AN ABSTRACT OF THE THESIS OF

---Jesse Blaine Holladay--------for the---MS---in Farm Crops------
(Name) (Degree) (Major)

Date Thesis presented-May 15, 1941----

Title-----Root Development of Certain Annual Legumes as Influenced----
----------by Soil Types---

Redacted for privacy

Abstract Approved:-------------------
(Major Professor)

Root and top growth of crimson clover (Trifolium incarnatum), subterranean clover (Trifolium subterraneum), Austrian winter peas (Pisum arvense L.), hairy vetch (Vicia villosa), and common vetch (Vicia sativa L.) was observed periodically in Willamette clay, Chehalis clay loam, and Melbourne clay soil types.

The object of the study was to obtain as much information as possible on the characteristics of root growth, their lateral spread, depth of penetration, rate of growth and nodulation, and to note the root responses of these crops to the varying conditions of the soil types in which they were growing.

Reasons for the study were twofold, (a) to aid in determining the most satisfactory soils in which to grow certain legumes, and (b) to aid in solving certain crop problems related to soil structure, moisture movement, aeration, bacterial action, and the increase of plant nutrients in various plant food zones.

Root observations on each crop were made at 28, 56, 84, 112, and 168 days from the time of seeding.

Seed bed preparation and rate of seeding were the same as those commonly practiced by good Western Oregon farmers.

The entire root systems were excavated by means of a stream of water under low pressure. A regular hand-pumped spray tank or a larger tank equipped with a motor were found to work satisfactorily in applying the water. The water was applied to the open face of a trench which was dug 6 to 8 inches from the plant or plants to be observed.

At the time of each observation, from three to five representative plants were selected and removed from the soil. The practice followed was to measure these plants as to length of roots and tops, lateral spread of the roots, and zone of greatest root concentration. These dates were then averaged, and the plant which most nearly represented this average was made the basis of the study.

The root systems were floated horizontally in a tank of shallow water in order to separate the roots, to eliminate all debris from the rooting system, and to aid in manipulating the roots into natural position over a photographic background.

The root system was then photographed and measured.

Pore space, mechanical analysis, and chemical analysis for Ph, Organic matter, nitrate nitrogen, and available phosphorus were determined for each soil type. This was done in order to standardize the information obtained from the root studies, and to serve as a basis for studying and analyzing root responses to soil type.

Climatic factors during the period of study were also included in order to standardize the results obtained from the study.

Results of the study were as follows:

(1) The structure and texture of the soil had the greatest influence on the vertical growth of the roots, and the most fertile soils produced the most marked lateral and top growth. In all crops the weight of the tops and the roots were greater in the most fertile soils.

(2) In all soils the number of lateral roots per three-inch section of taproot, as well as the lateral spread, were least in the more compact regions of the soil profile. It was also noticed that the roots which penetrated into these zones were more twisted and contorted, and were smaller in diameter than roots which grew in the more porous portions of the soil.

(3) It was found that during the winter the top growth of all the plants studied was very slow in comparison with the root growth. During the early spring the tops made the most rapid growth and weighed up to three times more than the roots even though they were only one-third as extensive.

(4) Of all the crops studied, Austrian winter peas produced the coarsest rooting system. This crop, along with hairy vetch and common vetch, made the most rapid growth after seeding, and possessed the most root and top growth 168 days from the time of seeding. These crops would therefore be most suitable from the standpoint of increasing soil organic matter, soil aeration, and in increasing the amount of plant food in the upper 30 inches of the soil.

ROOT DEVELOPMENT OF CERTAIN ANNUAL LEGUMES AS INFLUENCED BY SOIL TYPE

by

JESSE BLAINE HOLLADAY

A THESIS

submitted to the

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1941

APPROVED:

Redacted for privacy

Head of Department of Farm Crops

In Charge of Major

Redacted for privacy

Chairman of School Graduate Committee

Redacted for privacy

Chairman of State College Graduate Council

ACKNOWLEDGEMENT

The writer wishes to express his sincere appreciation to G. R. Hyslop, Head of the Division of Plant Industries, for his helpful advice and cooperation in making this investigation possible; to H. A. Schoth, Agronomist, H. H. Rampton, Assistant Agronomist, U.S.D.A., L. R. Hansen, Research Assistant, L. E. Harris, Assistant Agronomist, and R. E. Stephenson, Professor of Soils, for their cooperation, suggestions, and courtesy in supplying materials used in this study; and to D. D. Hill, Professor of Farm Crops, for his valuable assistance, suggestions, and reference material in the preparation of the manuscript.

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INTRODUCTION

The root system of a plant and the environment under which it develops represent a far more complex association than that of its aerial portion. Notwithstanding this fact, the roots of plants have been given much less attention than the aerial portion since the science of plant ecology began. Because the soil hides the roots from view, they are the least understood, and the least appreciated part of the plant. All who study plants and vegetation should have a vivid mental picture of the plant as a whole.

Something must be known of the character and activities of the roots that absorb water and nutrients for the plant, as well as the position which they occupy in the soil, before anything other than an empirical solution can be provided for problems concerning the following:

(1) the value of plants for soil-conserving purposes,
(2) the relative amount of organic matter a crop is capable of returning to the soil,
(3) the best time or method of applying fertilizers,
(4) the best crops to plant where various types of rotations are required to fit specific climatic and soil conditions, and
(5) to those problems relating to the biological effect of root residue on soil fertility and soil structure.

A complete scientific understanding of the relation between the soil and crop cannot be obtained until the mechanism by which these two are brought into relationship is thoroughly understood, namely, the rooting system.

IMPORTANCE OF THE STUDY

Annual legumes constitute the principal species of the leguminous crops grown in Oregon.

The importance of these crops is shown by their increasing acreage in Table I.

TABLE I. SHOWING ACREAGES SEEDED TO ANNUAL LEGUMES AND SWEET CLOVER, BIENNIAL AND PERENNIAL LEGUMES AND GRASSES IN OREGON, 1937-1940 INCLUSIVE*

	1937 acres	1938 acres	1939 acres	1940 acres
Seeding annual legumes of sweet clover **	115,957	220,449	379,594	500,000#
Seeding biennial and perennial legumes and grasses **	169,968	278,599	233,984	-------

* Data obtained from 1939 AAA Annual Report
** Acreages include farms cooperating under AAA program
# Acreage estimated

These annual legumes, which are grown for soil cover, green manure, pasture, hay, or seed, play important soil-conserving and economic roles in farming practices on various soil types. A knowledge of their rooting habits such as depth and penetration, spreading habits, rapidity of development, region of greatest lateral root development, and proportionate root and top growth should serve more fully as a guide to better crop usage and better farming practices.

Annual legumes included in this particular study are of primary importance because of the large acreage used as cover and soil-conserving crops. Throughout the Southern United States and in various sections of the Pacific Coast, including the Pacific Northwest, erodable lands are seeded to these crops in the fall for winter cover. One of the common problems connected with such practice is to determine which crop will be most effective in holding the soil against the forces of wind and water. Knowledge of root and top development of the more important annual legumes should help to determine which makes the most rapid growth after seeding, which produces the most extensive root growth in the upper portions of the soil, and which is more adaptable to various soil types and climatic conditions. Such data would also serve as a basis to determine the relative amount of organic matter that each would return to the soil in the form of root residue.

The application of commercial fertilizers to orchard cover crop seedings of annual legumes is becoming a standard practice in Western Oregon. A knowledge of root development is fundamental for scientific application of these fartilizers.

Crop rotations on different soil types and under different climatic conditions should be worked out with constant reference to root relations. For instance, it may be found practicable, especially in semi-arid regions, to grow crops with shallow, dense rooting systems alternately with those having more extensive, spreading root systems. In regions where plenty of soil moisture is available, both types of crops may be grown in the same field. This is a common practice in Western Oregon where annual legumes and cereals, especially oats, are grown in combination. Plasticity of root systems as to depth, lateral spread, and degree of branching go far in determining the ability of a crop to survive and yield under various moisture conditions. Moreover, under these conditions root competition is an important factor in determining the rate of seeding.

Weaver (37) considers healthy root development an important factor to disease resistance. For example, certain plant diseases that cause enormous economic losses are due to organisms that enter the root and cause it to decay entirely or in part. This often results in reduced yields or in total loss of the aboveground portion. Infestations of the root rots of clover, tobacco, and other crops cause the root system to be partially or totally destroyed by soil-inhabiting organisms. The extent of the damage is determined in a large measure by the environmental conditions surrounding the roots of the host.

An understanding of plant root development should help to explain why some crops are more drought resistant or winter-hardy than others; also why some crops recover more rapidly than others after having been subjected to adverse conditions. This type of information should be helpful in selecting crops adapted to various soil, soil water, and climatic conditions.

Weaver (35) calls attention to the fact that "irrigation water can be applied more effectively if a knowledge of the extent and position of the root system as modified by the physical and chemical nature of the soil is known."

Gibson (9) states that if soil acidity is considered from the standpoint of the tolerance of the plant to acidity rather than from the lime requirement of the soil, a knowledge of root development is again of primary importance. This is especially true for leguminous crops.

Weaver (39) further states, "It is an interesting fact that both in the field and garden the part of the plant environment beneath the surface of the soil is more under the control of the plant grower than is the part which lies above. He can do little toward changing the composition, temperature, or humidity of the aid or the amount of sunlight. Much may be done by proper fertilizing, cultivation, irrigation, drainage, etc. to influence the structure, fertility, aeration, and temperature of the soil. Thus, a thorough understanding of the roots of plants and the ways in which they are affected by the properties of the soil in which they grow is of utmost importance."

These are some of the more evident values to be gained from information about root development as concerning some important annual legumes. This information should not only help to better explain actual field results, but should be a scientific basis for improved cultural, fertilization, irrigation, and crop rotation practices under various soil and climatic conditions.

STATEMENT OF PROBLEM

The object of this study was to obtain as much information as possible on the characteristics of root growth, their lateral spread, depth of penetration, rate of growth and nodulation, and to note the root responses of these crops to the varying conditions of the soil types in which they were growing.

Reasons for the study were twofold, (a) to aid in determining most satisfactory soils on which to grow certain legumes, and (b) to aid in solving certain crop problems related to soil structure, moisture movement, aeration, bacterial action, and the increase of plant nutrients in various plant food zones.

REVIEW OF THE LITERATURE

The literature pertaining to these root investigations will be reviewed under three separate headings: (1) that relating to those physical and chemical properties of the soil which affect the root growth of plants, (2) that relating previous methods of root study, and (3) that relating to previous investigations of annual legumes included in this study.

Relating to Those Physical and Chemical Properties of the Soil Which Affect Root Development

Weaver (37) states that the root system of plants is as distinctive in character as the aerial portion, and that although root growth is governed principally by heredity, it is responsive to such environmental influences as soil moisture, structure, aeration, temperature, and plant nutrients.

Moisture is of paramount importance to root growth. Weaver (36) through numerous observations of grass roots in Kansas, Nebraska, North and South Dakota, and Colorado concluded that the most deeply penetrating roots are found where there is considerable rainfall, a low water table, and a deep soil with good structure and texture for adequate aeration and ample absorption of soil moisture.

Cannon (4) studied the roots of 50 or more annuals and perennials in the deserts of Arizona. He found that the roots of annuals rarely penetrated the soil deeper than six to eight inches and that greatest root development was in the upper two to three inches. He also observed that depth of root penetration depended upon the depth to which rains moistened the soil.

Conrad and Veihmyer (7) showed that if the soil is wet at the beginning of the season to full depth at which plant roots normally develop, subsequent additions of water can have little influence upon further depth of root development.

Weaver (35) indicates that a wet soil, especially early in the life of the plant, tends to promote a shallow root system; a moderately dry soil, a deeper rooting system. The latter is more branched and has a much greater absorbing surface.

Weaver and Crist (38) and Farris (8) in studying soil clay pan and root development advance the idea that moisture is the limiting factor in root growth since roots have been found to penetrate deeply into heavy clay subsoils during the rainy season. This was impossible when this subsoil was dessicated to any extent. From this, Farris also contends that texture itself in soil should be relatively unimportant to root expansion as long as moisture and nutrient supply are adequate.

The effect of soil texture and structure upon root growth appears to cause some disagreement between early and present investigators. Haasis (10) in studying roots of western yellow pine seedings discovered that roots grew longer in clayey than in loamy soils, and that branching was very profuse in loose soils. Carlson (6) reports that alfalfa varieties developed many branch roots in clayey soils, while in an open porous soil tap roots predominate. Anderson and Cheyney (2) concluded that the length of the tap root, regardless of moisture in soil, showed a decided increase from finer to coarser soils. The length of laterals showed no such increase, but the opposite in some cases. Turner (1936) finds the same condition in regards to the longer tap root in coarser soils, but finds many laterals on the pine tree roots. It was also found that roots of young white pine trees grew twice as much on sandy as in clayey soils.

Toumey (30) suggests that the tap root is largely controlled by hereditary influences, and is more used for anchorage than for absorption. He contends that if this is true then the tap root would not need to go in search of water but only to grow by the hereditary urge, and such a growth would be hindered by the density of the soil. He further concludes that this was adequately proved since roots from soils of high mechanical resistance were shortest in all proportions. Haasis (10) indicated opposite results. He states, "Due to the high capillary continuity of clayey soils, they dry out rapidly in the upper portions and thus root growth downward is stimulated". Since the side roots are more for absorption, all investigators tend to agree that the more compact soil structure causes less branching of the roots.

Weaver (37) reports that "loosened soil makes root penetration easier. Roots tend to develop a shorter more compact structure in dense than in loose soils". Rodgers (22) found that in sand, roots were very long, thin, and straight. In clay, they were shorter, stouter, more tapering and twisting. In loamy soils, the roots were intermediate in character.

In relation to the oxygen supply and root growth Miller (17) states that aeration of the soil is beneficial in an indirect way, since an adequate oxygen supply is necessary for proper functioning of bacteria that transform soil materials into forms directly available to the plant. In a direct way aeration of the soil furnishes oxygen which is essential for the proper functioning of the protoplasm in the root cells. A good supply of air in the soil is essential to nitrogen-fixing bacteria in the formation of nodules on the roots of legumes.

Cannon (5) indicates that some fundamental relations exist among rate of root growth, aeration, and soil temperature. Under normal conditions of aeration, the maximum, optimum, and minimum soil temperatures for root growth seem to be rather well-defined. As the oxygen in the soil air is decreased, rate of growth diminishes in a soil with high temperature. Cannon found that corn roots in a soil atmosphere of 96.4 percent nitrogen and 3.6 percent oxygen, at a temperature of 30 degrees C, grow about one-third as rapidly as at the same temperature under normal conditions of aeration. But at 18 degrees C, growth is increased to about two-thirds the normal rate at that temperature (18° C) when the soil is well aerated. It is agreed that plants which attain a fair rate of growth at high temperatures must be in well aerated soils; otherwise, growth is considerably reduced.

In nodule development on legumes, water content of the soil and the temperature exert a profound effect. Russell (23) noted that most soil bacteria do not become active until temperatures of 8 to 10 degrees C. are attained. In one experiment, the amount of nitric nitrogen produced per acre in a period of three weeks under favorable temperature, only 2.8 pounds were formed in dry soil and 8.2 pounds in one of medium water content, but 29.6 pounds per acre were formed in the same period where the water content was favorable. Much larger quantities are, moreover, produced in rich than in poor, eroded soils.

