship between weight of shoot and root, and shoot/ root ratio, and the nitrate level of the soil (stocks potted 3 weeks).

Treatment	Ave.shoot wt. gm.	Ave. root wt. gm.	Ave. shoot/root ratio
Low nitrate (heavy watering)	.56 ± .15	.09 ± .03	6.2 ± 1.3
High nitrate (supplementary nit.)	.65 ± .33	.12 ± .09	5.4 ± 1.5

An indication of the relative rates of nitrogen depletion under the three different treatments is obtained from data presented in Table 5. The values represent concentrations of nitrate ion in the soil in parts per million, each value being an average of four pots. The determination of concentration of nitrate in the soil was made by means of leachate analysis described previously.

There was a marked uniformity in nitrate concentration within each of the three groups under study. Leachate analysis of 12 individual pots at the 3-week period gave a range of nitrate concentrations in the leachate of from three to six parts per million, which is relatively insignificant when

Table 5. Reduction in nitrate concentration in the soil by watering practices. (stocks in $2\frac{1}{2}$-inch pots)

Time	Leached	Unleached	Unleached-plus-nitrogen
	(nitrate in parts per million in the soil)		
$1\frac{1}{2}$ weeks	1.25	7.0	22
3 weeks	0.08**	1.5	14
6 weeks	Trace	0.05	10

**Twelve pots were sampled in arriving at this value.

when calculated on the basis of concentration in the soil. In the unleached and unleached-plus-nitrogen groups, the variations were somewhat larger.

Little difference in growth occurred between the three groups until after the first four-week period; nevertheless, the concentration of nitrate in the soil in group 1 had been reduced to a fraction of a part per million at the end of three weeks. It is also important to note that there were no significant differences in the shoot/root ratio between the three groups at the end of the 3-week period, despite the extremely large differences in the nitrate levels of the soil. Plants had apparently obtained sufficient nitrogen from the soil in the seedling stage and in the first two weeks in pots to maintain a thrifty vegetative growth on reserves stored in their tissues.

Plants in the three groups showed a uniform development up to the time that nitrogen deficiency occurred. Afterwards, in nitrogen-deficient plants, there was a reduction in rate of shoot growth and a simultaneous stimulation in root development, resulting in a greater massing of roots at the periphery in group 1 than in groups 2 and 3, and this was followed by a browning of the mass of fine roots on the periphery and a characteristic absence of new white roots. Under the influence of more favorable nutrient conditions, groups 2 and 3 produced a larger mass of shoot and root, and showed the pot-bound condition to a greater degree at the end of the experiment.

Results with coleus.

Typical plants from each group and from each size of pot at five weeks are shown in Figs. 10 to 12. No marked differences in degree of pot-binding were obtained between different groups, and this was especially true in the case of coleus in 4-inch pots. It was noted, however, that plants in 2½-inch and rose pots receiving heavy watering and consequently a low level of nitrogen nutrition showed a somewhat greater degree of pot-binding than those receiving no leaching and supplementary nitrogen. The difference in pot-binding between groups 1 and 2 in all three pot sizes was very small, but there was only a slight degree of pot-binding exhibited by plants of group 3 in the 2½-inch and rose pots (Figs. 10 and 11). With plants in 4-inch pots, however, there was equally as much root development on the periphery of those plants receiving supplementary nitrogen as in those which were leached.

No differences in shoot growth of coleus were observed in 2½-inch and rose pots until six weeks after the initial potting, and in 4-inch pots, differences in shoot growth did not become evident until after eight weeks. This is remarkable in view of the fact that the nitrate level of the soil in leached 2½-inch and rose pots was reduced to approximately 0.2 parts per million at the end of 2½ weeks; in the 4-inch pots, a somewhat longer time was required to reach this low value. Leachate analyses were

Fig. 10. Relation of nitrate level to shoot growth and degree of pot-binding in coleus at 5 weeks (2½-inch pots).

1. Low nitrate (heavy watering)

2 Medium nitrate (light watering)

3. High nitrate (light watering plus nitrogen)

Fig. 11. Relation of nitrate level to shoot growth and degree of pot-binding in coleus at 5 weeks ($3\frac{1}{2}$-inch rose pots).

1. Low nitrate (heavy watering)	2. Medium nitrate (light watering)	3. High nitrate (light watering plus nitrogen)

Fig. 12. Relation of nitrate level to shoot growth and degree of pot-binding in coleus at 5 weeks (4-inch pots).

1. Low nitrate (heavy watering)

2. Medium nitrate (light watering)

3. High nitrate (light watering plus nitrogen)

made at $1\frac{1}{2}$, $2\frac{1}{2}$ and 6 weeks, the results of which were similar to those presented for stocks in Table 5.

The relation of nitrate level to degree of pot-binding in coleus at 5 weeks is therefore similar to that obtained in the case of column stocks the only difference being in degree of pot-binding and in the time required for this condition to occur. As differences in rate of shoot growth became wider between the three groups, there was a somewhat greater difference in degree of pot-binding between groups 1 and 3.

It has been demonstrated that at a certain state preceding reduction of shoot growth, there is less tendency for plants to become pot-bound when grown under conditions of favorable nutrition than when deficiencies exist. With some plants such as the Puritan Pure White variety of stocks which do not thrive under the extremely low nutritional levels used in this study, the reduction in shoot growth occurs at a very early stage and the development of roots is also reduced, although to a lesser degree. With such plants, the addition of supplementary nitrogen has the effect of increasing the mass of root and degree of pot-binding to a much greater degree than that which occurs under conditions of deficient nutrition. Growers, however, do not attempt to avoid pot-binding by withholding application of nitrogen since the limitation of shoot growth resulting from such a practice is undesirable. To what extent the relations established for stocks and coleus are general for other plants was not determined.

From the evidence presented, one might conclude that under ordinary greenhouse conditions, deficiency of nitrogen is an important factor in development of pot-binding. If shifting is delayed, it is probable that deficiency of available nitrogen has some influence upon the degree of pot-binding with all plants which exhibit a reduced rate of shoot growth as a result of a low level of nitrogen nutrition. With coleus, the Silvery Lavender variety of stocks and many greenhouse plants, it is unlikely that nitrogen deficiency is a matter of importance in commercial greenhouse practice insofar as pot-binding is concerned since plants are usually shifted before any significant reduction in rate of shoot growth sets in.

No consideration was given in this study to the influence of mineral nutrients other than the nitrate ion upon pot-binding. Whether other soil constituents were removed in the leaching process to the extent that they became limiting to plant growth was not determined. However, the fact that satisfactory growth was obtained when only nitrogen was added indicates that elements other than nitrogen did not become limiting within the plant during the period of these investigations.

Plants with divided root systems.

As was stated previously, it was thought that the influence of level of nitrogen nutrition upon pot-binding might be strikingly demonstrated by splitting the root system and the lower part of the stem and growing plants in two different media of varying nitrate levels.

One of the most striking observations in this particular study was an apparent lack of response of coleus, both in the development of shoots and roots to differential levels of nutrition. A similar observation was made when plants were grown in individual pots, as was shown in Figs. 10 to 12. In the first trial, no attempt was made to maintain concentrations of nitrate lower than 0.5 ppm. With this concentration, there was no consistent difference in degree of pot-binding between the two pots of different nitrate levels at seven weeks (Fig. 13), and this was true in all 12 pairs of pots in this series.

In the second trial, an extremely low level of nitrate nutrition was maintained in the one pot by leaching at every irrigation. The nitrate level was reduced to 1 ppm. in two weeks, and in three weeks, the range in concentration was from 0.08 to 0.12 ppm. This range was maintained relatively constant by frequent leaching until the time of final observation at 8 weeks. It was possible to maintain the nitrate level of the other pot within the range of 8 to 20 ppm. by adding supplementary nitrogen in solution. Concentrations of nitrate and potassium were checked at frequent intervals by leachate analyses.

As in the first trial, no consistent difference was noted in either shoot or root growth between the sides of individual plants until the nitrate level was reduced below 0.25 ppm. In four out of five plants in which one pot was maintained at a very low nitrate level, there was a definite stunting of lateral shoots on the sides of plants nourished from the medium of low nitrate level. The difference in degree of pot-binding was less pronounced than that of shoot growth, probably because insufficient time was given for this to occur. The plant shown in Fig. 14 was the specimen which showed the most extreme difference in lateral shoot growth, and also the greatest difference in degree of pot-binding. It is possible that failure to obtain consistent results may have been caused either by the storage in the plants of considerable amounts of nitrogen before beginning differential treatments, or perhaps by failure to obtain strictly unilateral distribution of nutrients, as was found by McMurtrey (26) with tobacco. It is unfortunate perhaps that coleus was used in this study owing to its apparent lack of response

Fig. 13. Lack of influence of level of nitrate nutrition upon degree of pot-binding in coleus with divided root systems.

Left: high nitrate (10 to 20 ppm.)

Right: low nitrate (0.5 to 1.0 ppm.)

Fig. 14. Lateral difference in shoot growth and degree of pot-binding under extreme difference in level of nitrate nutrition in coleus with divided root system (axillary leaves removed).

Left: high nitrate
(10 to 20 ppm.)

Right: low nitrate
(less than 0.25 ppm. for
5 weeks)

to low levels of nitrogen nutrition. This plant offers the advantage, however, that there is no cross-transfer of sugars between the two sides of the stem, according to Caldwell (7). Gile and Carrero (12) suggested that cross-transfer in corn occurs only slowly. Positive evidence of a failure of cross-transfer has been found by McMurtrey with tobacco, and Auchter (1) with apple trees.

The investigation has served to demonstrate the fact that coleus possesses an inherent ability to thrive under conditions of extremely low fertility. Differences in lateral shoot growth on the two sides of the stem only occurred when the nitrate level of the soil was reduced to a very low level and for a considerable period of time.