Hill (13), in studying the effects of temperature and day length on the growth of cereals with winter and spring habit, found the root systems to be longer and more extensive on plants grown outside in the fall under normal conditions than on plants grown in the greenhouse at warmer temperatures with the same day length.

Jones and Tisdale (14) have shown that nodules become larger when soil temperatures are most favorable. In the soybean, a consistent increase in dry weight of nodules occurred as soil temperature increased from 15° to 24° C. At higher temperatures, a progressive decrease occurred. Alfalfa, red clover, and field peas gave maximum nodule production at a soil temperature of about 24° C.

The soil nutrients which are generally considered to be most effective upon root growth are phosphates and nitrates.

In certain regions the application of phosphates is especially beneficial in root crop production. Miller (17) found that in the absence of phosphorus, root crops like turnips, mangolds, and rutabagas do not enlarge but remain permanently dwarfed.

It was observed by Turner (33) with barley, wheat, and cotton growing in water cultures, that the ratio of tops to roots decreased as the concentration of phosphate increased. The increase of phosphorus, however, retarded the development and growth in length of the lateral roots. Weaver (37) states that phosphates added to the soil are especially beneficial wherever drought is likely to occur, because they induce the young roots to penetrate into the more moist layers of the soil below the surface. Wheat, on land treated with phosphates, was found to be rooted almost twice as deep as in similar soil to which no phosphates had been applied, according to Lees (16).

The effects of nitrates on root development of plants appears to be almost exactly opposite from that of phosphates. Weaver (39) has shown that in every case where roots came in contact with a soil layer rich in nitrates, they not only developed much more abundantly and branched more profusely in the soil but also failed to penetrate as far into the deeper soil. On the other hand, Sievers and Holtz (27) found that wheat and barley seedlings grown in both soil and culture solutions low in nitrates produced remarkably extensive root systems, although the shoots were small. Fertilizing the surface layers of soil with nitrates and thus stimulating surface root production in regions where these layers have little or no available water during periods of drought appears to be distinctly detrimental to normal crop production.

Nutrients may also affect the size and shape of the fleshy portion of root systems. For example, Schermerhorn (24) found that potash fertilizers may result in sweet potatoes being considerably shorter and thicker, while nitrogen in excessive quantities produced long potatoes.

Relating to Previous Methods of Root Study

During the last three decades, root investigations have attracted much scientific and practical interest. Hales (11) as early as 1727 examined the root system of a sunflower and made root-top growth comparisons.

At present there are at least fifteen different methods or techniques which have been employed to extricate roots from the soil. Pavlychenko (19) cites twelve of these. Review of literature indicates that the method best suited to a particular situation will vary with soil type, funds available, and the type of root study being made. Of methods previously employed, the following are related to the method applied in this study:

1. Trench washing method

    This method described by Pavlychenko (19) was developed by Schubart (25) in 1858. It consisted of digging a trench beside the plant or plants selected for study and then washing the root systems directly from a vertical wall of the trench. This method enables the investigator to determine the depth of penetration and to procure the bulk root material of such crops as wheat, winter rape, and clover.

2. Hydraulic method.

This method was developed by Stoeckler and Kluender (28). It is applicable in sandy soils where the water table is within a reasonable distance from the surface. The method consists of using a power pump with suction to draw the water from the ground. The water is then used under pressure to wash the roots directly from a trench dug beside the plant. This method is somewhat limited because the finer roots have to be sacrificed at the expense of the added pressure and size of the spray employed. It is estimated to be 4 to 10 times faster than the dry ice-pick method employed by Weaver (37).

3. Bisect Wash method.

This method was employed by Tharp and Muller (29) in excavating native plants from the soil, however, it was used only to obtain a bisect of the plant root. A 40 to 50 gallon tank equipped with pressure and a nozzle were used to wash the soil from the vertical and horizontal face of a trench until a bisect of the entire root system was exposed. The root was then drawn to scale. This method enables the investigator to include the finest root hairs since the pressure and fineness of spray are easily adjusted.

4. Steel Cylinder method

This method has been used by Laird (15), Gibson (9), Hansen (12), and others in studying the roots of various grasses. It consisted of an iron cylinder being forced into the ground around the grass root to a depth of six inches below the maximum root penetration. To force the cylinder into the soil it was necessary to dig around the plant leaving a column of soil over which the cylinder could be placed.

The cylinder containing the soil and the root system was then transported to a washing table where the soil was washed away leaving the root of the desired plant.

The root system was floated, measured, dried on a plate in its natural position, and photographed.

Relating to Previous Root Investigations on the Annual Legumes Included in This Study

A complete review of literature pertaining to root studies of crimson clover (Trifolium incarnatum), subterranean clover (Trifolium subterraneum), Austrian winter peas (Pisum arvense L.), hairy vetch (Vicia villosa), and common vetch (Vicia sativa L.) indicates that very little has been published regarding their rooting habits.

The author was unable to find any previous root studies on these crops in Western Oregon, or in any section of the United States where these annual legumes are of any economic importance.

Furthermore, results which have been published are rather brief and do little more than name the crop.

The following is a summary of previous investigation of the above-mentioned crops:

Crimson Clover

Crimson clover at North Dakota, planted in the spring, was found to have a root system 3 feet deep by August 22. At Deleware Experiment Station, the tops and roots were determined to contain respectively 5,372 and 413 pounds of dry matter per acre, according to Piper (20).

Hairy Vetch (Vicia villosa)

Piper (20) found that the rooting system of hairy vetch is richly branched and extends deep into the soil. He states that at Cornell Experiment Station, plants from seed sown July 10 had roots which penetrated 3 feet 8 inches in tough clay by November 10. The young plants go largely to root development so that the top growth is slow at first.

At the Deleware Experiment Station the tops were estimated to produce 3,064 pounds and the roots 600 pounds of dry matter per acre, according to Piper (20).

MATERIALS AND METHODS

Crops and Soils Used

Plants of five important annual legumes grown in three representative Willamette Valley soil types are included in this study. The legumes observed are crimson clover (Trifolium incarnatum), subterranean clover (Trifolium subterraneum), Austrian winter peas (Pisum arvense L.), hairy vetch (Vicia villosa), and common vetch (Vicia sativa L.).

Soil types included in this study are Willamette clay, Chehalis clay loam, and Melbourne clay. These represent the three major soil groups of the Willamette Valley. The growing of annual legumes is of economic importance on all three of these soil types.

Root observations on each crop were made at 28, 56, 84, 112, and 168 days from the time of seeding.

Willamette clay is considered one of the best old valley filling soils for most agricultural purposes. This soil, which absorbs moisture slowly during the heavy rainfall period, suffers to some extent from sheet erosion and is benefited by cover-crop growth.

Chehalis clay loam is an alluvial soil classified as the youngest and most fertile soil of the Willamette Valley. Its agricultural importance as a producer of intensive row crops as well as its position with relation to stream overflow in the freshet periods makes it imperative that cover crops, preferably legumes, be used to prevent serious erosion and to maintain soil fertility.

Melbourne clay is representative of the hill soils and has developed from sedimentary material, principally shale and sandstone. Soil conservation observations indicate more serious erosion losses from this soil type than from any other in Western Oregon. Due to the seriousness of erosion and loss of fertility on these residual soils, large acreages have been taken out of cultivation and seeded to grasses, hairy vetch, and other soil-conserving crops.

Preparation of the Seed Bed

The methods employed in connection with seed bed preparation were comparable to those practiced by good Western Oregon farmers.

The seed bed was prepared by disking the land after plowing in the spring allowing it to lie fallow for one season. There was no weed growth at any time. The absence of weeds or foreign material in such a study is highly desirable because it aids in speeding up operations both in digging and photographing the roots.

Prior to fall planting, which is recommended in Western Oregon, the ground was worked into an excellent seed bed with a disk and harrow.

The land was divided into plots 6 feet wide and 25 feet long; a 10-foot roadway was allowed at the head of the range (See planting chart, page 22)

Seeding

All seedings were made between October 12, and 20, 1940.

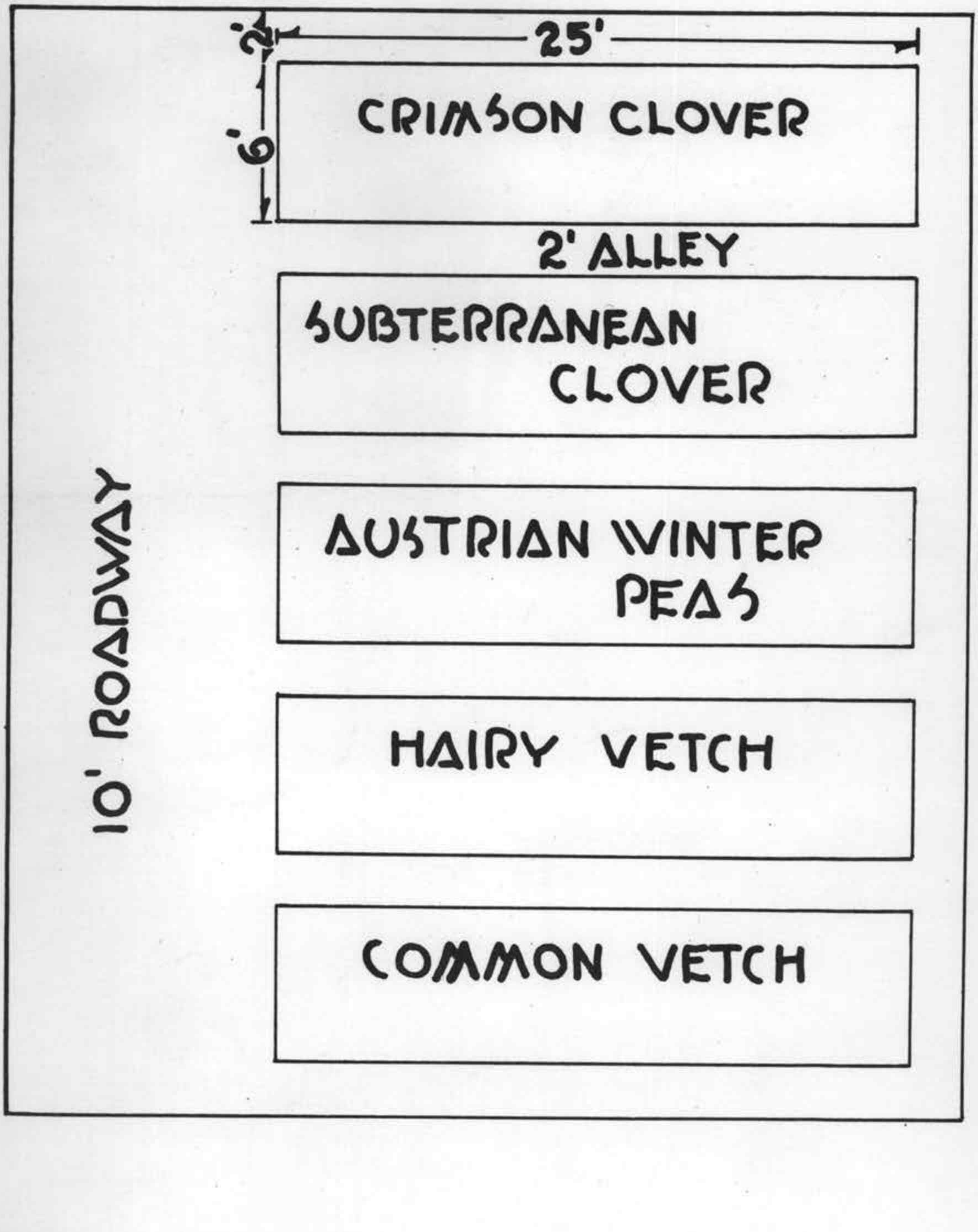
The seed was inoculated and planted at the following standard rates of planting for Western Oregon.

Crimson clover (Trifolium incarnatum) 15# per acre
Subterranean clover (Trifolium subterraneum) 16# per acre
Austrian winter pea (Pisum arvense L.) 85# per acre
Hairy vetch (Vicia villosa) 50# per acre
Common vetch (Vicia sativa L.) 70# per acre

Except for subterranean clover, which was imported from Australia, locally-grown seed was used. All seed was broadcast by hand and covered to a depth of one inch.

Planting Chart

ROOT DEVELOPMENT STUDIES



Methods Used in Making Root Observations

After a thorough review of methods previously used in root studies, the steel cylinder method adopted by Laird (15) Gibson (9) and others was first employed in these studies. Although this method proved successful in excavating grass roots, it was rather impractical for these legumes.

The tendency for legume roots is to produce a rather extensive lateral spread as well as to penetrate deeper into the soil than grass roots. This made it desirable to use a larger cylinder than was used by investigators in grass root studies.

The unusually high clay content and the columnar structure, characteristic of some soils on which these legumes were grown, caused them to break along vertical lines while being transported within the cylinders from the field to the laboratory. This created considerable difficulty in obtaining unbroken root systems.

Gibson (9) in studying the roots of various grass species noted that soils of Western Oregon have unusually high clay content which causes them to cement together especially when dry. This condition, therefore, definitely limited the direct tracing of the roots by the method used by Weaver (37)

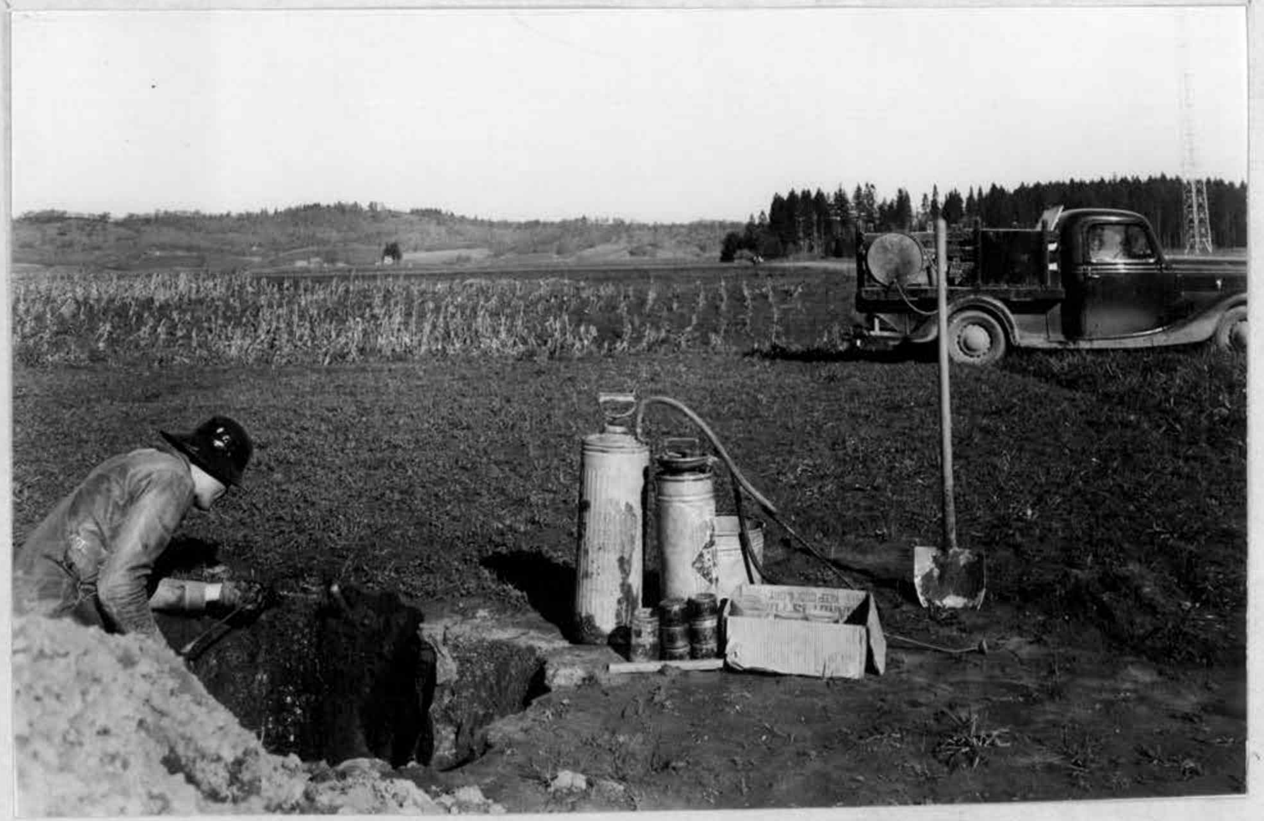
The method finally adopted in this study was a suggestion by G. R. Hyslop. It consisted of a combination between the trench washing method adopted by Schubert (25) in 1858, and the direct tracing of roots used by Weaver (37).

A trench 4' x 4' x 4' was dug 6 to 8 inches from the plant or plants selected for observation. This afforded an open face which allowed the use of the ice pick or other apparatus so as to remove the entire root system. The root system was washed out of the soil by means of a stream of water under low pressure. (Plate I) A regular hand-pumped spray tank or a larger tank equipped with a motor proved to be satisfactory in applying the water. A pressure of 15 to 20 pounds per square inch was used. Accumulated water was bailed from a sump which was dug in the portion of the trench directly beneath the plants being excavated. This provided drier working conditions for the operator.

An ice pick was used to supplement the spray in reducing the larger soil aggregates and to aid in loosening the soil from the roots. Care was taken to wash the soil carefully from the roots and to use the ice pick as little as possible, since digging resulted in the irregular breaking of soil chunks from the face of the trench

Plate I

The Root System Is Washed From the Face of the Trench By a Stream of Water Under Low Pressure



and caused the roots to be broken or entirely lost. This apparently simple process, however, requires much practice, not a little patience, and considerable knowledge of soil texture and structure.

The most satisfactory method of excavating the roots was first to wash the soil completely away from the main tap roots, then to reduce the pressure of the spray, and to wash each lateral with its roots from the soil by beginning at the lower ones and working upward until the entire root system was removed. Incidentally, the amount of pressure applied varies somewhat with the fineness or coarseness of the roots, the structure and texture of the soil, and the technique used by the individual operator.

At the time of each observation, from three to five representative plants of each crop were carefully selected and removed from the soil. The practice followed was to measure these plants as to length of roots and tops, lateral spread of the roots, and root concentration. These data were then averaged, and the plant which most nearly represented this average was made the basis of the study herein reported. Although the data presented, herein, are based primarily upon a representative plant, it is believed that the results are a fair representation of the nature and extent of the rooting systems. It was the object to select plants of average growth which were surrounded by others of their kind rather than to select isolated individuals.

While a larger number of plants observed would have provided better representation of the root systems, the limited period of time under which this study was conducted, and the great amount of time involved in making accurate root investigations prevented more extensive activities.

The next step consisted of floating the soil-free roots horizontally in a shallow tank of clear water. This not only served as an aid in separating the roots and all foreign material from the rooting systems, but it also allowed the roots to be manipulated into natural position prior to being photographed. The tank was drained and refilled until the water became entirely free from any root residue. Prior to refilling the tank the last time the root system was removed and a black-lacquered 14-gauge iron plate, which served as a photographic background, was placed in the tank. The tank was then refilled, and the roots were replaced for further manipulation.

To get the roots in condition for photographing it was first necessary to arrange them in their normal position. This was done by spreading them out in the tank directly above the iron plate. (Plate II) While in water, some of the roots will ordinarily assume the position occupied in the soil, however, the finer roots had to be manipulated into place by hand. Root systems which were in any way damaged were discarded.

As soon as the specimen was in its normal position, the water was slowly drained from the tank and the plate with the adhering root was taken up, blotted dry, and photographed immediately.

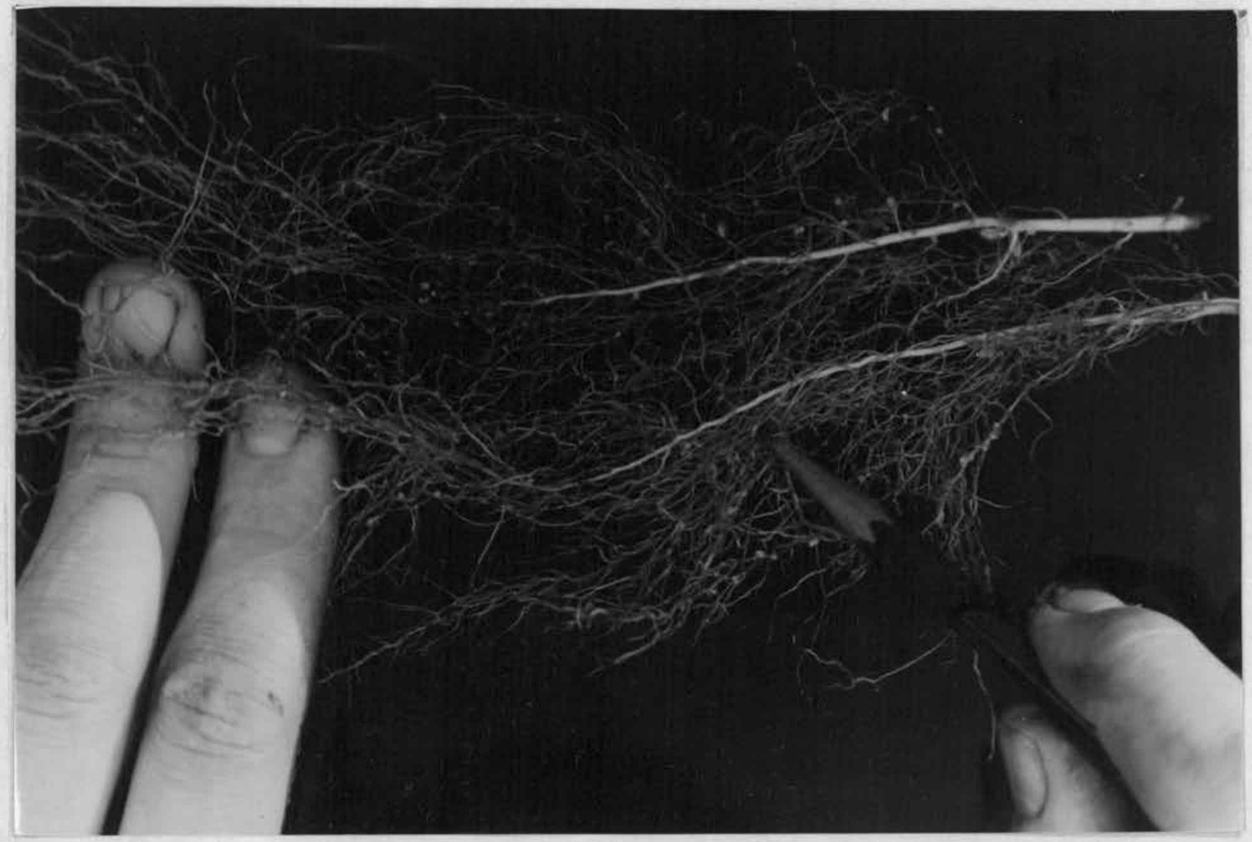
The intensiveness of the root system, especially lateral growth, as shown by the photographs is somewhat misrepresented. Actually the roots were excavated in a three-plane formation; however, on the flat surface they appear only in two planes. Depth is rather difficult to express by individual photographs.

When the root systems became too large for the size of the iron plate, they were spread out and photographed in the bottom of the tank, which was somewhat larger.

All measurements of the roots were taken while they lay in position on the black plate or in the tank. (Plate III) The finer roots tend to dry out and shrink if allowed to remain on the plate too long. Enough moisture, however, around the roots was usually present to prevent any dessication until the data could be taken. A little water sprinkled on the roots was found to be

Plate II

The Soil-free Root Systems Are Separated Under Water



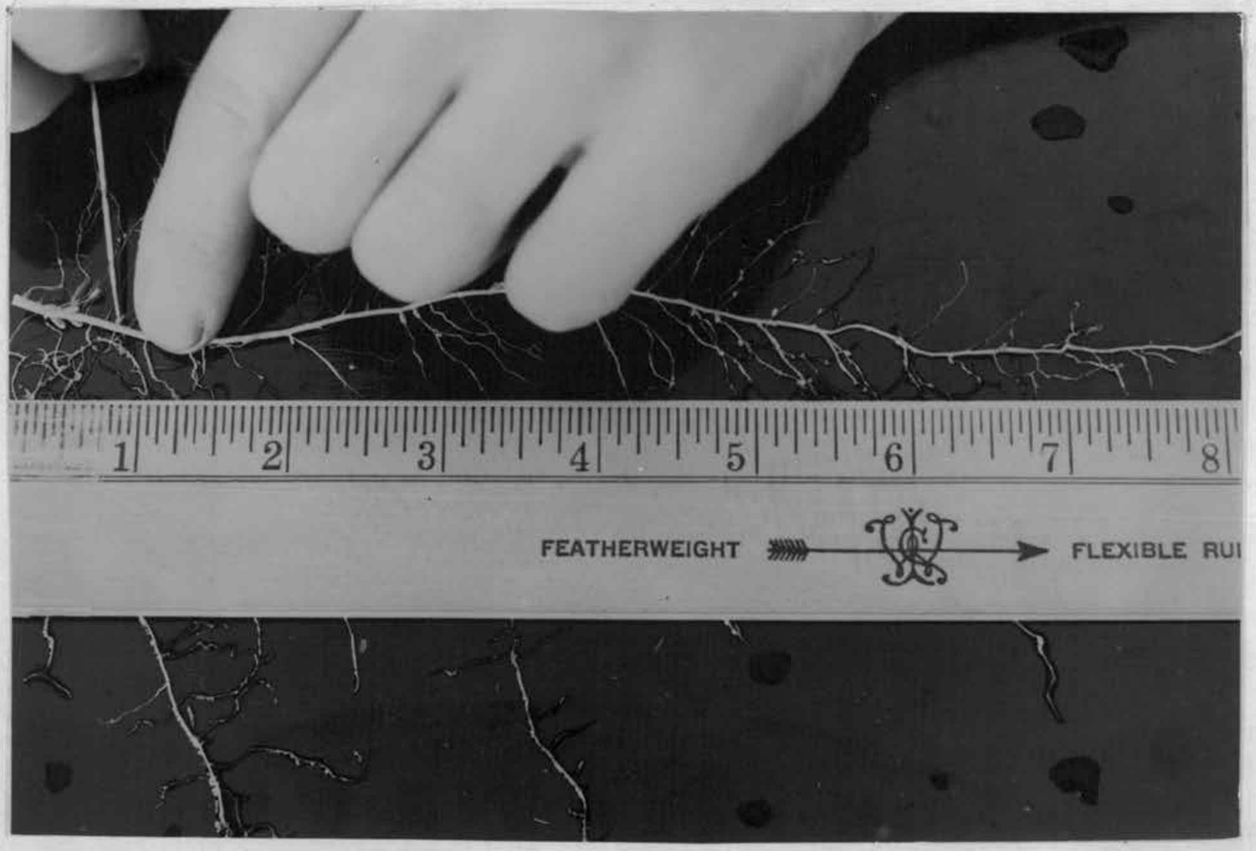
satisfactory as a means of preventing their drying out too rapidly.

This proved to be an excellent method for studying the root systems of legumes for the following reasons: (a) It lends an opportunity for the investigator to study and to observe the natural positions of the roots in the soil; to observe any physical characteristics of the soil profile, as pore space, clay pan, or hard pan which may in any way influence the growth of the rooting system, and to note the direct effects of plant competition. (b) The soil is not disturbed in such a manner as to cause excess root damage. (c) When carefully followed, it is very economical, easy to use, and saves considerable time in excavating entire root systems. (d) Rainfall during the winter months in Western Oregon greatly favors this method for root study, especially with legumes, because of their particular type of rooting habit. The moist soil washes away from the roots much more easily than the same soil in a drier condition and requires far less water to do the same amount of work.

A disadvantage of the method may be that the increased amount of water required during the drier parts of the season creates a problem of water supply unless plots are conveniently located near such a supply.

Plate III

The Roots Are Measured While in Position
on the Photographic Background



Methods Used in Making Soil Observations

A rather complete analysis was made of each soil type on which root observations were takne. This was considered necessary in order to standardize the information obtained from the root studies, and to serve as a basis for studying and analyzing root responses to soil type.

A complete review of the literature indicates that soil properties most likely to influence root growth are:

1. Structure--amount of capillary and non-capillary pore space. Presence of obstructing layers, i.e., tillage pan or hard pan.
2. Texture--relative amounts of sand, silt, clay and colloids.
3. Amount of available plant foods, i.e., nitrogen, phosphorous, and organic matter.
4. Acidity or pH of the soil.
5. Water relationships--usable water and height of water table.

Observations and tests made to determine these properties of each soil type were as follows:

1. Structure--a detailed observation was made of each soil horizon. Capillary and non-capillary pore space was determined by the steel rim method perfected by Stephenson (26). Profile characteristics such as

tillage pan, hard pan, and resistance to pulverization were taken by examining the wall of a pit dug especially for this purpose. This is considered the most practical way to study the soil profile.

2. Texture--a mechanical analysis was made at 6-inch intervals throughout the entire soil profile using the method developed by Bouyoucos (3). This information was considered to give clearer and more accurate pictures of the soil on which these legumes were grown.
3. Available plant food--organic matter content was determined by Walkley's (34) method; phosphorous by Truog's (31) method; and nitrate nitrogen was determined by the phenol disulphonic acid method.
4. Acidity--was determined by the colorimetric method.
5. Water relationships--during the period of this study there was sufficient usable water at all times. Moisture samples at one, two, and three feet were taken at every observation period. Since moisture was not considered a determining factor of root development in this particular study, it has not been included with the data.

A summary of observations and tests made of each soil type is given under, "EXPERIMENTAL RESULTS--Relating to Physical and Chemical Properties of the Soils on Which Root Observations Were Made".

CLIMATIC FACTORS DURING PERIOD OF STUDY

The development and responses of plant roots as well as the tops are influenced by climatic factors. The following data are considered significant and are necessarily a part of records on this study.

Table 2 includes the precipitation and temperature data during the period of study.

The soil was frozen to a depth of 3.50 inches at the 56-day observation period in December 1940. Austrian winter pea tops were the only plant parts which showed any winter injury. The root systems were not injured by the frost; however, the presence of the frozen layer of soil made it more difficult to excavate the roots by the washing method.

EXPERIMENTAL RESULTS

Experimental results on root development of the annual legumes observed will be presented in the form of photographs and accompanying tables. Photographs were used because they convey a much clearer picture of actual results than can be expressed by figures alone.

Results will be discussed by crops for each period of observation. All observation periods date from the time of seeding.