V. Distribution of Nutrients in Porous Pots in Relation to Pot-binding.

Methods of Study

In a preliminary study designed to show the effect of adding nitrogen in solution to the center of the soil mass upon root distribution, it was found that, regardless of the amount of nitrogen added, there was no detectable increase in root concentration within the soil mass. This was found to be true in the case of schizanthus, cineraria, and primula. It appears likely that rapid diffusion of nutrients throughout the soil mass was responsible for the failure to obtain any differences in root response in the various parts of the soil.

By means of lysimeter studies and chemical analyses in the field, it has been demonstrated that certain salts, among others those containing nitrate and potassium, are carried down through the soil by rain or irrigation; through evaporation of water from the surface of the soil, these soluble salts may again return to the surface where they form a gray crust.

Jones and Haskins (20) demonstrated the decrease in water-soluble solids in porous pots from the center to the periphery, and evidence was presented to show that the massing of roots on the periphery of the soil might be attributed to the stimulated root growth resulting from nutrients absorbed by porous pots. Furthermore, it is commonly held that the nitrate ion becomes concentrated in the layer of soil adjacent to the pot wall as evaporation of water occurs from the outer surface of the pot, and that this phenomenon is responsible for the massing of roots at the soil-pot interface.

In view of conflicting opinions of the movement of ions in porous pots and its significance in pot-binding, a systematic study of the question was undertaken.

Methods of sampling

It was realized at the beginning of this study that the error in sampling would be much greater than that incurred in the method of analysis employed or by small losses of nutrients from some pots by leaching. In order to show the variability in different parts of the soil to be sampled, some preliminary tests were made of the vertical and horizontal distribution of nutrients in pots. The data presented below represent the variability in nutrient concentration vertically under the conditions of this study:

	Nitrate ppm.	Potassium ppm.
Scraping from top surface	18	18
Scraping from bottom surface	108	84
Top half of pot	28	9
Bottom half of pot	64	40

In addition to variation in the vertical distribution of nutrients, there are also differences in concentration of nutrients in different parts of the periphery on the same horizontal plane. It is believed that these differences are to be attributed to variations in the properties of the pot wall, since the pattern of salt accumulation on the outside surface of pots is never uniform. In the case of some of the pots studied, these differences were as great as those occurring in the vertical plane. A determination of the variability in nutrient concentration in different parts of the periphery was made by analysing 8 samples from leached 8-inch pots and a similar number from unleached pots. The following data were obtained:

Leached pots				Unleached pots			
NO_3		K		NO_3		K	
		(parts per million)					
15.2	5.9	21.5	2.0	31.5	3.8	26.0	2.7

It is evident from a comparison of the magnitude of the standard deviations that the variability in the nitrate level on the periphery of the soil was considerably greater than that of potassium. The difference in nitrate concentration on different parts of the periphery in the unleached pot was quite small in relation to the size of the mean. The standard deviation of individual determinations was consistently smaller when samples were taken from the center of the soil mass than when taken from the periphery.

Four composite samples were taken from each of the following parts of the soil mass: (1) scraping from the surface (2) at a distance of approximately 1.5 cm from the periphery, and (3) from the center. In some instances, samples were also taken at a distance of three cm from the periphery. Owing to the greater uniformity in individual samples from the center of the soil mass, as indicated by the smaller standard deviation of individual determinations, only three samples were taken in some instances.

In this investigation, it would have been advantageous to have obtained analyses from a large number of samples from each sampling region and from each pot. This was impractical, however, on account of the amount of labor involved, even when rapid chemical tests were used. Owing to variations in distribution of nutrients in different pots receiving the same treatment, it was thought that more reliable average values could be obtained by taking four samples from each sampling region from a large number of pots than by taking a larger number of samples from a smaller number of pots.

Composite samples were made from several thin slices of soil from each sampling region, care being taken to sample as uniformly as possible from the top and bottom halves of the soil mass. These samples were screened and thoroughly mixed. Each composite sample from the periphery and from the region 1.5 cm from the periphery represented an arc of approximately seven cm on the circumference of the soil mass. Samples from the center were taken by sectioning the soil mass vertically and then scraping from the exposed surfaces. Samples from the periphery and from the area 1.5 cm from the periphery were taken in such a way that the entire periphery was uniformly sampled.

Unleached pots maintained fallow

The first experiment was designed to study the movement of individual ions in soil since it was considered that pot-binding might be associated with concentration of individual ions in particular parts of the soil rather than with concentration of water-soluble solids. In this study, 24 six-inch pots were filled with greenhouse compost with a uniform amount of packing. Three pots were selected for analysis each week for a period of 8 weeks in order to determine what changes in concentration of individual ions might occur over a definite period. Watering was performed in such a manner that the soil was maintained in the moist end of the available range, yet leaching seldom occurred. Control of soil moisture was made possible by adding water only when the surface layer of soil began to turn gray, at which time a volume of 250 to 300 cc of river water was added.[1] The amount of nitrate and potassium present in the

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[1] Using 1450 cc as the volume of soil, 24 per cent soil moisture on a volume basis as the moisture content at the time of change in color of the surface layer of soil, and 58 per cent as the moisture content at saturation, the volume of added water required at the moisture equivalent to bring about drainage was calculated to be 493 cc.

river water used was too small to be detected by the rapid method of chemical analysis employed. Samples were taken from one to three days after watering, in order that sampling might be more accurately performed, and also to allow for a re-distribution of nutrients.

Determinations of concentration of nitrate and potassium ions were made systematically throughout the period of the test. Some incidental analyses for magnesium, calcium and phosphorus were also made.

Leached pots, fallow and with plants

The experiment first described was extremely artificial as far as greenhouse conditions are concerned, primarily because of the absence of plants in the pots, but also because no leaching occurred throughout the period of study. Consequently, a study of nutrient distribution in pots with growing plants and under conditions of heavier watering seemed necessary. Movement of nutrients was studied in pots of standard shape in which the height was greater than the diameter, and in bulb pots in which the same volume of soil was placed as in standard pots. A number of 3½-inch rose pots were also used in this study.

A total of 32 pots was used in the leaching study, some of which were maintained fallow, while others contained three plants of pennisetum (Pennisetum Ruppellii) or coleus. These species were chosen on account of the large root systems produced in a relatively short period of time. The same number of plants received no leaching, some of which contained plants while others were maintained fallow. Unleached pots with no plants served as a check on the previous experiment, the only difference being that a considerably higher temperature and a higher average level of soil moisture prevailed during the second trial.

Application of water to unleached pots was more systematically controlled in this study than in the previous one since their daily requirements could be readily approximated from the volume of water required by leached pots to bring about drainage. Water was applied on an average of once every two days, while in the previous study, the interval between irrigations was approximately four days. The slight graying of the surface layer of soil was used as the indication of the time when water should be applied.

On account of the large number of pots used in this study, it was impossible to make analyses of all pots within the short period of time that would have been desirable. Analyses of samples was begun at eight days after setting up the experiment and was not concluded until 2½ weeks later. Samples were taken in the same manner and from the same locations as was described previously.

Results of Study

At the beginning of this study, the compost gave a test of 90 parts per million of nitrate and 40 parts per million of potassium. At the end of one week, the nitrate level had dropped to about half of its former level while the change in level of potassium was relatively small. The manner in which these ions became distributed in the soil over a period of two months is shown in Fig. 15. Each bar in the chart represents an average of 12 determinations, since four samples were taken from each sampling region and analyses were obtained from three pots at each period of sampling. Averaging of the results of the 12 determinations was permissible because of the similar trend in all individual values from the three regions of sampling. Standard deviations have not been calculated on account of the marked consistency of values for individual pots.