TABLE 2

* WEATHER DATA FOR CORVALLIS, OREGON
FROM
AUGUST 1940 TO APRIL 1941 INCLUSIVE

Month	Precipitation	Temperature					
1940	inches	Max.	Min.	Mean Max.	Mean Min.	Days Below 32° F	Greatest Daily Range
August	trace	100.0	48.0	84.2	54.1	0	45
September	2.75	88.0	41.0	75.4	53.9	0	35
October	4.14	83.0	34.0	66.8	49.6	0	27
November	4.46	61.0	26.0	51.7	37.1	4	24
December	4.71	63.0	20.0	50.4	37.7	5	24
1941							
January	4.38	57.0	28.0	49.4	37.2	6	20
February	1.65	63.0	31.0	56.5	37.6	2	29
March	1.22	77.0	30.0	65.1	40.6	1	37
April	1.27	64.0	40.0	60.0	43.9	0	21
TOTAL	29.74					20	

* Weather data obtained from E. F. Torgerson, Cooperative Observer, Oregon Agricultural Experiment Station.

Crimson Clover (Trifolium incarnatum)

28 days

Results on Plate IV show that the extent to which roots penetrated in Willamette clay, Chehalis clay loam, and Melbourne clay did not vary significantly. The depth of penetration was 5, 5, and 4.50 inches respectively. The tap roots predominated with few laterals extending one inch. Nodules appeared on the tap root in all three soil types. None were formed on the laterals.

56 days

At this age the tap root predominated in all three soil types. Plate V shows that finer second-order roots had formed on most of the upper laterals. Lateral roots were formed on half the total length of the tap root in all three soils.

Nodules appeared on the upper laterals at this age.

Plate V and data in Tables 3, 4, and 5, show that root penetration was greatest in Chehalis clay loam with very little difference between the length of the roots in Willamette clay and Melbourne clay. Roots penetrated 12, 8, and 8.50 inches respectively.

The influence of soil compaction on root growth is very significant at this age. A comparison of Tables 23, 24, and 25 shows that the Tillage pan in Willamette and Melbourne soils lies between 6 and 12 inches. In this same region, the taproots grew more slowly. In Chehalis soil the first foot of soil is very porous, thus favoring rapid root penetration.

84 days

At this age, inherent characteristics of the roots appear as well as the influence of soil type on root growth. Results as shown by Plate VI and Tables 3, 4, and 5 show that roots penetrated deepest in Chehalis clay loam and were shortest in Melbourne clay. In Willamette clay they were intermediate.

The tap roots were more twisted and distorted in the more compact regions of the soil.

Referring to Tables 23, 24, and 25 it will be noticed that of the three soils listed Chehalis clay loam is the most porous and most fertile. This undoubtedly accounts for the advanced root growth in this soil. Weaver (37) and Rodgers (22) also noted that roots tend to grow shorter in dense than in loose soils.

112 days

The tap root again grew most vigorously in Chehalis clay loam and grew least in Melbourne clay, as shown in Plate VII. Tables 3, 4, and 5 forther indicate that the lateral spread during this period was greatest in the Chehalis soil.

Laterals were formed on the upper half of the tap-root in all three soil types.

168 days

The data found on Plate IX, and in the accompanying tables, show the length of the tap root to be nearly the same in all three soils. However, it will be noticed that the degree of branching was least in Melbourne clay. Larger feeding laterals began to appear at 9 and 12 inches respectively on tap roots in Willamette and Chehalis soils. Examination of the data in Tables 23, 24, and 25, and Table 6, may aid in explaining the increased branching of roots grown in Willamette clay and Chehalis clay loam. The data show that there is more nitrate nitrogen and available phosphorous from 6 to 24 inches in the profile of these two soils than for the same region in Melbourne clay. Weaver (39) found that the presence of these elements induced more root growth in the soil where they were most abundant.

The formation of these larger laterals on the lower portions of the root may also be a successive stage in the root development of crimson clover. These roots extending in the lower portion of the subsoil will very likely possess the greatest absorbing power during the drier parts of the season when the upper laterals lose their soil moisture supply.

A larger diameter of roots was noted in Chehalis clay loam than those grown in other soil types. The greater fertility and less compact nature of this soil may be a possible explanation for this condition.

Nodules were largest at this date of observation. The increase in day temperatures as well as the age of the plants may explain this condition.

An average of root and top growth shown in Tables 3, 4, and 5, shows that the roots penetrated 22.50 inches while the tops grew only 3.80 inches in 168 days from the time of seeding. Despite this difference in growth, the tops weighed more at all periods.

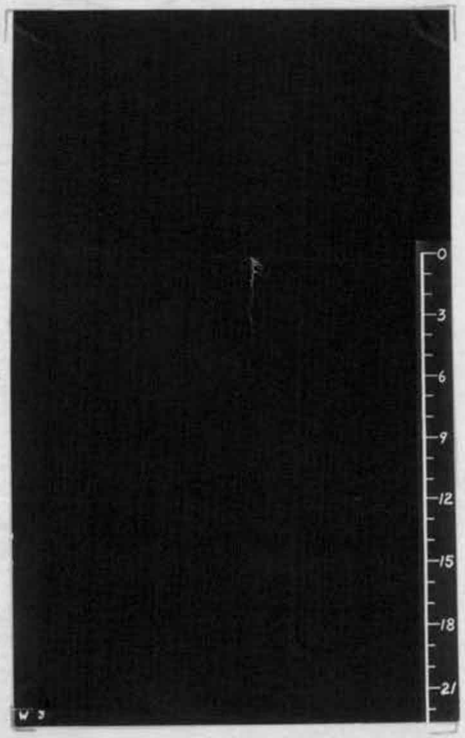
At 168 days the top-root ratio was 2.40 in Willamette clay, 2.93 in Chehalis clay loam, and 1.52 in Melbourne clay.

Plate IV

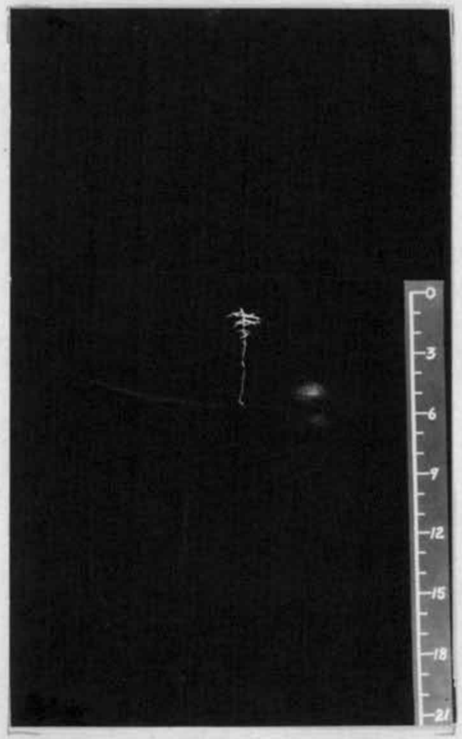
CRIMSON CLOVER

Root Development at 28 Days
on

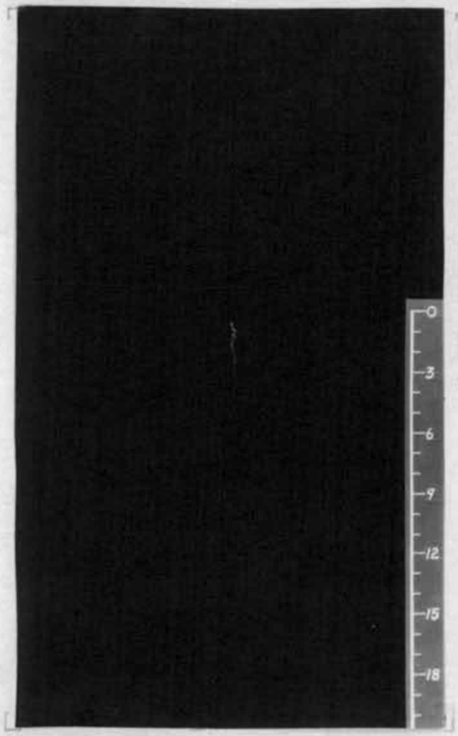
*Willamette



*Chehalis



*Melbourne



* Indicates soil type on which plants were grown

Plate V

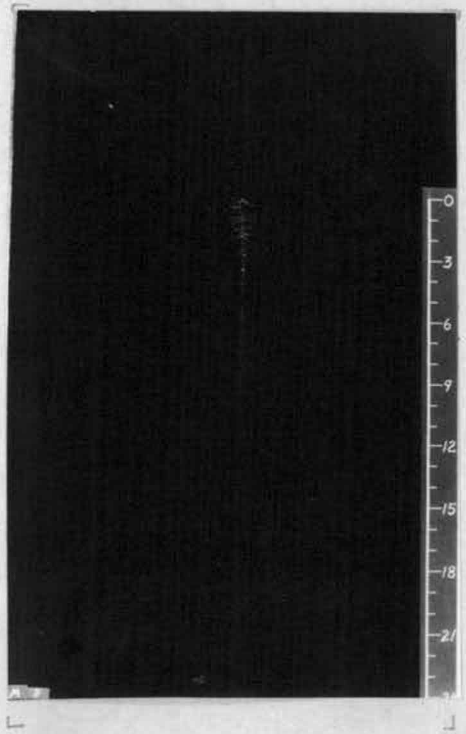
CRIMSON CLOVER

Root Development at 56 Days
on

*Willamette

*Chehalis

*Melbourne



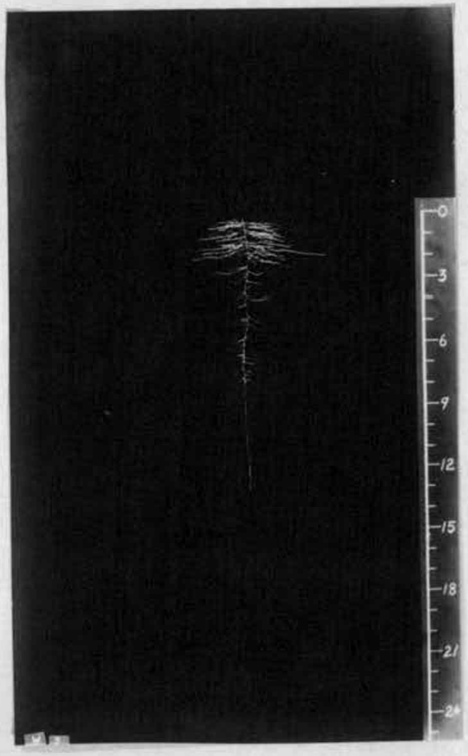
* Indicates soil type on which plants were grown

Plate VI

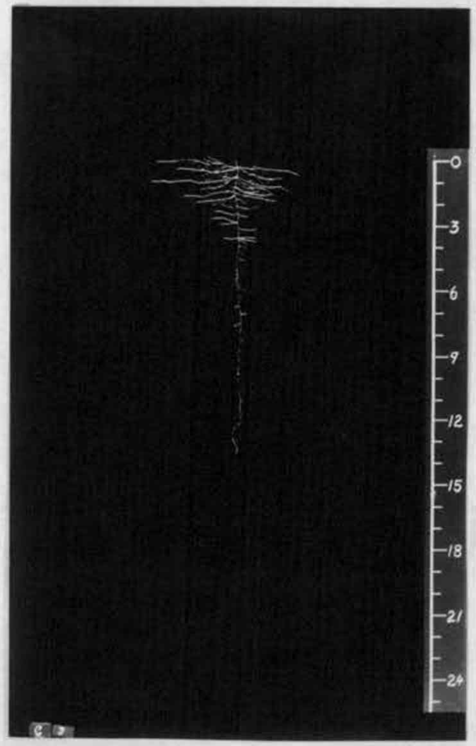
CRIMSON CLOVER

Root Development at 84 Days
on

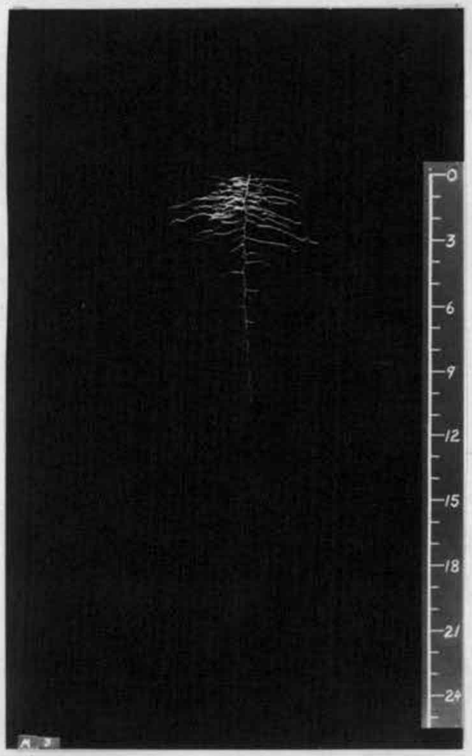
*Willamette



*Chehalis



*Melbourne



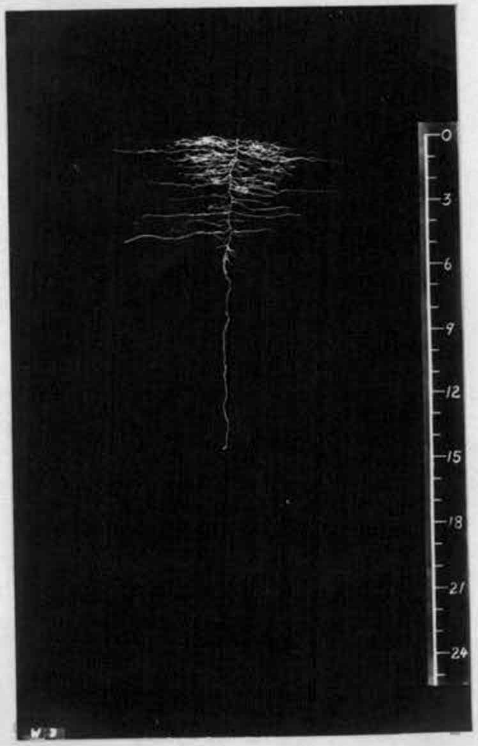
* Indicates soil type on which plants were grown

Plate VII

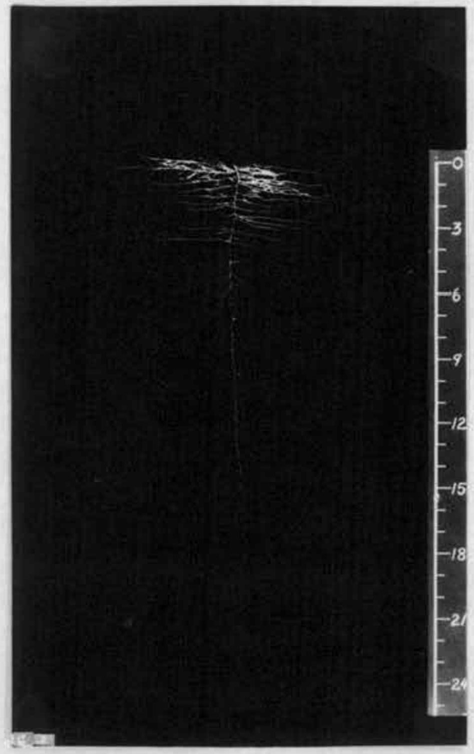
CRIMSON CLOVER

Root Development at 112 Days
on

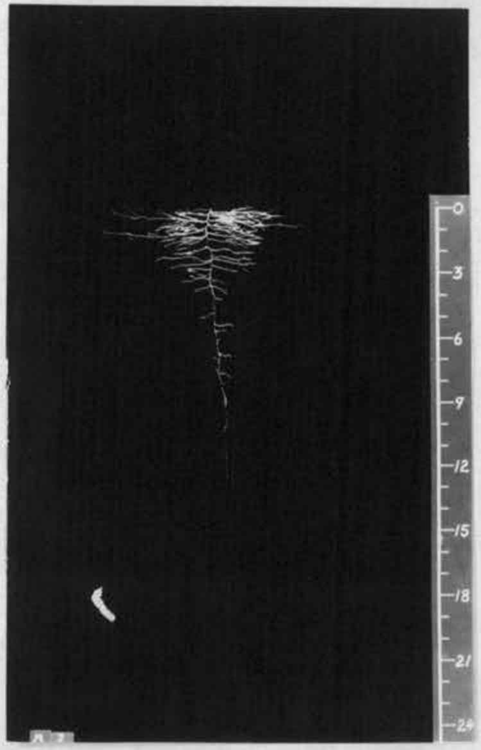
*Willamette



*Chehalis



*Melbourne



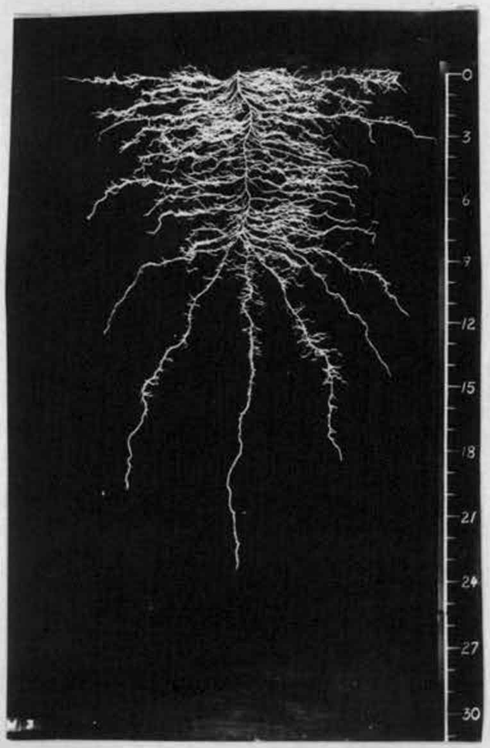
* Indicates soil type on which plants were grown

Plate VIII

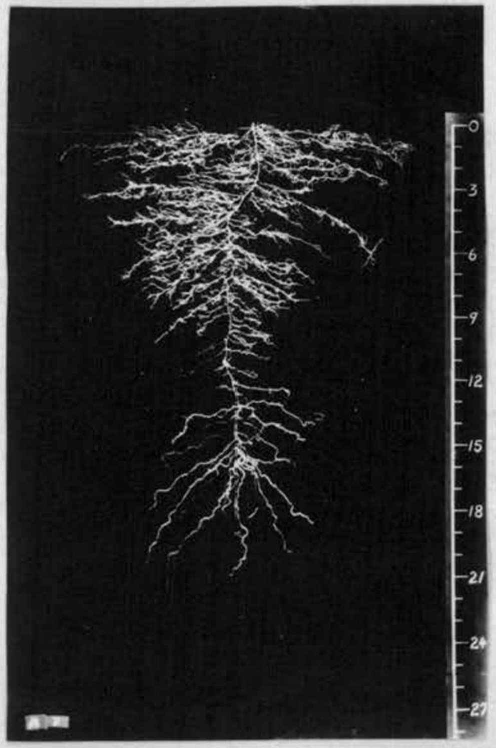
CRIMSON CLOVER

Root Development at 168 Days
on

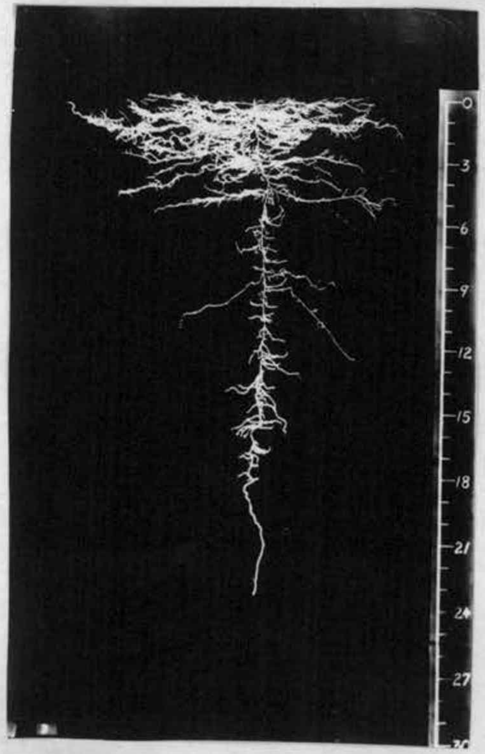
*Willamette



*Chehalis



*Melbourne



* Indicates soil type on which plants were grown

TABLE 3

CRIMSON CLOVER
ROOT DEVELOPMENT AND TOP GROWTH* IN
WILLAMETTE CLAY

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams **	.0022	.0042	.0168	.0300	.1500
Length of roots in inches	5.00	8.00	12.75	15.00	23.50
Weight of top in grams**	.0026	.0052	.0222	.0350	.3600
Length of top in inches	0.70	0.70	1.00	1.25	4.00
Lateral spread in inches	1.30	2.50	6.00	10.50	18.00
Zone of root concentration in inches from surface	0-1.00	0-3.00	0-3.50	0-4.00	0-8.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 4

CRIMSON CLOVER
ROOT DEVELOPMENT AND TOP GROWTH * IN
CHEHALIS CLAY LOAM

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams **	.0032	.0092	.0118	.0240	.2015
Length of roots in inches	5.00	12.00	14.00	15.00	20.00
Weight of top in grams **	.0054	.0152	.0150	.0438	.5900
Length of top in inches	0.75	0.75	1.00	1.50	4.50
Lateral spread in inches	1.00	3.00	8.50	11.00	18.00
Zone of root concentration in inches from surface	0-.50	0-2.50	0-3.00	0-4.00	0-8.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 5

CRIMSON CLOVER
ROOT DEVELOPMENT AND TOP GROWTH * IN
MELBOURNE CLAY

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams **	.0030	.0068	.0146	.0238	.1320
Length of roots in inches	4.50	8.50	10.50	12.00	23.00
Weight of top in grams **	.0102	.0072	.0220	.0280	.2000
Length of top in inches	0.50	0.50	0.75	1.00	3.00
Lateral spread in inches	1.00	3.50	8.00	10.00	17.00
Zone of root concentration in inches from surface	0-.50	0-1.00	0-3.00	0-4.00	0-5.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 6

NUMBER OF LATERAL ROOTS PER THREE-INCH SECTION OF TAPROOT AT DIFFERENT DEPTHS AND AT SUCCESSIVE STAGES OF CRIMSON CLOVER

Soil type	Willamette clay					Chehalis clay loam					Melbourne clay				
Age of plant (days)	28	56	84	112	168	28	56	84	112	168	28	56	84	112	168
Depth of Section (inches)	Number of laterals per section														
0- 3	75	31	30	30	34	25	27	24	29	30	24	28	30	32	33
3- 6		18	17	20	19		19	17	21	24		14	15	17	21
6- 9			14	15	18			9	11	15		8	9	14	15
9-12				8	12				10	12					9
12-15					11					12					12
15-18					9					15					6
18-21					10					9					4
21-24					9										
24-27															

Subterranean clover (Trifolium subterraneum)

<u>28 days</u>

At this state the taproot predominated in each soil type, with some laterals extending on inch from the taproot. This is shown in Plate IX. No second order roots appeared. Greatest length and weight of roots occurred in the Melbourne clay. The crops were planted a week earlier in Melbourne clay than in the other two soils. The period following the previous planting was more favorable for a quick germination, and could,therefore, be a possible explanation for the advanced growth in the Melbourne soil.

Nodules had formed on the upper 4 inches of the primary root.

<u>56 days</u>

In comparing roots on Plate IX and Plate X it will be noted that at the 56 day period all roots had nearly doubled their length at 28 days. Those grown in Chehalis soil were slightly longer than those grown in Willamette and Melbourne soils. The depth of penetration was 12, 10.50, and 10 inches respectively. However, the weight of roots in Melbourne clay continued to be greatest.

Over one-half the upper portion of the taproot bore laterals. They were longest in the upper two inches of soil, and they were just beginning to form second-order roots.

No nodules appeared except on the taproot.

84 days

Results shown on Plate XI and in Tables 7, 8, and 9 indicate that roots grew longest and possessed one inch more lateral spread in Willamette clay than in Chehalis clay loam or Melbourne clay. The depth of penetration was 15, 12.75, and 10.75 inches respectively. Laterals grew 9, 8, and 8 inches respectively.

The greatest root concentration was found in the upper 4 inches of soil.

Nodules appeared on the laterals at this age.

112 days

The influence of soil type on root growth and the inherent root characteristics appear at this period of observation. Plate XII and Tables 7, 8, and 9 show root penetration and lateral growth to be greatest in Chehalis clay loam,intermediate in Willamette clay, and least in Melbourne clay. In observing the roots of Willamette and Melbourne soils on Plate XII, distortion of the taproots below 6 inches suggests the influence of a compact tillage pan in the soil horizon from 6 to 12 inches. Below the nine-inch level, more irregularity is noticed. This is corroborated by the less amount of non-capillary pore space present in this region, as shown by the pore space date in Tables 23, 24, and 25.

<u>168 days</u>

The results at this stage are similar to those shown for the 112-day period, except for the additional growth. Plate XIII shows the roots grown in Chehalis clay loam to be most developed in total weight, length, and in lateral spread. It was also found that the diameter of the roots were larger in the regions where non-capillary pore space was greatest. This was especially true of roots grown in Willamette clay which, as shown in Table 10, has most abrupt changes of structure in the upper portions of the profile from 6 to 24 inches.

In comparing the data on the three soil types in Tables 23, 24, and 25, with that found in Table 10, the region of the soil profile which contains the least amount of non-capillary pore space also shows the least lateral growth and number of lateral roots per three-inch section of taproot in all three soil types. The development of more profuse root growth above and below these zones of soil, and the amount of organic residue and difference in nitrate nitrogen, may have an influence on root development in relation to actual pore space.

Laterals extended down at least three-fourths the length of the taproot in all three soil types. Third order roots had formed at this age.

Nodules appeared at a maximum depth of 32 inches in Melbourne clay, 21 inches in Chehalis clay loam, and 18 inches in Willamette clay. This shows that all soils were fairly well aerated. The reasons for the difference in depth of nodulation is not accounted for in this study.

Tops grew an average of 3.50 inches and the roots averaged 31.80 inches in length after 168 days of growth.

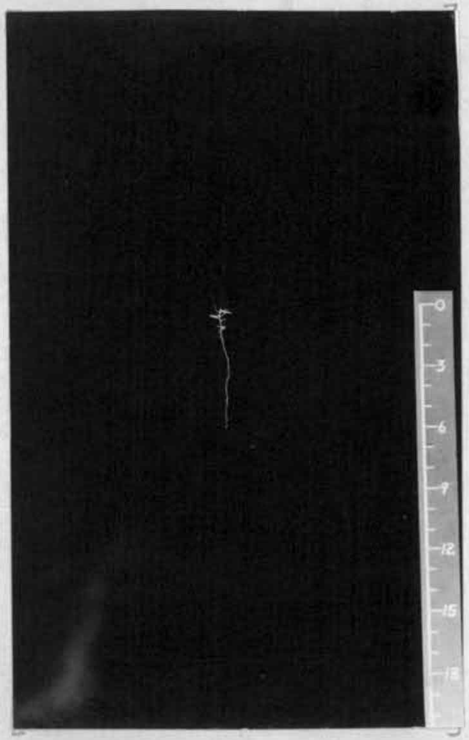
The weight of the tops was consistently greater than that of the roots in all three soil types. The top-root ratio was 3.94, 3.37, and 1.43 respectively in Willamette, Chehalis, and Melbourne soils.

Plate IX

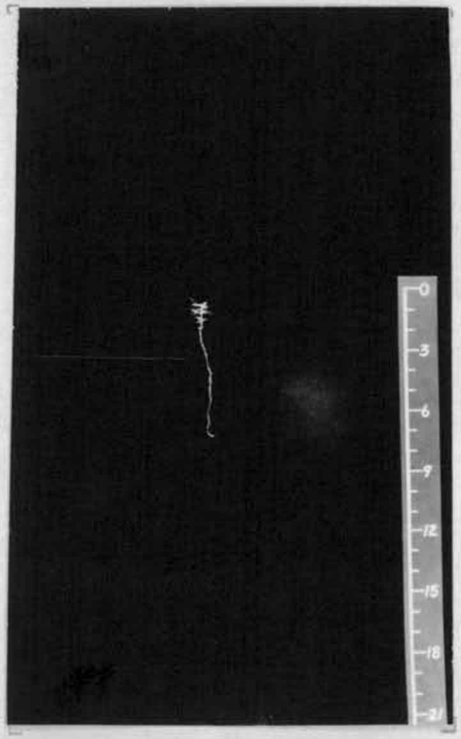
SUBTERRANEAN CLOVER

Root Development at 28 Days
on

*Willamette



*Chehalis



*Melbourne

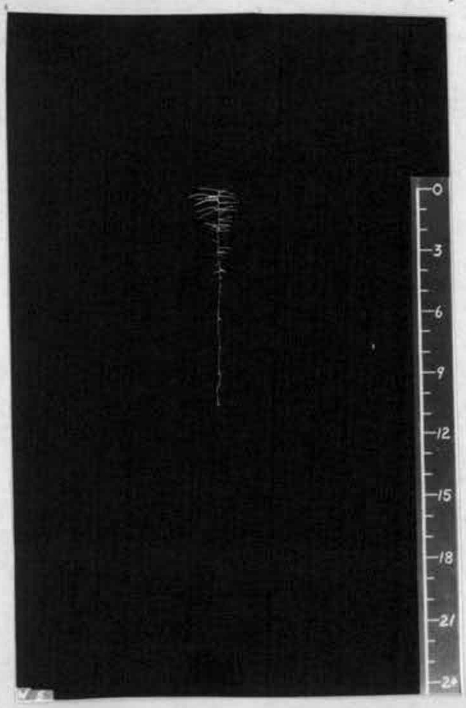
* Indicates soil type on which plants were grown