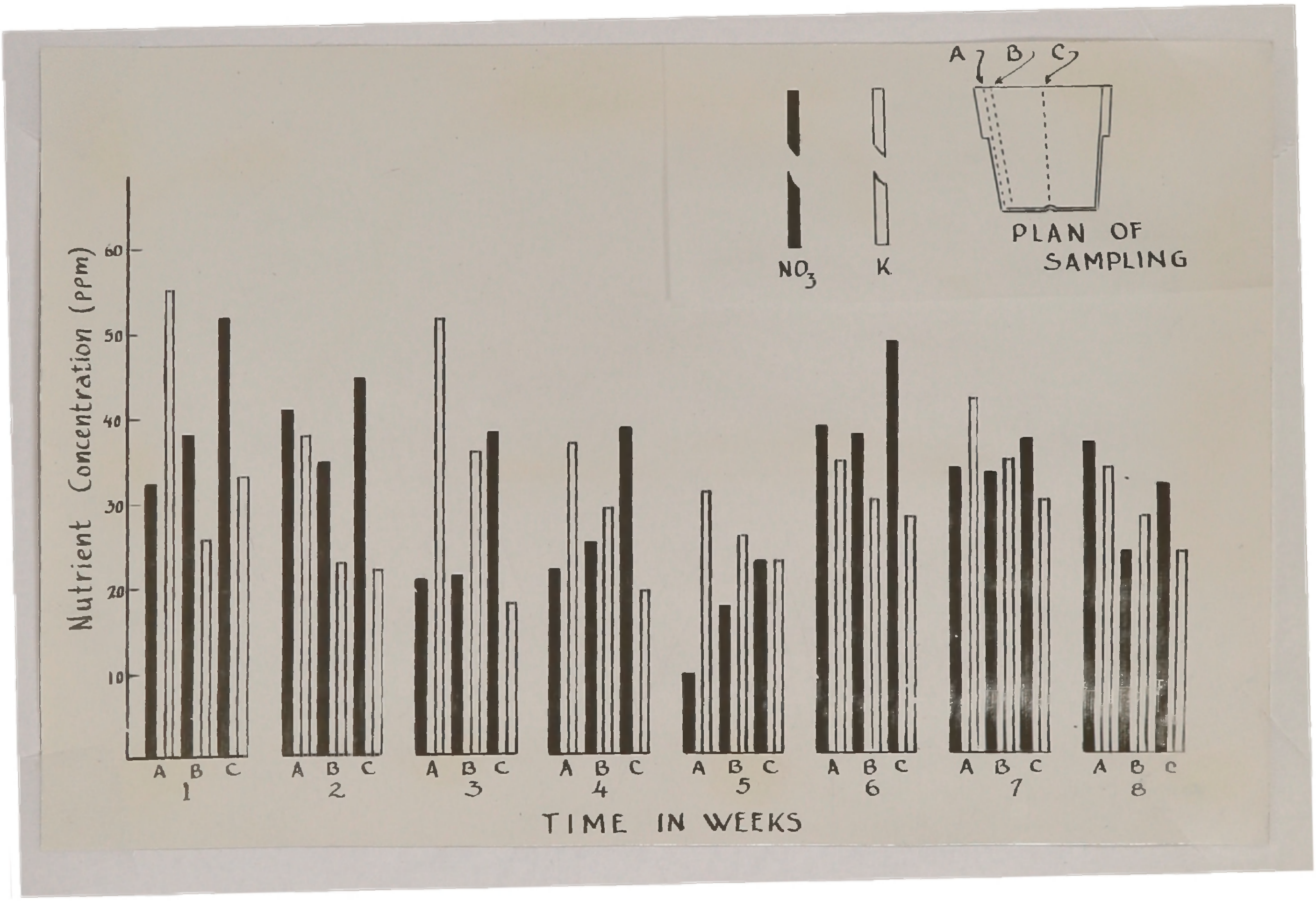
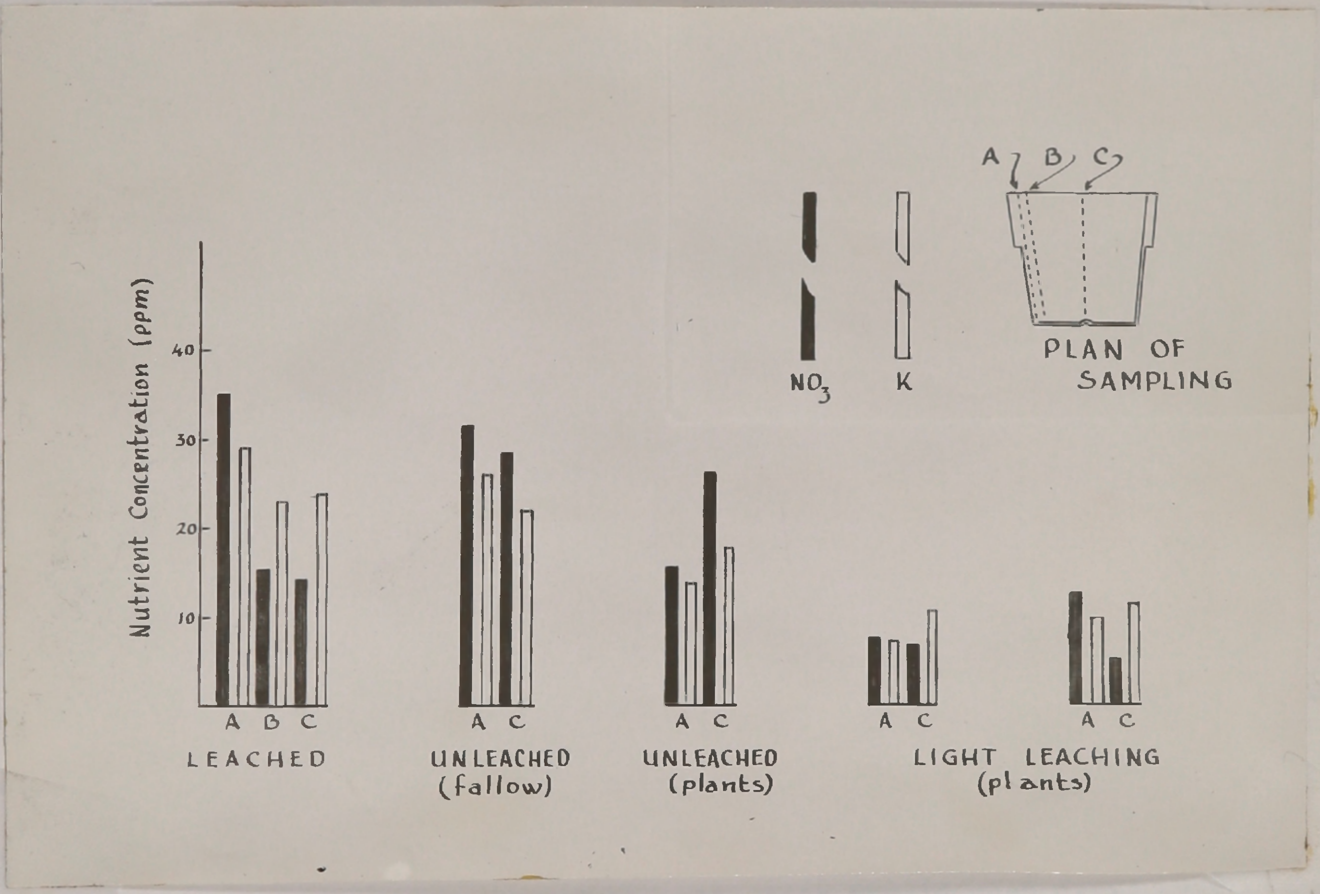


Fig. 15. Concentration of nitrate and potassium at varying distances from periphery in fallow soil in porous pots with no leaching over an 8-week period.



Fig; 16. Concentration of nitrate and potassium at varying distances from periphery in porous pots, with and without plants, leached and unleached.

At the end of one week, the concentration of potassium on the periphery was considerably greater than in the center of the soil, indicating that this ion had moved from the center toward the periphery with the movement of soil moisture. The relative concentrations of the nitrate ion, on the other hand, were exactly the reverse of those obtained for potassium. This situation continued with no exception for seven weeks, at which time potassium was still highest on the periphery, but an equalization in the concentration of nitrate had occurred. At eight weeks, the nitrate ion appeared to be more concentrated on the periphery than within the soil mass.

Such was the situation which existed where no leaching occurred and where pots were maintained fallow. Where leaching occurred frequently, however, the order of concentration of the nitrate ion was exactly the reverse of that obtained without leaching as is shown in Figs. 15 and 16 and in Table 6 (Appendix). In the 20 pots of standard shape and in the seven rose pots used, the nitrate ion was in every instance more concentrated on the periphery than at either the 1.5 cm point or in the center of the soil mass. Moreover, the difference between mean nitrate concentrations at the periphery and at the center of the soil mass was in most cases significant at the 1 per cent point.

An inspection of the values for potassium concentration in different parts of the soil mass does not reveal any consistent trend. In about half of the cases studied, potassium was more concentrated at the periphery than in the center of the soil, but the differences were too small to be statistically significant. There was no difference between concentrations of calcium or magnesium in the few instances studied.

Where pots received no leaching for $3\frac{1}{2}$ weeks, either with plants or in the fallow state, there was no consistent trend in either nitrate or potassium concentrations in different parts of the pot, as is shown in Fig. 16 and Tables 8 and 9 (Appendix). Where plants were grown in the pots, there appeared to be a greater tendency for the nitrate ion to be concentrated in the center than where pots were maintained fallow. Frequently, the difference between means was not large enough to be statistically significant. There was no consistent difference between concentration of potassium in different parts of the soil under these treatments. In view of the marked consistency in the trend of potassium concentrations illustrated in Fig. 16, it is difficult to explain the discrepancy between the results of the two experiments. Whether the cooler temperature or lower level of soil moisture prevailing at the time of the 8-week study of differences in nutrient concentration exerted any influence upon movement of potassium from the center to the periphery has not been determined. It is possible that the more frequent application of water during the $3\frac{1}{2}$-week study did not allow sufficient time between irrigations for either of the ions under investigation to concentrate in any part of the soil mass.

As a final test of the difference between concentrations of nitrate and potassium in different parts of the soil, a study was made of coleus and petunias growing in pots for four months and two months respectively. Since the pots used in this study received only light leaching, the conditions of this study were perhaps as similar to those occurring under commercial practice as could be obtained. As is shown in Fig. 16 and in Table 10, there was no consistent trend to the concentrations of either the nitrate or potassium ions in different parts of the soil mass in the same horizontal plane.

In the entire study of movement of nutrients in porous pots and their lateral distribution in different parts of the soil, only two definite trends were observed-: (1) with no leaching and in most instances where pots were maintained fallow, the nitrate ion followed an increasing gradient from the periphery to the center while the gradient for potassium was exactly the opposite; (2) where pots received considerable leaching, either in the fallow state or with plants, the nitrate ion followed a decreasing gradient from the periphery to the center. Results of experiments conducted under conditions similar to those prevailing under commercial practice failed to show any consistent tendency for either the nitrate or potassium ion to become more concentrated laterally in one part of the soil mass than in another. Despite the fact that certain of the treatments involved in this study produced a significant difference in nitrate concentration between the periphery and center of the soil mass, nevertheless, it is unlikely that these variations were sufficiently great to cause a differential stimulation of root growth in the two regions.

VI. Pot-binding in Porous and Glazed Containers

It has been previously demonstrated in this investigation that pot-binding is conditioned in part by the level of nitrogen nutrition, and it has been suggested, though not definitely proven, that the level of soil moisture is also a factor determining degree of pot-binding. Jones and Haskins(20) reported that a much larger mass of roots was produced in porous pots than in glazed pots of the same capacity under their experimental conditions, and it was also concluded that plants become pot-bound only in porous containers. They suggested, however, that no difference in total mass of roots would have occurred had soil moisture been maintained at a uniform level in the two kinds of pots.

As a final test of the influence of level of nitrate nutrition upon degree of pot-binding, and to demonstrate whether or not porous pots exert any influence on pot-binding apart from their effect upon levels of soil moisture and nutrition, an investigation was conducted in which pot-binding was compared in porous and glazed containers. In a preliminary trial, 16 plants of column stocks were set in 2½-inch porous pots, and the same number of plants in waxed pots of the same capacity. Plants in waxed pots exhibited as much pot-binding as did those in porous pots, but definite conclusions could not be drawn because of insufficient care in controlling soil moisture.