Plate X

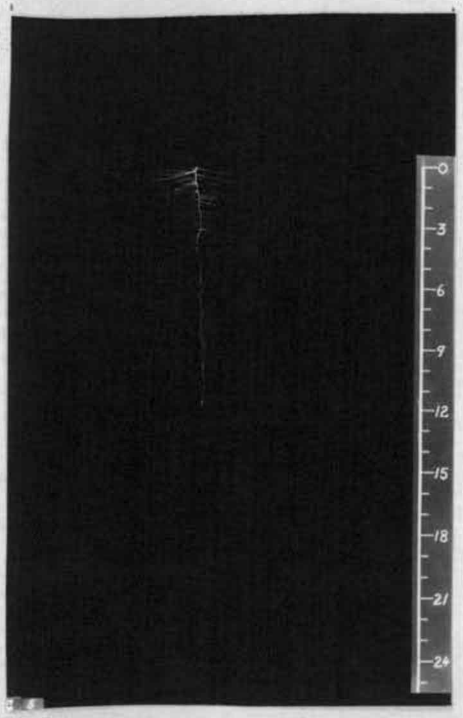
SUBTERRANEAN CLOVER

Root Development at 56 Days
on

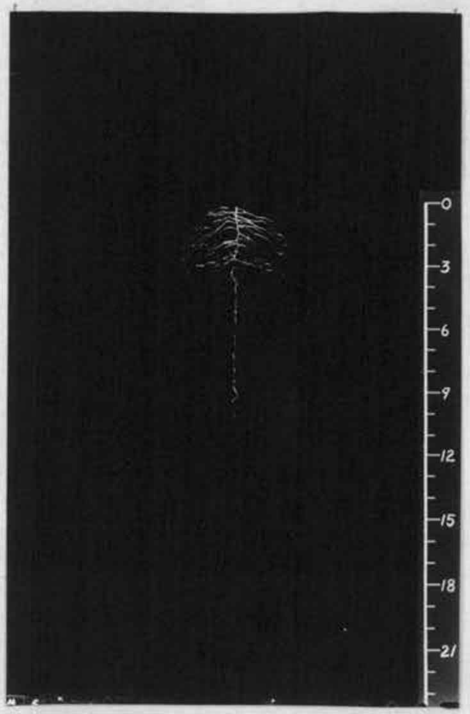
*Willamette



*Chehalis



*Melbourne



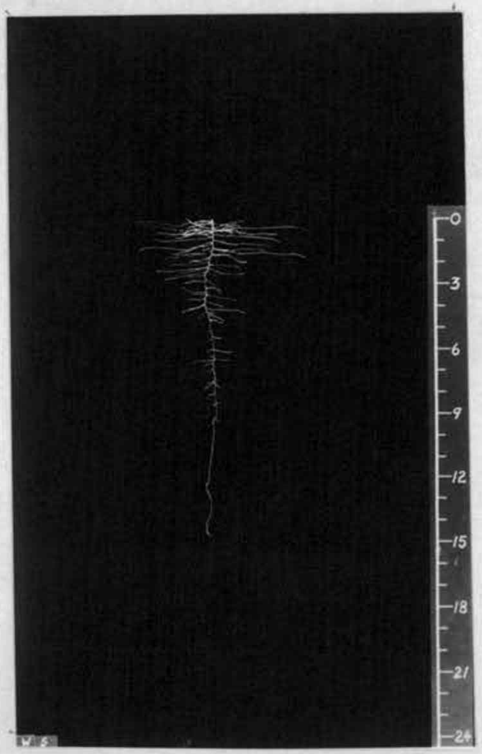
* Indicates soil type on which plants were grown

Plate XI

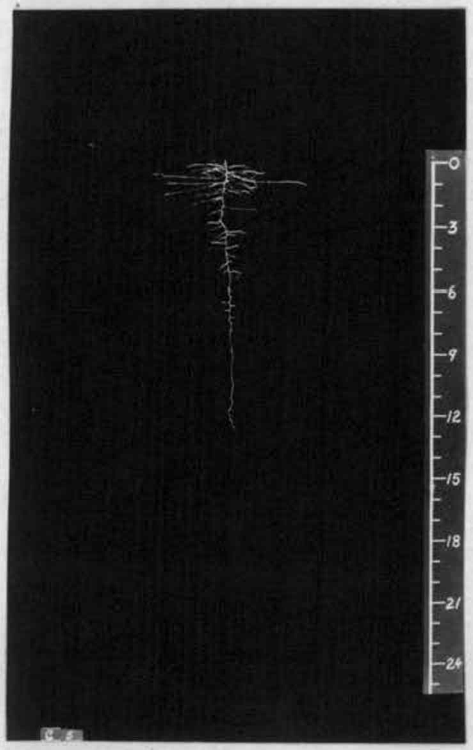
SUBTERRANEAN CLOVER

Root Development at 84 Days
on

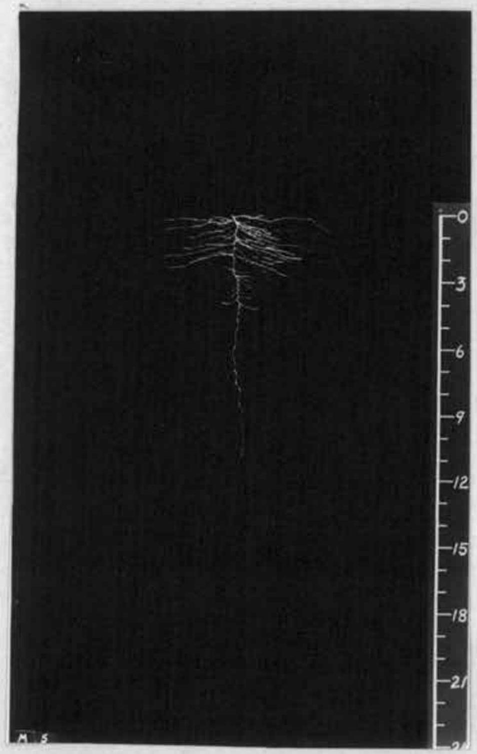
*Willamette



*Chehalis



*Melbourne



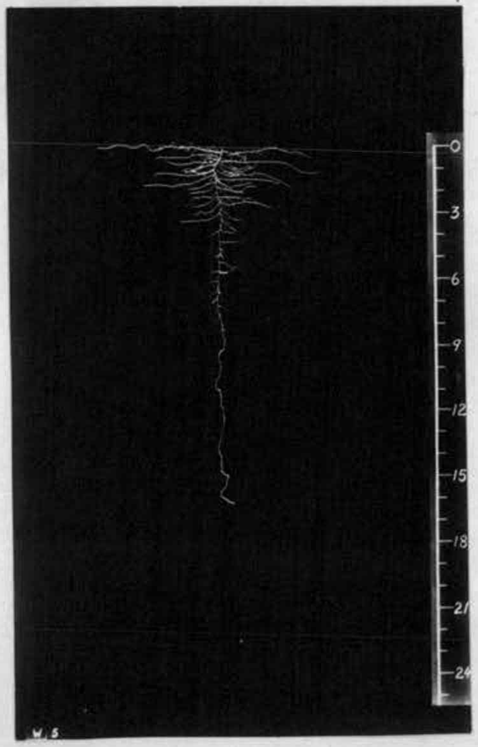
* Indicates soil type on which plants were grown

Plate XII

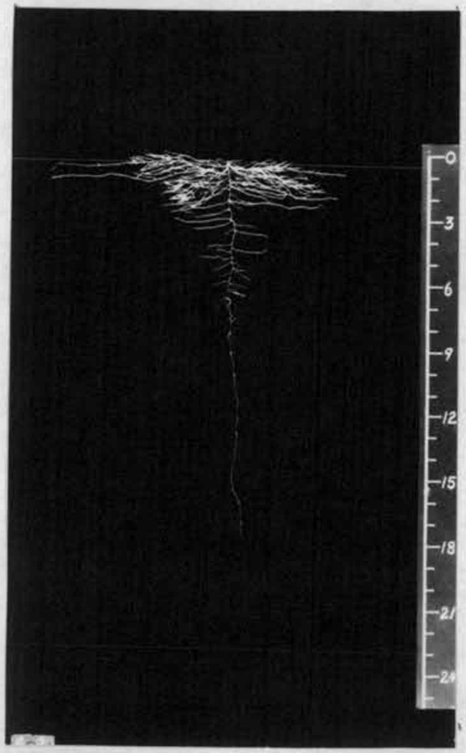
SUBTERRANEAN CLOVER

Root Development at 112 Days
on

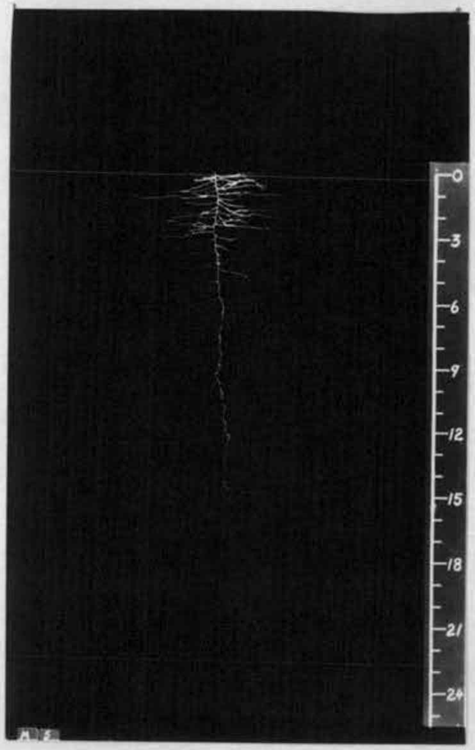
*Willamette



*Chehalis



*Melbourne



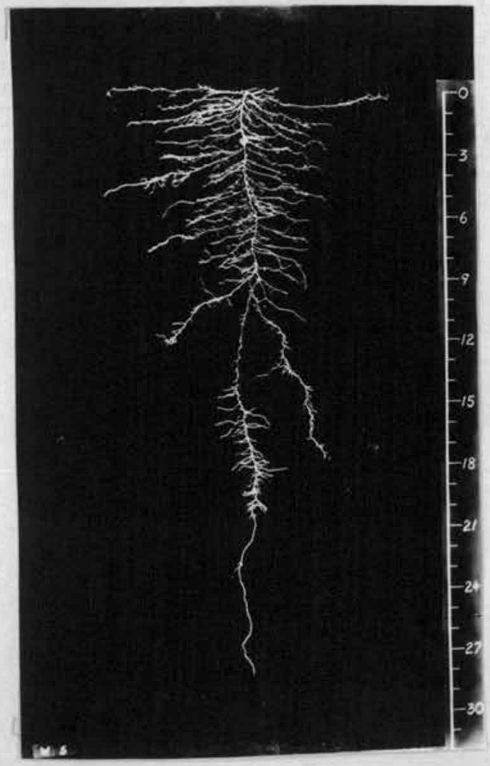
* Indicates soil type on which plants were grown

Plate XIII

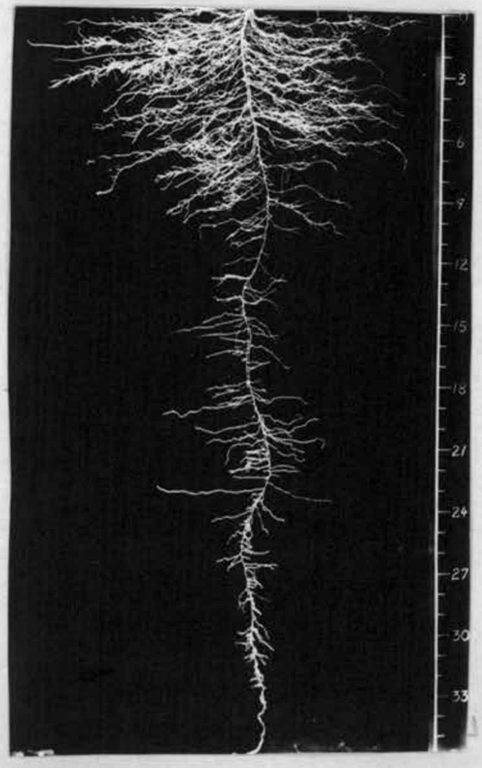
SUBTERRANEAN CLOVER

Root Development at 168 Days
on

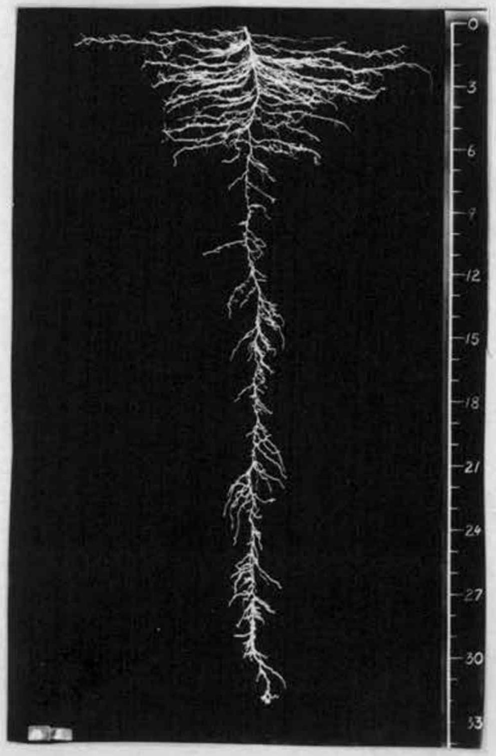
*Willamette



*Chehalis



*Melbourne



* Indicates soil type on which plants were grown

TABLE 7

SUBTERRANEAN CLOVER
ROOT DEVELOPMENT AND TOP GROWTH * IN
WILLAMETTE CLAY

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of root in grams **	.0042	.0140	.0286	.0285	.1046
Length of root in inches	5.75	10.50	15.00	17.00	28.00
Weight of top in grams **	.0070	.0150	.0356	.0448	.4120
Length of top in inches	1.00	1.00	1.25	1.50	3.00
Lateral spread in inches	0.70	3.00	9.00	12.00	18.00
Zone of root concentration in inches from surface	0-1.50	0-2.00	0-3.00	0-4.00	0-9.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 8

SUBTERRANEAN CLOVER
ROOT DEVELOPMENT AND TOP GROWTH * IN
CHEHALIS CLAY LOAM

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams **	.0038	.0120	.0198	.0440	.3201
Length of roots in inches	6.50	12.00	12.75	17.50	35.50
Weight of top in grams **	.0074	.0296	.0234	.0620	1.080
Length of top in inches	.75	.75	1.00	1.50	3.50
Lateral spread in inches	1.00	4.00	8.00	16.00	22.00
Zone of root concentration in inches from surface	0-1.50	0-2.00	0-3.00	0-3.50	0-9.00

TABLE 9
SUBTERRANEAN CLOVER
ROOT DEVELOPMENT AND TOP GROWTH * IN
MELBOURNE CLAY

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams **	.0078	.0174	.0228	.0364	.2220
Length of roots in inches	6.75	10.00	10.75	14.75	32.00
Weight of top in grams **	.0128	.0268	.0278	.0374	.3184
Length of top in inches	1.25	1.25	1.50	1.75	4.00
Lateral spread in inches	0.60	6.00	8.00	9.50	18.00
Zone of root concentration in inches from surface	0-1.50	0-3.50	0-4.00	0-5.00	0-6.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 10

NUMBER OF LATERAL ROOTS PER THREE-INCH SECTION OF TAPROOT AT DIFFERENT DEPTHS AND AT SUCCESSIVE STAGES OF SUBTERRANEAN CLOVER

Soil type	Willamette clay					Chehalis clay loam					Melbourne clay				
Age of plant (days)	28	56	84	112	168	28	56	84	112	168	28	56	84	112	168
Depth of section (inches)	Number of laterals per section														
0- 3	24	26	30	34	38	26	27	27	30	38	30	34	33	33	39
3- 6		15	20	18	20	10	14	15	15	26		14	16	15	18
6- 9			15	15	24			13	12	21			12	9	13
9-12					12					15				8	14
12-15					10					15					16
15-18					14					18					16
18-21					18					20					20
21-24					15					21					14
24-27										14					18
27-30										12					10
30-33										10					

Austrian winter pea (Pisum arvense L)

28 days

The length and weight of roots at this period of observation were greater in Willamette clay and nearly the same in Chehalis clay loam and Melbourne clay. The lengths were 10, 7.50, and 7.50 inches respectively. Lateral spread as indicated by Tables 11, 12, and 13, was greatest in the two soils producing the shortest roots. No explanation is offered for this condition.