This experiment was repeated using column stocks in 2½- and 3-inch porous, waxed and glazed pots, and with coleus, pelargonium(*Pelargonium domesticum*) and calendula(*Calendula officinalis*)in 3-inch porous and glazed pots under controlled nitrate and moisture levels. Periodic leachate analyses were made to determine the nitrate level in porous and glazed pots, and nitrogen in solution in the form of potassium nitrate was added to some pots in order to maintain the desired level of this ion. Watering was performed in the manner described previously, so that plants in porous pots received irrigation much more frequently than did those in glazed pots. Eighty-four plants of coleus, 40 plants of column stocks, 16 calendula and 16 pelargonium were used in this investigation. Plants were allowed to grow in their containers until pot-binding occurred, observations of root development being made at weekly intervals.

Plants in glazed pots showed equally as much pot-binding as did those in porous pots when soil moisture and nutrition were controlled as is shown in Figs. 17, 18, and 19, with column stocks, coleus and calendula respectively. This was also true in the case of pelargonium, and it can be concluded that, under the conditions of this investigation, there is no difference in pot-binding between porous and glazed containers.

Fig. 17. Pot-binding in porous and glazed pots with column stocks under controlled levels of soil moisture and nutrition.

Left: porous pot Right: glazed pot

Fig. 18. Pot-binding in porous and glazed pots with coleus under controlled levels of soil moisture and nutrition.

Left: porous pot Right: glazed pot

Fig. 19. Pot-binding in porous and glazed pots with calendula under controlled levels of soil moisture and nutrition.

Left: porous pot Right: glazed pot

VII. Relative Importance of Geotropism and Nutrition in Determining the Root Pattern of Potted Plants.

Casual observation of pot-binding in many different kinds of potted plants showed that roots on reaching the pot wall rarely turn back into the soil, excepting in the case of fine fibrous roots which apparently do not follow any definite root pattern. Roots of vigorously growing tomato plants have been found to follow the concave pot wall for distances of more than 10 inches without any apparent tendency on the part of the roots to turn back into the soil.

Observations of rooting habits of different plants have suggested that the varietal pattern of rooting should be considered in connection with the present investigation. In the case of cineraria, heavy massing of roots on the periphery was first noted at a point within 1 inch of the surface of the soil; likewise, in coleus, the first massing of roots on the periphery occurred at a relatively shallow depth as is shown in Fig. 20. In the case of pennisetum, on the other hand, massing of roots occurred on the bottom of pots (Fig. 21).

Methods of Study

Study of rooting habits in triple pots

In a preliminary experiment designed to show the effect of maintaining porous pots continuously moist upon pot-binding, plants in 2½-inch pots were surrounded with peat enclosed by a concentric 3-inch pot. Roots of the plants penetrated the hole in the bottom of the 2½-inch pots and were then unobstructed in ramifying through the concentric

Fig. 20. Relatively shallow rooting habit of coleus (potted 2½ weeks).

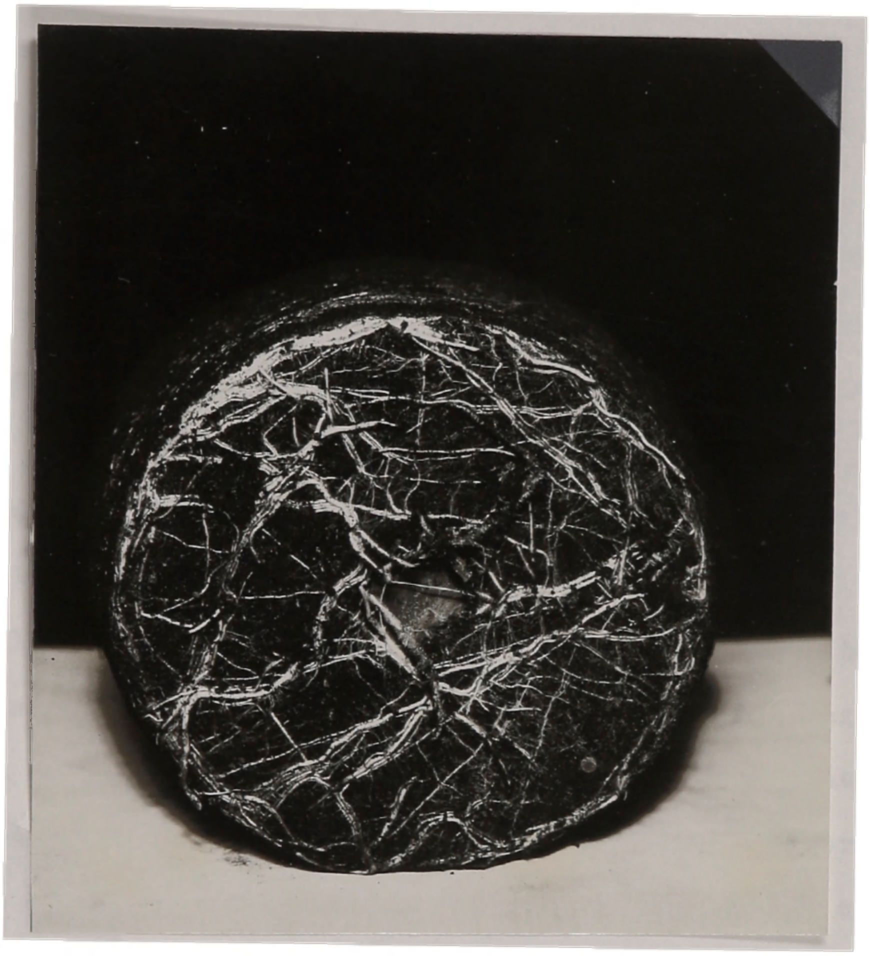


Fig. 21. Massing of roots of pennisetum on bottom of bulb pot. (Note relatively few roots on the periphery of the soil mass).

layer of peat. Considerable development of roots occurred in the surrounding layer of peat, and in all cases, this development was restricted almost entirely to the outside pot wall. The few roots found on the inner pot wall were rarely exposed for distances greater than 1 inch, while those on the outside wallcontinued their growth along the soil-pot interface.

A more extensive experiment was set up using a third pot (Fig. 22) in order to eliminate the possibility of differences in aeration, moisture and nutrient level within the concentric layer of peat surrounding the inner pot. Besides serving to control the variable conditions noted above, this second concentric layer provided a third rooting medium. This medium consisted in some instances of peat, which in others, soil of varying fertility levels was used. Careful attention was paid to the matter of watering; an attempt was made to maintain all three rooting media under conditions of uniform moisture tension, but with the greatest concentration of roots and absorbing surface occurring in the center pot, and the rapid loss of water that occurred under summer greenhouse conditions, it was usually found that the soil in the small pot required irrigation before that in the two outer pots. By making frequent applications of water, it was possible to maintain relatively uniform moisture conditions in all three rooting media. As in all other experiments conducted on the causes of pot-binding, water was applied at the time that the surface layer of soil became slightly gray.

Plants of coleus, pennisetum and column stocks were used in this study, these being selected to represent both shallow and deep-rooting

Fig. 22. Triple pot arrangement showing plant of column stocks in the center pot

plants. Observations of the root growth of coleus and pennisetum were made after a period of seven weeks, at which time duplicate samples of soil were taken from the inner and outer surface of the middle rooting medium for nutrient analysis. A total of 30 plants was used.

Besides conducting the study of root distribution in the three rooting media, with the pots in the normal position as shown in Fig. 22, another series of triple pots was set up using the same kinds of plants as noted above, but in this case the pots were set horizontally on the bench instead of in the normal vertical position. By this means, it was believed that further information could be obtained concerning the reason for variations in the root pattern of different potted plants than by restricting the study to plants grown in the normal vertical position. Twelve individual plants were used in this experiment.

Effect of growing plants in single pots in the horizontal and inverted positions upon the characteristic root pattern

The influence of geotropism on the root pattern of such deep-rooting plants as pennisetum has already been suggested. It has also been suggested that roots of coleus are much less responsive to gravity than those of pennisetum, for instance. In order to demonstrate even more clearly the effect of geotropism upon the characteristic root pattern of different plants, specimens of coleus, pennisetum and column stocks were grown in single pots both in the horizontal and in the inverted positions. Water was applied to the upper surface of the soil after first returning the pots to the normal upright position. Pots of a larger size were placed over the inverted pots in order to prevent excessive drying out of the porous pots and of the outer layer of soil. All plants used in this study were grown in 6-inch pots. At five weeks, and at weekly intervals thereafter, an addition of 10 cc of solution containing 0.05 per cent nitrogen was made to each pot in order to maintain thrifty vegetative growth.

Plants were allowed to grow in the horizontal and inverted positions until a characteristic root pattern had developed. In the case of plants in the horizontal position, a definite root pattern had formed in all plants studied within a period of five weeks, but a somewhat longer period was required when plants were grown in the inverted position owing to the reduced photosynthetic activity caused by shading from the mechanical supports.

Effect of maintaining differential nutrient levels vertically in the same pot upon the root pattern of potted plants

In a preliminary study of the influence of surface watering upon the distribution of nutrients vertically in the soil mass, it was noted that there was a marked increase in the concentration of such mobile ions as nitrate and potassium from the top to the bottom of the soil mass (page 52). By reversing the normal flow of water through the soil, that is by introducing water through the hole in the bottom of the pot instead of applying it at the surface, it was thought that a greater concentration of the nitrate ion could be maintained in the top half of the soil than in the bottom half. In order to establish wide differences in nutrient concentration between the top and bottom halves of the soil from the beginning of the study, soils of high and low fertility level but of similar physical properties were placed in the desired positions in the pots. Plants watered from the upper surface were set in pots containing soil of high fertility on the bottom (80 ppm. of nitrate) with soil of low fertility on top (4 ppm. of nitrate). This order of arrangement was reversed in plants receiving subirrigation.

Plants of coleus, pennisetum and geranium were set in 5-inch pots, four plants of each kind receiving their water at the top surface, and the same number of plants watered by means of wicks of glass wool from below. Plants receiving their water through wicks required about six hours to reach what was considered to be optimum moisture conditions, and they were then removed from their water supply in order to prevent water-logging of the soil which may result when this method of watering is used continuously. As far as soil aeration is concerned, plants watered by means of wicks appeared to be under equally as favorable conditions as those receiving the standard surface watering. Water was applied from either the top or bottom only when the change in color of the surface soil indicated its need.

Results of Study

Root patterns in triple pots

Owing to the more positive control of such variable conditions as soil moisture, aeration and nutrition, it was believed that the pattern of root development on the inner and outer surfaces of the middle rooting medium was the most reliable critierion of the influence of the spreading tendency of roots upon pot-binding. Typical root patterns of pennisetum and coleus on the inner and outer surfaces of the middle and outer rooting medium are shown in Figs. 23 and 24.

In every plant set in triple pots, regardless of the kind of rooting medium employed, massing of roots occurred almost exclusively on the outer surface of the middle and outer rooting media. The tendency of roots to assume a vertical direction of growth on the outside of the middle rooting medium in Fig. 24 is noteworthy since the heavier massing of roots on the outer surface appeared to be merely the results of roots following a concave rather than a convex surface. Regardless of whether the roots were arranged vertically or horizontally on the outer surface of the middle layer of soil, there was no marked tendency for roots to mass on the inner surface. In some instances, roots appeared on the inner surface for a distance of a few centimetres, but invariably they turned back into the thin layer of soil; on the other hand, roots appearing on the outer surface did not turn back into the soil, but continued to develop in length and branch on the periphery.

When plants were grown in triple pots maintained in the horizontal position, the relative degree of massing of roots on the inner

Fig. 23. Pattern of root development of pennisetum on the inner and outer surfaces of the middle and outer rooting media.

Left: inner surface Right: outer surface

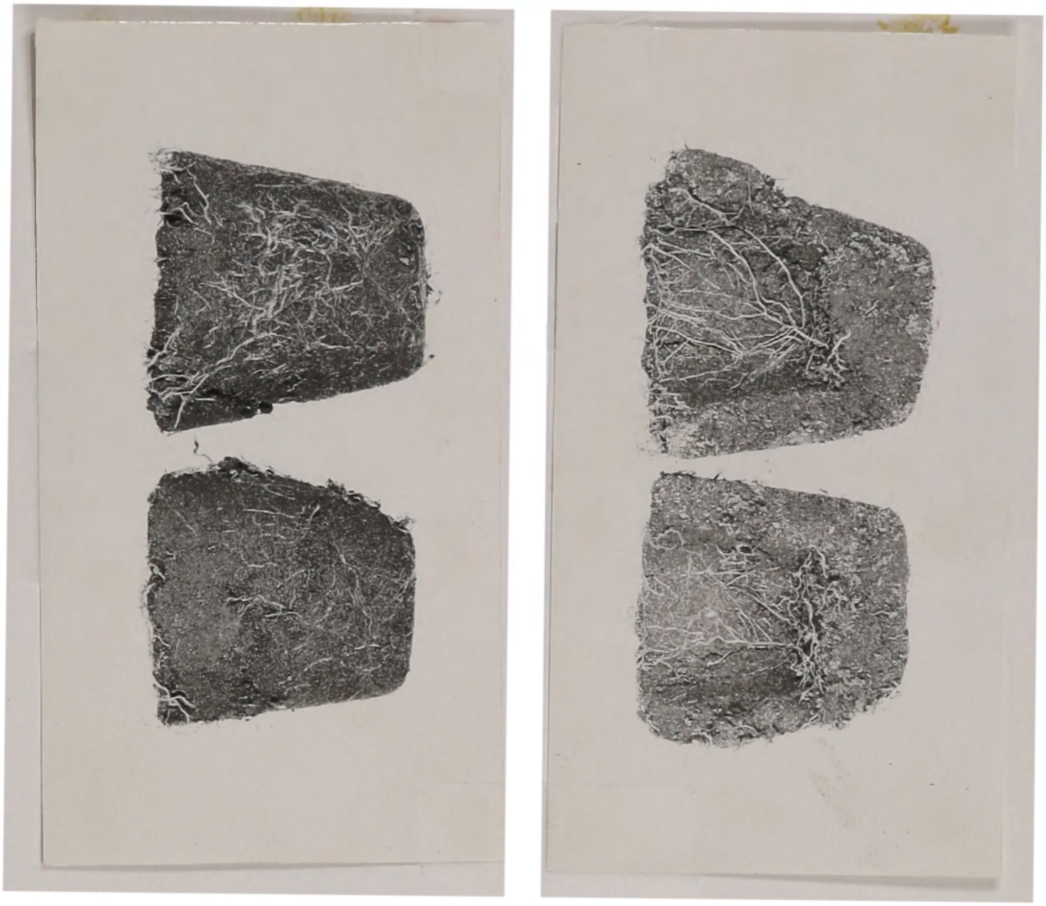
Fig. 24. Pattern of root development of coleus on the inner and outer surfaces of the middle and outer rooting media.

Left: inner surface Right: outer surface

(Note the vertical direction of root growth on the outside of the middle layer of soil and sparse development of roots on the corresponding inside surface.)

and outer surfaces of the middle layer of soil was somewhat different from that obtained when pots were maintained in the normal position. (Fig. 25). It is evident that roots have developed on the inner surface of the middle rooting medium to a much greater degree when pots were maintained in the horizontal position than in the normal vertical position as in Fig. 23 and 24. Further, it can be seen that the massing of roots on the outer surface of the top half of the middle rooting medium was greater than on the lower half of this layer of soil. Since this condition held in all triple pot arrangements with this variety of coleus, it is clearly indicated that certain varieties of coleus tend to produce their roots at a relatively shallow depth as was previously observed in Fig. 20. With other varieties, however, there was equally as much root development on the lower as on the upper half of both the middle and outer rooting media, indicating that these varieties were inherently more deeply-rooted. A more complete illustration of the shallow rooting habit of coleus is given in Fig. 26; this representation is equally as typical of column stocks as it is of coleus.

In the case of pennisetum growing in the horizontal position in triple pots, only a few roots developed on the outer surface of the upper half of the middle layer of soil, while on the lower half, there was a considerable massing of roots. This was to be expected since it was observed previously that roots of this plant massed on the bottom of bulb pots rather than on the sides. The difference in degree of pot-binding between the upper and lower surfaces of pots containing pennisetum growing in the horizontal position is strikingly demonstrated in Fig. 27.



Left: inner surface of middle rooting medium

Right: outer surface of middle rooting medium

Fig. 25. Relative degree of pot-binding on the inner and outer surfaces of the top and bottom sides of the middle rooting medium of coleus grown in the horizontal position in triple pots.

Top: upper half of middle rooting medium

Bottom: lower half of middle rooting medium

(Note greater development of roots on the inner surface of the middle rooting medium as compared with Fig. 24, and the greater massing of roots in the upper half of this layer of soil than in the lower half.)

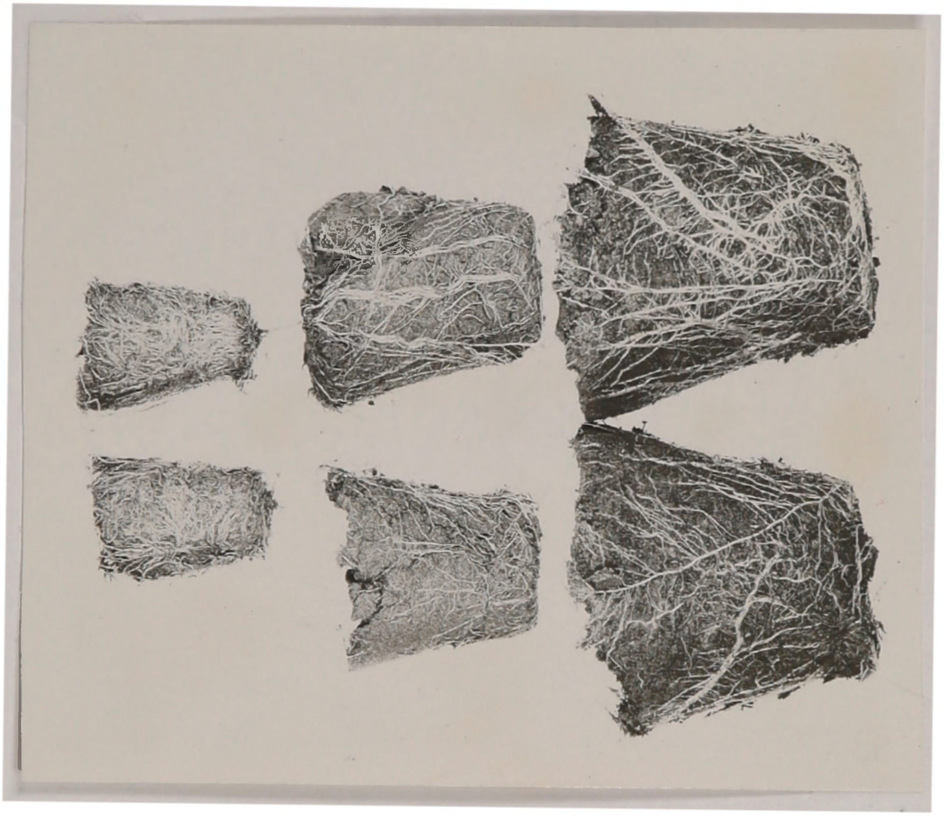


Fig. 26. Massing of roots of coleus on the outer surface of the top and bottom halves of the middle and outer rooting media (pots in the horizontal position).

Top: upper surface of middle and outer rooting media.

Bottom: lower surface of middle and outer rooting media.

Fig. 27. Massing of roots of pennisetum on the upper and lower surfaces of the soil mass in a single pot in the horizontal position.

Top: upper surface

Bottom: lower surface

(compare with root pattern of coleus in Fig. 26.)