Cotyledons remained attached and nodules appeared on the tap root.

56 days

Plate XV and Tables 11, 12, and 13 show the roots to be longest in Melbourne clay, more branching in Chehalis clay loam, and shortest in Willamette clay. Laterals extended down farthest on roots grown in Willamette soil as well as being most uniform in length. The fact that the roots were better established in Melbourne and Chehalis soil at 28 days may explain their advanced growth in lateral spread at this age. The roots in Melbourne clay were more distorted, again showing the influence of soil structure on root growth.

Second order roots were formed at this age, and nodules appeared on the laterals.

84 days

At this age, the influence of soil type on root growth was rather noticeable. Plate XVI and accompanying Tables 11, 12, and 13 show that the roots grew from 14.75 to 21 inches in Willamette clay; in Chehalis clay loam the growth was from 16.25 to 24.50 inches, and in Melbourne clay the tap root grew from 18.75 to 19 inches.

The advanced growth of the taproots in Willamette and Chehalis soils from 14.75 to 21 inches and from 16.25 to 24.50 inches may be due to the less compact condition of the soil in these regions as shown in Tables 23 and 24. Table 25 shows that Melbourne clay has ample non-capillary pore space in the region from 18 to 24 inches, but that the clay and colloid content is highest in this region. Soil texture accompanied by the low fertility of the soil undoubtedly caused root penetration to be the least marked in Melbourne clay.

In areas where the roots had encountered less non-capillary pore space, they had a smaller diameter and showed considerable contortion.

112 days

Austrian winter pea roots shown on Plate XVII grew longest in depth and lateral spread, and there were more roots in the upper 9 inches of soil in Chehalis clay loam than either of the other soil types. The second order roots were also most developed in Chehalis clay loam. The tap roots bore laterals over three-fourths their total length in Willamette and Chehalis soils. Laterals were least developed in Melbourne clay, which may again suggest that the comparative amount of plant nutrients shown in Table 25 may be the limiting factor for lateral growth.

Second order roots were formed at this age.

Nodules were largest on the upper roots, and the cotyledons had disintegrated.

168 days

After 168 days of growth, the roots showed most marked development in Chehalis clay loam. A remarkable depth of 55 inches was reached in comparison with 37 and 38 inches on Willamette clay and Melbourne clay respectively. These data are shown in Plate XIV and Tables 11, 12, and 13.

Plate XIV also shows the large feeder roots beginning in the two-foot region and extending downward through the lower regions of the soil. These roots were larger than the laterals and will function as feeders for the system after the upper portions of the soil have dried out.

Tables 11, 12, and 13 show that the top growth averaged nine inches and the root penetration averaged 43.30 inches for all three soil types. The influence of soil compaction on the number of lateral roots per three-inch section is clearly shown in Table 14. The regions between 6 to 9 inches and 9 to 12 inches in Willamette clay and Melbourne clay have the least number of laterals. In Chehalis soil the least number of laterals is found from 9 to 15 inches. These regions are identical to zones of lowest non-capillary pore space shown in Tables 23, 24, and 25.

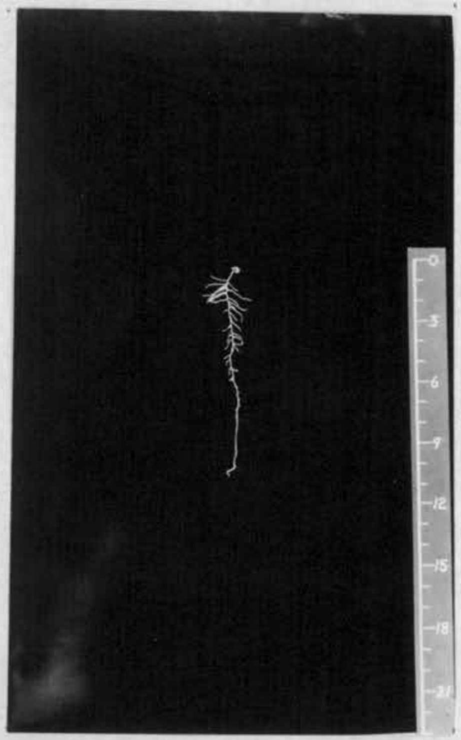
The weight of the roots and tops, as shown in Tables 11, 12, and 13 were also most in the Chehalis soil. The top root ratio was 1.90 in Willamette clay, 3.07 in Chehalis clay loam, and 2.93 in Melbourne clay.

Plate XIV

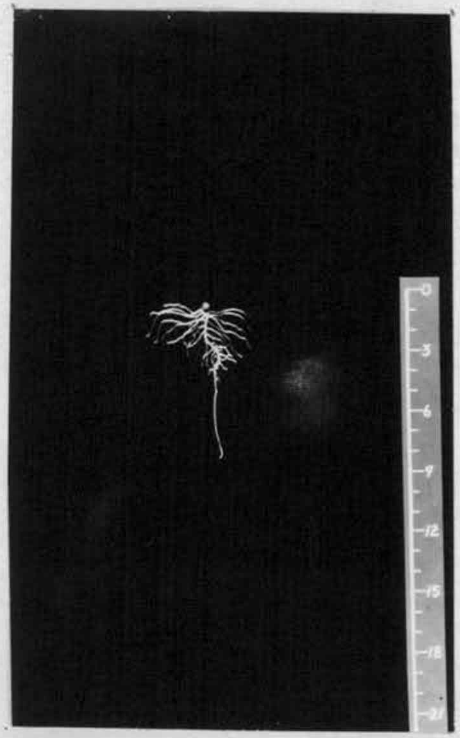
AUSTRIAN WINTER PEA

Root Development at 28 Days
on

*Willamette



*Chehalis



*Melbourne

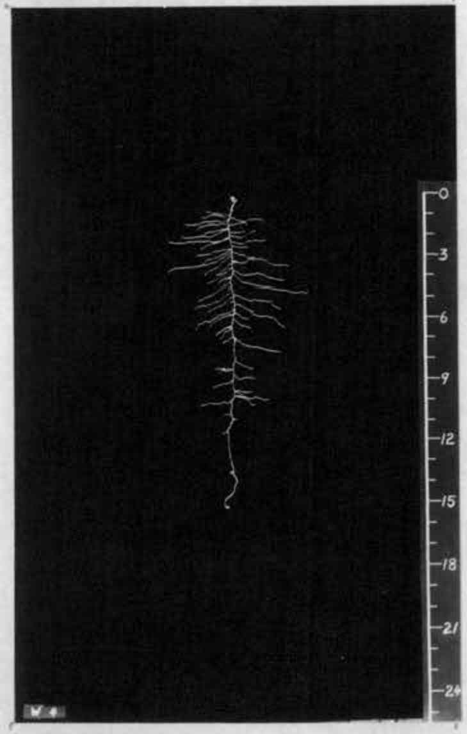
* Indicates soil type on which plants were grown

Plate XV

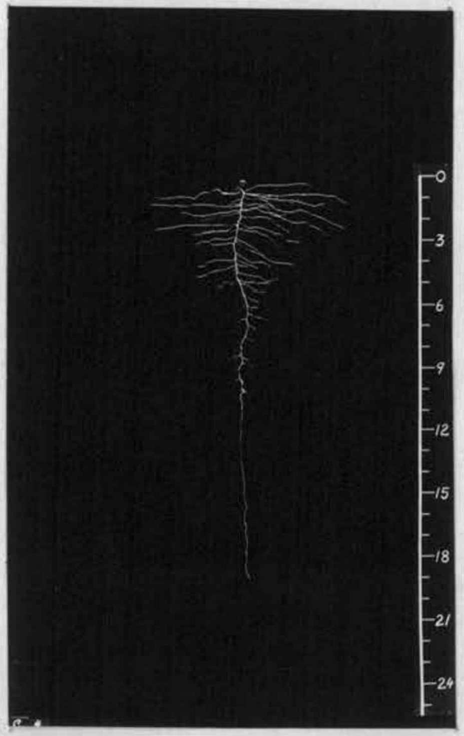
AUSTRIAN WINTER PEA

Root Development at 56 Days
on

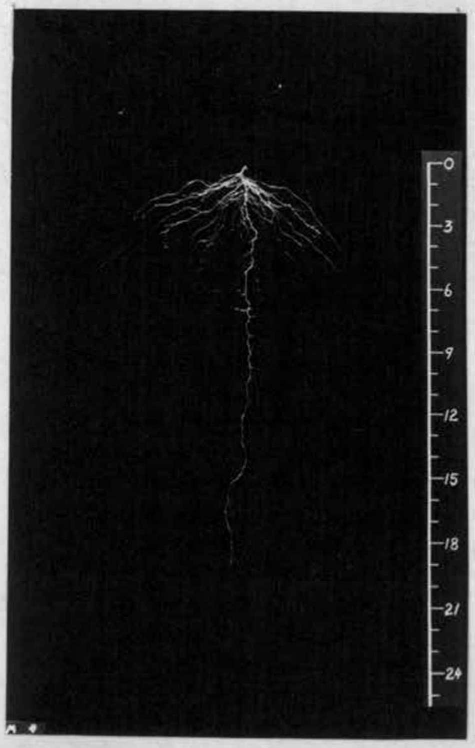
*Willamette



*Chehalis



*Melbourne



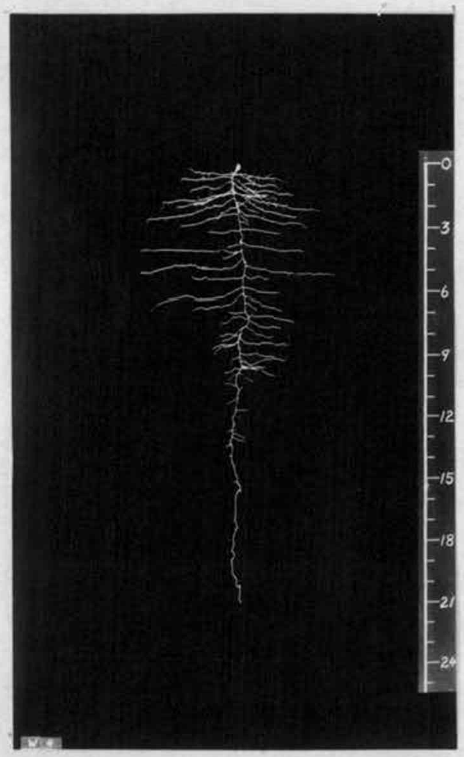
* Indicates soil type on which plants were grown

Plate XVI

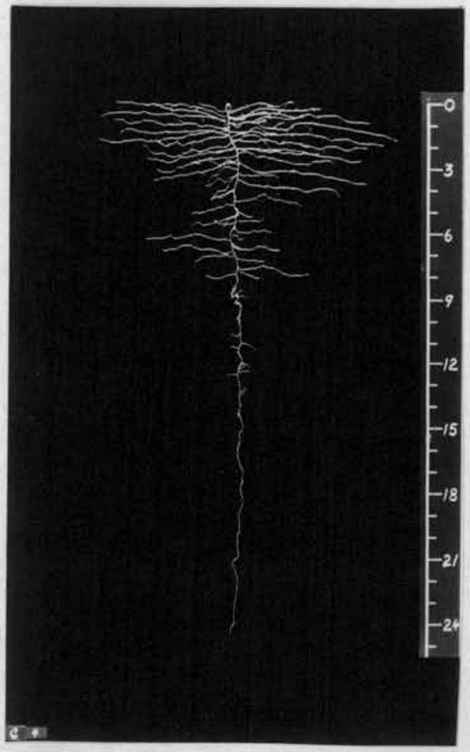
AUSTRIAN WINTER PEA

Root Development at 84 Days
on

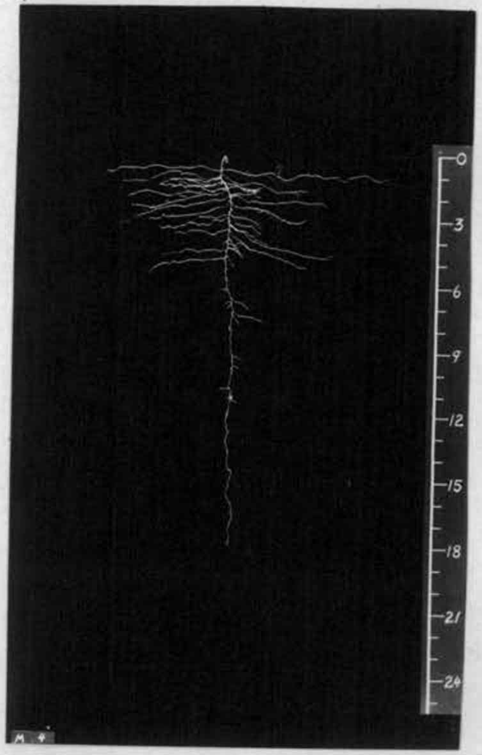
*Willamette



*Chehalis



*Melbourne



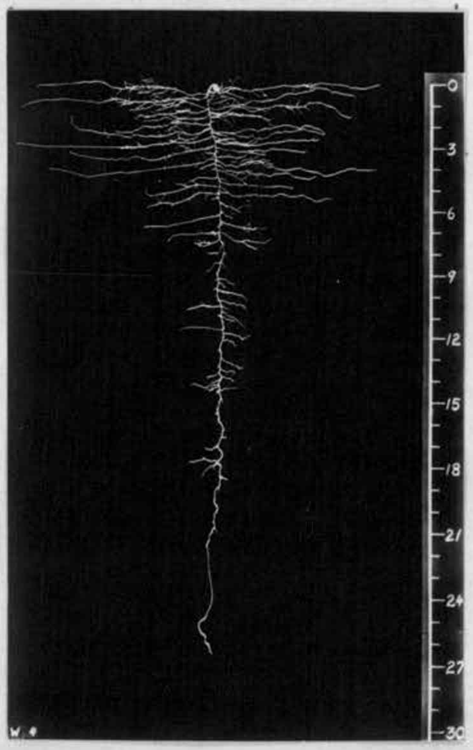
* Indicates soil type on which plants were grown