With coleus in single pots in the horizontal position, there was little difference in degree of pot-binding between the upper and lower surfaces.

In order to be able to attribute the massing of roots on the outer surface of the middle rooting medium to the inherent spreading tendencies of roots, it was necessary to eliminate as far as possible such variable factors as differences in nutrient level, moisture and aeration. from consideration. Samples of soil from the inner and outer surfaces of the middle rooting medium of eight triple pots were used in the study of differences in the nutrient level. Duplicate samples from the inner and outer surfaces gave very uniform values for concentration of nitrate and potassium. Whether any significant difference in nutrient level occurred between the inner and outer surfaces of the outer rooting medium was not determined, but from the results of the study of movement of nutrients in porous pots, it is unlikely that any considerable difference in nutrient level could exist at the two surfaces. Furthermore, in the arrangement of pots used in this study, with the center mass of soil drying out the most rapidly, there would be a tendency for moisture to move from the outer surface of the middle rooting medium to the inner surface. Consequently, in the unlikely event that differential nutrient concentrations should occur in such an arrangement of pots, it is certain that a greater concentration of nutrients would be found on the inner surface of the middle rooting medium than on the outer surface.

Since it has been reported by Baver(3), and confirmed by the writer from the results of moisture distribution in porous pots (page 22) that moisture moves rapidly through the soil in the range of soil moisture from saturation down to the moisture equivalent, and since the two surfaces of the middle rooting medium were separated by only a thin layer of soil, it is certain that no significant difference in either soil moisture or soil aeration could have occurred between the inner and outer surfaces. Concentration of roots on the outer surface, or pot-binding, can in this experiment be attributed definitely to the natural spreading habits of roots, and not to differences in nutrient level, moisture or aeration.

Effect of growing plants in the inverted position upon the characteristic root pattern

Coleus grown in the inverted position for six weeks gave the pattern of root development illustrated in Fig. 28. One might conclude from the manner in which the roots have concentrated on the upper part of the soil mass that roots of this variety of coleus were negatively geotropic as in the case of the shoot. It is probably more nearly correct to state that roots of some varieties of coleus are not responsive to the force of gravity, but that there is a definite tendency for their roots to spread laterally. Even when the lower surface of the soil was protected from the desiccating effects of the atmosphere, there was no marked tendency for roots to penetrate downwards.

When plants of pennisetum were grown in the inverted position, the pattern of root development was entirely different from that of coleus. As is shown in Fig. 29, there was no marked development of roots on the periphery of the soil mass. A few very fine roots were found on the periphery, and it is probable that these are the roots which form the sod when these plants are grown in the field.

The development of pennisetum roots on the lower soil surface when protected from the atmosphere by means of a disc of asphalt paper is shown in Fig. 30. It is certain that these large white roots have accumulated at the lower soil surface because of response to the geotropic stimulus. It is noteworthy that the roots developed radially from the crown of the plant, thus indicating that there is a tendency for roots of this plant to spread obliquely instead of directly downwards. Special attention is called to the right angle curvatures made by the roots on reaching the inner wall of the pot; roots on reaching the pot wall seldom turned back towards the crown of the plant but rather continued to grow along the inner wall of the pot. In some instances, roots of pennisetum have been found following the inner wall of the pot for a distance of 25 cm. Likewise within the soil, roots follow the concave inner wall of the pot because of the inherent tendency of roots to spread laterally.

Effect of maintaining different nutrient levels vertically in the same pot upon the root pattern of potted plants.

Plants of pennisetum had produced a considerable mass of roots on the periphery of the soil in four weeks, and in coleus and geranium, this condition developed in eight weeks. Coleus showed only a slight response to differential nutrient levels produced by the two methods of watering, and in pennisetum and geranium, there was no apparent response as is illustrated in Fig. 31. The root pattern of all individual plants of each kind receiving the same method of watering was quite similar. In coleus receiving intermittent subirrigation with the more fertile soil above, there was a tendency for roots to mass near the upper soil surface and at the bottom of the pot, with less development in the intermediate region. Where water was applied to the upper surface, and the soil in the lower part of the pot maintained at the higher level of fertility, there was a uniform distribution of roots over the entire periphery of the soil.

In geranium and pennisetum, there was no difference in the root pattern as a result of maintaining different fertility levels in the upper and lower halves of the soil.

Analyses of samples from the upper and lower halves of soil masses in which coleus were grown showed the following differences under the two methods of watering:

	1 week		6 weeks	
	NO_3	K	NO_3	K
	(parts per million)			
Subirrigation				
High fertility on top	36	24	2	38
Low fertility on bottom	3	10	Trace	8
Surface watering				
Low fertility on top	2	32	1	14
High fertility on bottom	50	76	5	44

It is quite possible that the massing of coleus roots near the surface of pots receiving subirrigation has resulted from the very favorable nutrient level in this part of the soil. One would accordingly expect to find a similar massing of roots at the bottom of pots when the higher level of fertility was maintained in this region, but this did not occur. It is noteworthy that geranium and pennisetum showed no response to the different fertility levels in the two halves of soil masses. The varietal root pattern was not altered despite the widely varying fertility conditions.

Fig. 28. Effect of growing coleus in the inverted position upon the pattern of root development.

(Note massing of roots near the upper soil surface and the sparse development near the lower soil surface.)

Fig. 29. Effect of growing pennisetum in the inverted position upon the pattern of root development.

(Note sparse development of roots on periphery.)

Fig. 30. Massing of pennisetum roots on the lower soil surface with plants grown in the inverted position.

(Note the tendency of roots to follow the concave pot wall.)

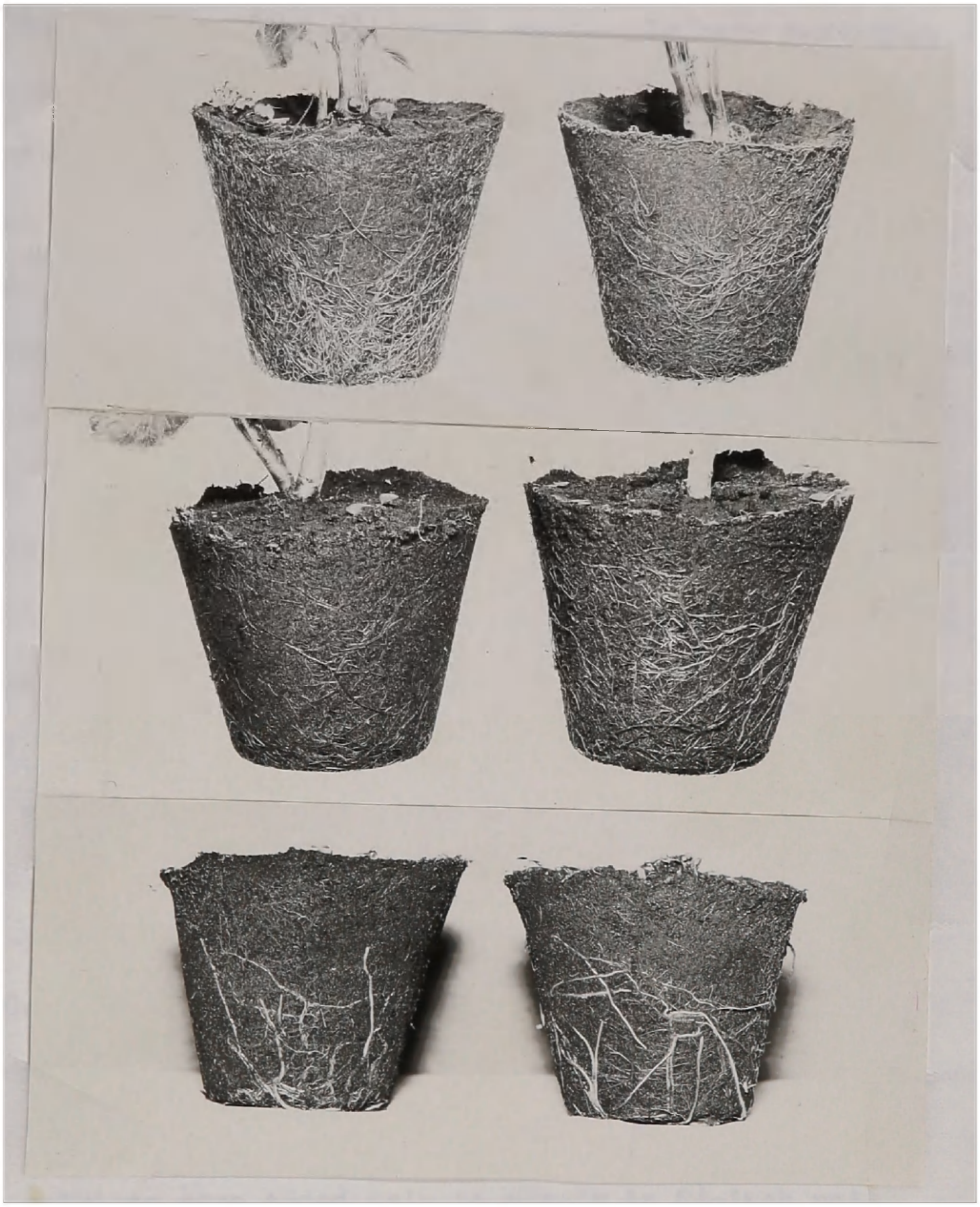


Fig. 31. Root pattern of coleus, geranium and pennisetum resulting from different fertility levels vertically in the same pot.

Left: subirrigation and $\frac{\text{high fertility}}{\text{low fertility}}$

Right: surface watering and $\frac{\text{low fertility}}{\text{high fertility}}$

VIII. How Large Can Plants Be Grown in Pots of a Given Size.

Results of investigations discussed previously have suggested that plants can be maintained in a state of thrifty vegetative growth in small pots long after pot-binding has occurred (in the sense in which the term is used in this investigation) providing that favorable nutrient and moisture conditions can be maintained. Even when roots on the periphery turn brown, the most probable requirement for renewed vegetative growth is a supply of readily available nitrogen; this requirement can be met by adding nitrogen in solution to plants in small pots equally as well as by supplying it by means of new soil provided by the shifting operation. The problem has therefore been presented of determining whether plants can be grown in small pots as successfully as in large ones even after pot-binding has occurred, up to the time that the practical difficulty of furnishing adequate moisture for the large shoot growth becomes the limiting growth factor.

Six plants of column stocks grown for five weeks in 2½-inch pots were shifted to 5-inch pots; six other plants were retained in the 2½-inch pots as checks. Owing to the fact that this study was conducted in a cool greenhouse in October and November, it was possible to maintain a favorable soil moisture level in the small pots. For the first three weeks after shifting, nutrients in solution were added only to plants in 2½-inch pots, but during the remaining period of the study, a complete nutrient solution was added in equal volumes to both small and large pots. Periodic leachate analyses served as the basis of the fertility program, nutrient solution being added whenever the nitrate level became less than two parts per million in the soil. Plants of coleus, calendula, primula and begonia (Begonia semperflorens) were also used in this study.

Fig. 32. Independence of size of plant on soil volume with column stocks when nutrient and moisture supply were maintained within a favorable range (7 weeks after shifting).

Left: 2½-inch pot Right: 5-inch pot

Fig. 33. Independence of size of plant on soil volume with coleus when nutrient and moisture supply were maintained within a favorable range (7 weeks after shifting).

Left: 2½-inch pot Right: 5-inch pot

That column stocks can be grown equally as successfully in small pots as in large ones under the cool greenhouse conditions of this investigation is demonstrated in Fig. 32. Careful observations were made at weekly intervals, but at no time during the 7-week period following shifting was any difference in shoot growth apparent. Similar results were obtained with coleus (Fig. 33), and with calendula and begonia. Only in the case of primula was there a reduced rate of shoot growth in the small pots, and this was unexpected in view of the very high shoot/root ratio found in mature plants of this kind. A slight chlorotic condition on the margins of some leaves suggested that some undetected soil factor in the small pots was responsible.

A review of investigations concerning the relation of soil volume to plant growth has been presented by Blanck (4). It appears to be generally agreed that, up to a certain limit at least, volume of soil has no influence upon amount of plant growth providing that adequate soil moisture and nutritional levels can be maintained. A marked reduction in the volume of the larger pore spaces must eventually result from the increase in the absolute quantity of roots in the soil, and thus prevent or restrict adequate aeration of the roots. Furthermore, there is a limit to the mass of roots that can be contained in a pot of a given size as evidenced by root systems of <u>Pandanus</u> being forced out of their containers, and limiting the growth of roots must necessarily reduce the rate of shoot growth.

The question of what factor limits the size of plant that can be grown in a pot of a given size lies outside the field of this investigation. It has been demonstrated that, with certain plants at least, rate of shoot growth can be maintained equally as well in 2½-inch as in 5-inch pots long after it is commercially practical to do so owing to the difficulty of maintaining favorable soil moisture conditions. Thus the difficulty of providing a continuous supply of soil moisture becomes the factor which determines practically the size of plant that can be grown in a small pot, and consequently the time of shifting, and not deficient nutrition as is commonly believed.

DISCUSSION

The view has long been held and often expressed that massing of roots at the soil-pot interface may be caused primarily by the more favorable aeration conditions in that area than in other parts of the soil. Such a difference in aeration could only exist under the following conditions (1) a smaller percentage of the pore space being filled with water (2) shrinkage of the soil mass allowing free movement of air in the space between the soil mass and the wall of the pot, and (3) an exchange of gases occurring through the wall of the pot. From the evidence presented in this paper and that reported by other investigators, it is improbable that soil aeration is of any significance in pot-binding apart from its influence on the total mass of roots produced by a plant. Moisture moves readily through the soil at levels between the limits of saturation and the moisture equivalent, resulting in a uniform air capacity in all parts of the soil on the same horizontal plane when the soil is uniformly packed. Since shrinkage of the soil from the pot wall only occurs when the soil moisture is reduced below the range normally prevailing under greenhouse conditions, and since aeration of the entire soil mass is favorable at the time that this shrinkage occurs, it is possible to eliminate this as a factor in the development of pot-binding, insofar as its influence on soil aeration is concerned. Finally the results of investigations by Jones (19) and Breschke (6) show that there is no significant flow of air through the pot wall in the moist state.

The relationship between the absolute and relative masses of shoot and root of plants, and the levels of nutrition and soil moisture have been well-established (14), (28), (31), (34). In order to utilize the results of these investigations in the study of pot-binding, it is only necessary to demonstrate the relationship between degree of pot-binding, the concentration of roots within the soil mass, and the absolute mass of roots produced. This investigation shows that a direct relationship exists between both concentration of roots within the soil mass and the absolute mass of root, and degree of pot-binding. It follows, therefore, that pot-binding is conditioned by any factor which affects root development, and that such factors as levels of soil moisture and nutrition contribute to the degree of pot-binding.

When a marked retardation in rate of shoot growth occurs at an early stage in the development of the plant, the pot-bound condition is never exhibited since only a small mass of root is produced from the limited amount of photosynthate supplied by the dwarfed shoot. If, however, a greater mass of shoot is produced before the dwarfing effect of nitrogen deficiency is exerted upon the shoot, there occurs an increased root development, and for a certain period of time a greater degree of pot-binding is exhibited than under conditions of optimum nutrition. As the amount of shoot growth increases, owing to the more favorable level of nutrition, there occurs also an increase in root growth, although this is proportionately less than the increase in shoot growth. As is to be expected, the greatest degree of pot-binding is finally exhibited by those plants growing under the most favorable nutrient conditions. This explanation is in agreement with the Growth-Differentiation concept advanced by Loomis (25).

Results of this study suggest that the influence of level of nitrogen nutrition upon pot-binding is to be determined by the following factors (1) the susceptibility of the species or variety to nutrient deficiencies (2) the capacity of the soil to supply nitrogen in an available form, and (3) time. Different varieties of column stocks, for instance, respond at varying rates to extremely low levels of nitrogen nutrition, one variety showing little tendency to become pot-bound owing to the restricted vegetative growth, while other varieties produce a larger shoot growth and therefore exhibit the condition to a greater degree. With coleus, there is no retardation in rate of shoot growth for several weeks after the nitrate level of the soil has reached an extremely low value, so that little increase in pot-binding occurs in soils of low nitrate level as compared to those characterized by a more favorable level of nutrition.

Time is a factor which must be taken into consideration in a discussion of the relation of nutrition to pot-binding since at one stage of development there may be no apparent difference in degree of pot-binding between plants at high and at low levels of nutrition; at a somewhat later stage, however, plants growing under a deficiency of nitrogen will exhibit pot-binding to the greatest degree, while at a still later stage, those plants receiving optimum nutrition will exhibit the most pot-binding.

Harris (14), Tucker and vonSeelhorst (31) and others have demonstrated the influence of level of soil moisture upon the absolute mass of roots. Since a deficiency of soil moisture exerts an influence upon shoot and root growth similar to that of low available nitrogen, it is suggested that different plants will respond at different rates to low soil moisture levels, and varying degrees of pot-binding will be exhibited. Under conditions of favorable soil moisture, nutrition and temperature, and with sufficient illumination, a very rapid vegetative growth occurs owing to the utilization of sugars in the formation of new tissue, most of which occurs in the shoot. When soil moisture or nutrition effects a retardation in rate of shoot growth, an accumulation of sugars occurs, which on translocation to the root, stimulates root development.

No confirmation has been found for the statement of Jones and Haskins (20) that the pot-bound condition is characteristic only of plants grown in porous pots. Under conditions of low soil moisture and nitrate deficiency which frequently occur when plants are grown in porous pots, owing to absorption of nutrients and loss of water by the pots, it is possible to have pot-binding occur at an early stage of plant development, and to a greater degree than in glazed containers. However, plants in glazed pots become pot-bound equally as readily as do those in porous pots when conditions of soil moisture and nutrition in both kinds of pots are maintained within a favorable range.

A rather exhaustive study of concentration of plant nutrients in different parts of the soil in porous pots under widely varying conditions has shown that significant differences in concentration of nutrients occur in different parts of the soil in the same horizontal plane, but it is improbable that concentrations of the nitrate ion of the order of ten and five parts per million at the periphery and center of the soil mass respectively, could exert any significant influence upon root development in the two regions. Under commercial watering there appears to be no large nor consistent difference in concentration of ions in different parts of the soil horizontally. It is certain that under commercial surface watering much greater differences in concentrations of mobile ions occur between the top and bottom halves of soil masses than between the periphery and center, for instance, yet it is rarely observed that massing of roots is greater on the lower half of the periphery or in the bottom of the pot, than on the upper half excepting when plants of deep-rooting habits are concerned.

It is also improbable that absorption of nutrient ions by the pot material has any influence upon stimulation of root growth at the soil-pot interface.

Analyses of used pot material has shown the presence of considerable amounts of nitrate, potassium, calcium and magnesium, the tests for the reserve materials being especially high as compared to analyses of new pot material. It is unlikely, however, that such absorbed nutrients are of any significance insofar as pot-binding is concerned since in porous pots there is a continual movement of water from the inside to the outside of the pot wall so that a concentration of nitrate ion, in particular, on the inside pot wall is not likely to occur. Evidence supporting the above hypothesis is provided in this investigation by the fact that roots massed on the outer surface of the middle rooting medium in triple pots, whereas only a few roots were found on the inner surface of this layer of soil. Used pots were employed in this experiment, so that the possibility of root stimulation from absorbed nitrate was equally as great at the inner as at the outer surface of this middle layer of soil.

The results of this investigation show very clearly the inherent tendency of roots of many kinds of plants to spread and to follow a more or less definite root pattern. Most plant roots on reaching the pot wall do not reenter the soil mass, but rather continue to develop on the periphery, apparently because the stimulus to spread is continually being exerted on the direction of growth of the root tips. It has been shown that roots in a dry soil tend to spread farther than in a wet or waterlogged soil (33), and it has also been shown that roots of plants are longer in a medium containing a more favorable level of nitrate than in one deficient in this ion (34). Apparently the tendency of roots to spread is a fundamental cause of pot-binding, and such factors as levels of soil moisture and nutrition, although exerting some influence upon this spreading tendency, are of most significance in pot-binding because of their effect upon the mass of roots produced.

Pot-binding, in itself, cannot be considered to have a detrimental effect upon plant growth. Rather, it would seem that, providing attention has been given to the matter of maintaining favorable levels of soil moisture and nutrition, a pot-bound condition is an indication that plants have been maintained in a state of thrifty vegetative growth. Shifting of plants to pots of a larger size when massing of roots has begun on the periphery of the soil may be considered a safe practice for those growers who are not in the habit of making supplementary fertilizer applications. Nevertheless, when adequate levels of soil moisture and nutrition are maintained, a satisfactory rate of shoot growth can be expected long after the plants have become pot-bound. When the soil becomes deficient in nutrients, particularly in available nitrogen, it is necessary either to add supplementary nutrients, or provide new soil by shifting the plant to a pot of a larger size.

There is, of course, a limit to the size of plant that can be grown economically in a small pot, since it becomes impractical to maintain soil moisture within the necessary range when a large mass of shoot must depend for its moisture supply upon a relatively small volume of soil. In commercial practice, however, deficient nutrition is frequently the factor which limits the size of plant that can be produced in a pot of a given size. It has been demonstrated with column stocks, coleus, begonia and calendula that as large plants can be grown in 2½-inch as in 5-inch pots up to the time that it is impossible to maintain favorable moisture relations, providing that plant nutrients and particularly nitrates are added as required. Shifting of plants entails considerable labor and increases the requirement for bench space. Proper attention to the maintenance of a moderately high nutrient level through avoiding unnecessary leaching and the use of fertilizers in a slowly available form, are suggested as means of reducing such requirements.

It is emphasized that the time for shifting plants should not be based entirely upon the massing of roots on the periphery of the soil. The writer has observed a considerable massing of roots of tomatoes on the periphery of the soil by the eighth day after having been shifted from 3½ to 6-inch pots. Although these plants were becoming pot-bound, vigorous growth was maintained for a further period of two weeks, and this without the addition of supplementary nitrogen.

SUMMARY

A study of the influence of moisture and aeration, nutrient level of the soil and lateral movement of nutrients in porous pots, and of the geotropic stimulus upon the development of the pot-bound condition has been conducted.

Study of the distribution of soil moisture by the conventional oven-drying method and by means of tensiometers placed in different parts of the soil mass has indicated that no significant difference in soil moisture, and consequently in soil aeration, occurred in different parts of the soil until the moisture equivalent of the soil was reached. Massing of roots on the periphery of the soil could not be attributed to differential aeration conditions.

There was a direct relationship between the massing of roots on the periphery and root concentration within the soil mass in all plants studied.

Pot-binding was shown to be influenced by the level of soil moisture and nutrition, low soil moisture and nitrate deficiency being conducive to a greater massing of roots on the periphery at a certain stage of growth than occurred when these factors were favorable for plant growth. Plants in porous pots did not exhibit pot-binding to a greater degree than did those in glazed pots, providing that attention was given to the maintenance of uniform levels of soil moisture and nutrition in the two kinds of pots.

A comprehensive study of the movement of nutrients in the soil in a total of 104 porous pots failed to show any significant differences in concentration of individual ions in different parts of the soil mass in the same horizontal plane excepting where heavy leaching was practiced, and where no leaching occurred and pots were maintained fallow. There was, however, a much greater concentration of all mobile ions in the lower part of the soil

than in the upper part when water was applied to the upper surface; this situation was exactly reversed when subirrigation was practiced. The root pattern was not altered significantly by the different methods of watering used excepting in the case of coleus.

Growing plants of coleus, column stocks and geranium in pots maintained in the inverted position resulted in a uniform distribution of roots over the entire periphery of the soil, while in the case of pennisetum, development of roots occurred only on the lower surface of the soil mass. Pot-binding in the lower part of pots in the normal vertical position can be attributed chiefly to the tendency of roots to grow in a downwards direction.

Growing plants in triple pots with three separate rooting media showed that roots massed on the outer surface of the middle rooting medium, but in no instance was any massing of roots observed on the inner surface of this medium. Since the levels of soil moisture, aeration and nutrition were identical on the two surfaces, the massing of roots on the inside walls of pots was caused by the inherent tendency of roots to spread and form a definite root pattern. Main roots of plants on reaching the inside wall of pots, turned and followed the pot wall, and in no instance were they observed to re-enter the soil.

Shifting of plants should be based upon the nutrient level of the soil, the volume of available water supplied by the soil mass, the appearance of the shoot, and the degree of pot-binding exhibited.

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APPENDIX

Table 6. Concentration of nitrate and potassium at varying distances from periphery in porous pots with leaching.

(some pots maintained fallow, others with plants)

Periphery		1.5 cm from periphery		Center	
NO3	K	NO3	K	NO3	K
		(parts per million)			
3 ± 1.4	19	1 ± 0	19	Tr.***	21
4 ± 1.4	19	3 ± 0.6	21	2 ± .06**	24
4 ± 1.6	14.5			1 ± .2***	17
4 ± 1.3	19	1 ± 0	20	1 ± 0***	23
5 ± 0	16			1.5± .5***	19
5 ± 2.7	24			2 ±1.3*	17
5 ± 2.0	15	3.5± 1.4	19	2.5± .5	14
6 ± 2.4	22.5			3 ±1.2***	24
6 ± 2.3	15.5			2 ± .8**	15
11 ± 1.4	17			5 ±1.0***	21
11.5± 1.7	23	7 ± 2.6	21	4 ±1.0***	20
12 ± 1.7	23.5	11 ± 2.4	23	9 ± .2**	21
14 ± 5.2	21	8 ± 2.8	19.5	4 ± .2***	20
14.5± 1.8	17	10 ± 4.0	17	5 ±1.5***	16.5
14.5± 3.3	19.5	11 ± 2.4	17.5	7 ± .6***	17
15 ± 6.4	19.5			7.3±2.3*	22
17 ± 5.7	22	15 ± 6.2	19	11 ±1.9*	17
35 ± 3.4	29	15 ± 7.0	18	13.5±2.1***	24
50 ± 1.6	35	47 ± 2.7	35	22 ±1.3***	35
75 ± 3.4	32	36 ± 0.5	18	48 ±2.5***	42

*** indicates significance at 1% point between means of nitrate concentrations of periphery and center.

** indicates significance at 5% point.

* indicates near significance at 5% point.

Table 7. Concentration of nitrate and potassium at varying distances from periphery in porous pots with leaching(rose pots). (some pots maintained fallow, others with plants)

Periphery		Center	
NO_3	K	NO_3	K
(parts per million)			
3 ± 1.7	21	Trace ***	20
4.3 ± 2.1	24	2.5 ± .5	23
5 ± .6	16	4 ± 1.0	15
8.5 ± .6	18	2.5 ± .5***	15
12 ± .6	22	2.5 ± .5***	17
18 ± .8	22	3 ± 1.0***	18
25 ± 5.0	33	9 ± .6***	25

Table 8. Concentration of nitrate and potassium at varying distances from periphery in unleached pots maintained fallow.

Periphery		Center	
NO_3	K	NO_3	K
(parts per million)			
10.7 ± 3.4	21	18.5 ± 1.0 ***	22
11 ± 1.7	28	12.5 ± .5	28
12 ± 1.0	24	10 ± .08 $\underline{***}$	18
14 ± 2.8	22	12.5 ± .6	25
20 ± 7.6	24	10.5 ± 3.4	19
26 ± 7.1	23	57 ± 8.2 ***	20
31.5 ± 3.8	26	28.5 ± 1.5	22
58 ± 7.7	21	43 ± 2.0 $\underline{***}$	15

*** indicates significantly higher concentration of nitrate at periphery than in center.

$\underline{***}$ indicates significantly higher concentration of nitrate in center than at periphery.

Table 9. Concentration of nitrate and potassium at varying distances from periphery in unleached pots with plants.

Periphery		Center	
NO_3	K	NO_3	K
	(parts per million)		
8 ± 4.3	18	2.5 ± 1.0**	21
9.5± 1.0	22	14.5 ± 4.4	22
10 ± 2.3	24	11.5 ± 2.7	21
12 ± 1.3	23	Tr. ***	18.5
14 ± 4.1	20.5	17 ± 2.4	24
15.5± 2.7	13.5	31 ± 3.4 $\underline{***}$	17.5
22 ± 6.3	24	7.5 ± 1.5 ***	23
25 ± 6.6	22.5	36 ± 5.6 $\underline{***}$	18
34 ± 8.0	29	39 ± 6.2	24.5
37 ± 5.0	25	51 ± 2.0 $\underline{***}$	23

Table 10. Concentration of nitrate and potassium at varying distances from periphery in pots subjected to light leaching a nd with plants.

Periphery		Center	
NO_3	K	NO_3	K
	(parts per million)		
<u>Petunias in 6-inch pots for 2 months</u>			
2.2± .5	9.7	4.2 ± 1.5 $\underline{**}$	10.0
2.7± 1.5	9.5	2.7 ± 1.1	9.2
3.0± 1.4	10.0	3.2 ± .5	8.0
3.2± .5	9.0	4.6 ± .6	10.1
3.7± .5	7.7	4.7 ± .9	8.2
4.5± 1.3	10.2	4.5 ± 1.3	9.0
5.5± .9	9.2	5.5 ± 1.3	11.0
5.7± .5	9.0	3.0 ± .5 ***	11.0
<u>Coleus in 4-inch pots for 4 months</u>			
2.0± .5	6.7	4.0 ± .8	9.0
3.0± .8	16.5	2.7 ± .5	11.5

(legend same as in Table 8.)