Plate XVII

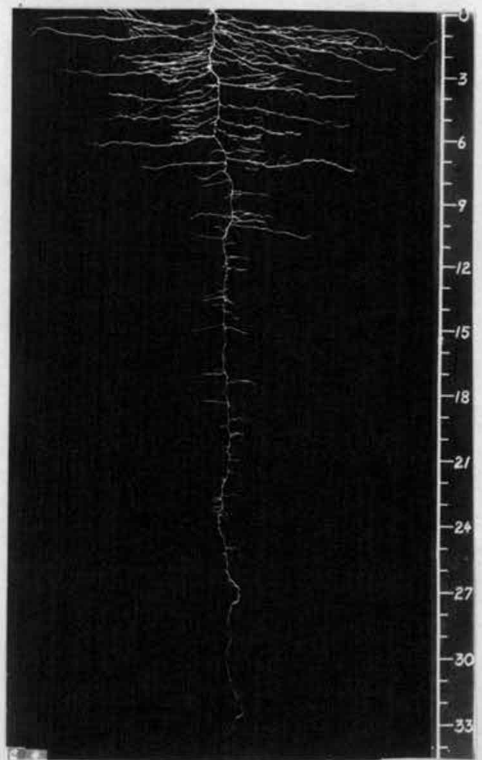
AUSTRIAN WINTER PEA

Root Development at 112 Days
on

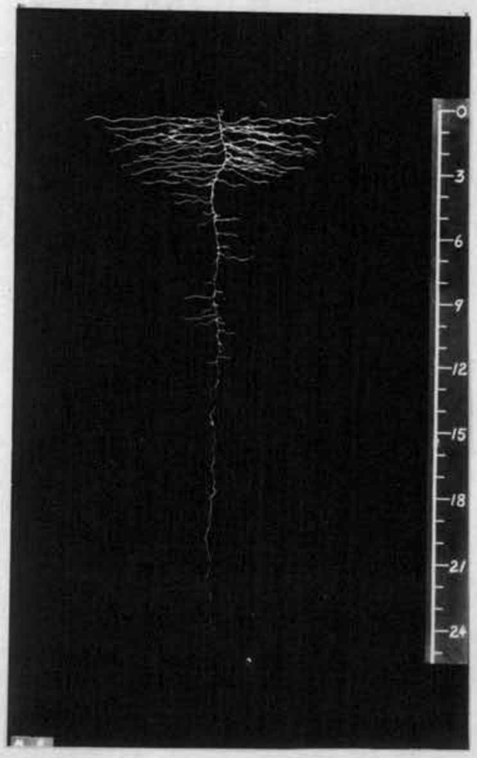
*Willamette



*Chehalis



*Melbourne



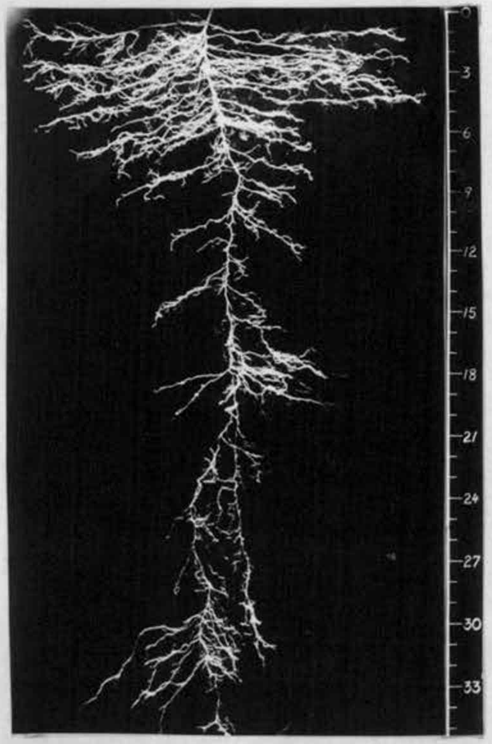
* Indicates soil type on which plants were grown

Plate XVIII

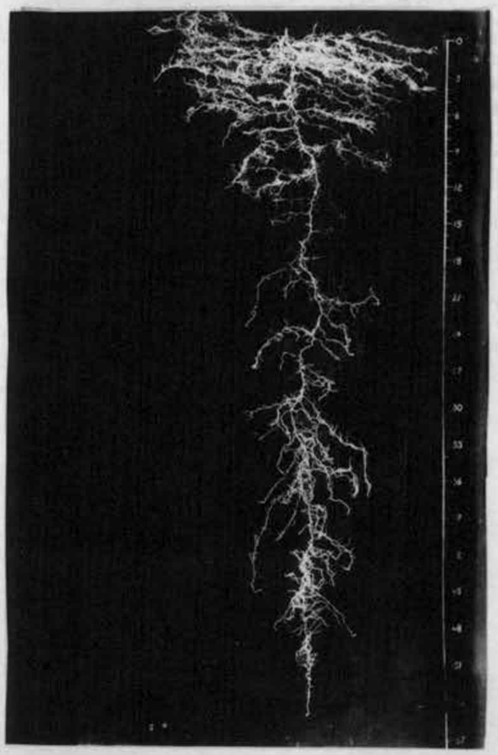
AUSTRIAN WINTER PEA

Root Development at 168 Days
on

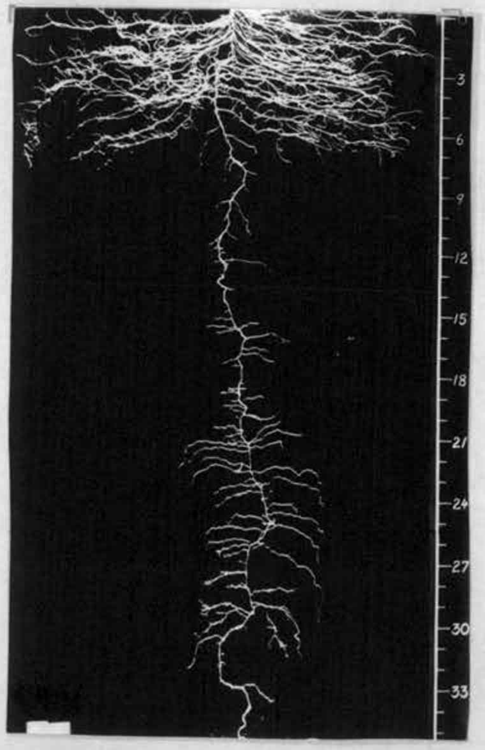
*Willamette



*Chehalis



*Melbourne



* Indicates soil type on which plants were grown

TABLE 11

AUSTRIAN WINTER PEA
ROOT DEVELOPMENT AND TOP GROWTH * IN
WILLAMETTE CLAY

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams **	.0572	.0712	.0966	.1206	.4105
Length of roots in inches	10.00	14.76	21.00	26.75	37.00
Weight of top in grams **	.0338	.0836	.0888	.1900	.7806
Length of top in inches	1.80	2.25	2.25	2.50	8.00
Lateral spread in inches	2.00	8.00	9.50	18.00	28.00
Zone of root concentration in inches from surface	0-3.00	0-7.50	0-10.00	0-12.00	0-10.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 12

AUSTRIAN WINTER PEA
ROOT DEVELOPMENT AND TOP GROWTH * IN
CHEHALIS CLAY LOAM

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams **	.0538	.0768	.1196	.1330	.5100
Length of roots in inches	7.50	16.25	24.50	35.00	55.00
Weight of top in grams **	.0386	.0744	.0956	.1334	1.570
Length of top in inches	1.50	2.00	2.00	2.50	9.00
Lateral spread in inches	4.25	10.50	16.00	21.00	30.00
Zone of root concentration in inches from surface	0-3.00	0-4.00	0-6.00	0-8.00	0-12.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 13

AUSTRIAN WINTER PEA
ROOT DEVELOPMENT AND TOP GROWTH * IN
MELBOURNE CLAY

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams **	.0590	.0696	.0728	.0926	.2200
Length of roots in inches	7.50	18.75	19.00	24.00	38.00
Weight of top in grams**	.0436	.0766	.0578	.0626	.6209
Length of top in inches	2.00	2.00	1.50	1.50	7.00
Lateral spread in inches	4.00	9.00	16.00	18.00	26.00
Zone of root concentration in inches from surface	0-3.00	0-4.00	0-4.00	0-5.00	0-8.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 14
NUMBER OF LATERAL ROOTS PER THREE-INCH SECTION OF TAPROOT AT DIFFERENT DEPTHS AND AT SUCCESSIVE STAGES OF AUSTRIAN WINTER PEA

Soil type	Willamette clay					Chehalis clay loam					Melbourne clay				
Age of plant (days)	28	56	84	112	168	28	56	84	112	168	28	56	84	112	168
Depth of section (inches)	Number of laterals per section														
0- 3	21	24	27	30	33	30	29	31	30	30	30	30	30	30	34
3- 6	12	14	15	15	24		12	15	18	21		15	18	18	28
6- 9	6	9	12	15	14		9	15	15	21		9	16	16	18
9-12		4	8	13	10		4	12	15	21			8	9	12
12-15			4	9	15			10	12	18				9	10
15-18				9	20				15	15					16
18-21				9	24				18	18					15
21-24					27				15	18					9
24-27					18				9	12					12
27-30					21					6					15
30-33					15					8					14
33-36					16					8					10
36-39					12					8					
39-42					9					9					
42-45					12					9					
45-48					9					5					
below 48					8					4					

Hairy vetch (Vicia villosa)

28 days

Plate IX and Tables 15, 16, and 17 show that the roots in Melbourne clay grew slightly longer and exhibited more weight and lateral growth than roots in Willamette or Chehalis soils. The possible explanation for this advanced growth is that the crops were seeded one week earlier in the fall on the Melbourne clay. During this period conditions were especially favorable for germination and crop growth. The period following the seeding of this crop on Willamette clay and Chehalis clay loam was somewhat cooler; thereby, delaying the germination to some extent.

Cotyledons remained attached.

56 days

A comparison of Plate XX with Tables 15, 16, and 17 shows root penetration, weight, and spread to be most extensive in Melbourne clay. The tap root penetrated 19 inches in Melbourne as compared to 10.50 and 12.25 in Willamette clay and Chehalis clay loam respectively.

The earlier establishment of the roots in Melbourne soil may be the reason for greater growth at this age of observation.

Second order roots were just beginning to form on the upper laterals. Nodules were present on the upper laterals in all soil types.

84 days

In Plate XXI and Tables 15, 16, and 17 data show that from 56 to 84 days the root system continued to be larger but had penetrated only one-fourth of an inch further in Melbourne clay. However, the lateral growth had increased 10 inches. Similarly, roots in Willamette clay and Chehalis clay loam increased 3.50 and 4.50 inches in lateral spread and grew downward 2.75 and 5.50 inches respectively. Effects of the early establishment in the Melbourne soil may be responsible for the size and growth of the rooting system at 84 days.

112 days

Data presented on Plate XXII and in Tables 15, 16, and 17 show rather clearly the influence of soil type on root growth at this age.

Roots in Willamette clay penetrated from 13.25 to 21.50 inches, from 17.75 to 20.50 inches in Chehalis clay loam, and from 19.25 to 20 inches in Melbourne clay. Greatest root concentration was in the upper 8 inches of soil in Willamette and Chehalis soils, and it was more sparce in Melbourne clay.

The soils data in Tables 23, 24, and 25 indicate that in Melbourne clay is slightly inferior in plant nutrients and soil structure throughout the entire profile. Less root growth might, therefore, be expected.

The most significant data are in connection with root penetration and the zones of soil compaction in the soil profiles. Roots in Willamette clay penetrated from 13.25 to 21.50. The soils data show that from 12 to 18 inches is the most porous zone in the entire profile which would favor root penetration.

The downward growth of the taproot in the Chehalis soil was from 17.25 to 20.50. Table 24 shows the region between 12 to 18 inches to be the most compact portion of the entire profile. Root penetration was slightly retarded.

In Melbourne clay the root penetration was least, being only from 19.25 to 20 inches. Table 25 shows that the region from 18 to 24 inches is lowest in total pore space, highest in non-capillary pore space, and that the amounts of clay and colloids are greatest and the percentage of sand is least. Available phosphorus is also lowest in this particular region. Soil texture and soil fertility appear to have the most influence on root penetration in this soil type at 112 days after seeding.

Second order roots were most abundant on roots grown in Chehalis clay loam.

<u>168 days</u>

Plate XXIII and Tables 15, 16, and 17 show that the influence of soil structure on root growth is very distinct. Roots in Melbourne clay penetrated to 27 inches. At this depth the hard, impervious remnants of parent material begin to appear. This material definitely caused root growth to be slower. In Willamette clay, the root penetrated to a depth of 33 inches, while in Chehalis clay loam a depth of 34.50 inches was reached by the roots. These regions as shown in Tables 23 and 24 were open and pervious, thereby, encouraging more root growth.

Cotyledons disappeared at this age.

A dense mass of fine laterals filled the upper 8 inches in all three soils. The roots in Chehalis clay loam branched most profusely and were slightly coarser than those grown in Willamette or Melbourne soils.

A comparison of the pictures with the data in Tables 23, 24, and 25, and with Table 18 show the relationship existing between the number of lateral roots per three-inch section of taproot and the degree of soil compaction is the same as that found with Austrian winter peas; namely, soil compaction and root abundance are inversely proportional to each other in Willamette and Melbourne soils. The compact layer from 12 to 18 inches in Chehalis clay loam appeared to have only a slight influence on the length of the laterals in this region.

An average of root penetration and top growth in Tables 15, 16, and 17 shows that the tops grew 10 inches while the roots penetrated 32 inches in 168 days.

The root system, as a whole, was not as coarse as that of common vetch.

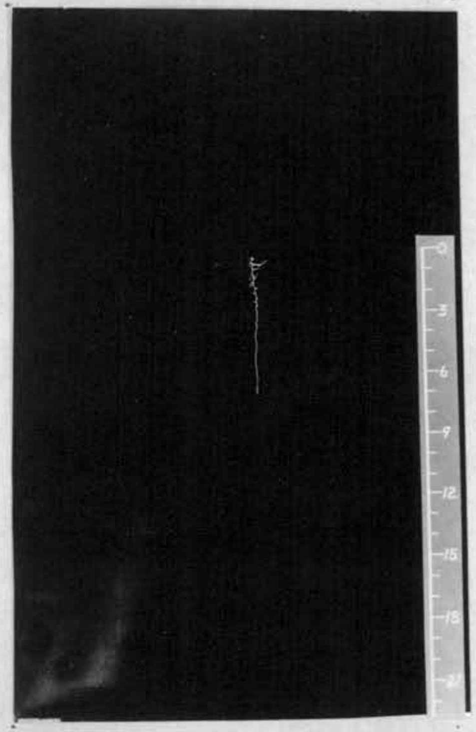
The top-root ratio in Willamette, Chehalis, and Melbourne soils was 2.44, 3.88, and 3.84 respectively.

Plate XIX

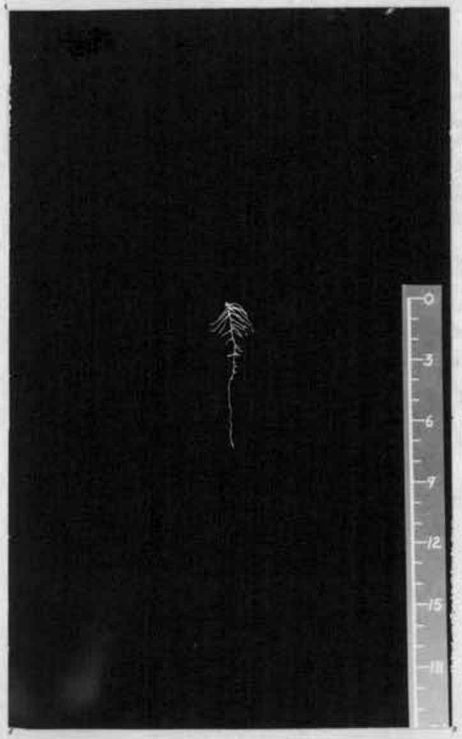
HAIRY VETCH

Root Development at 28 Days
on

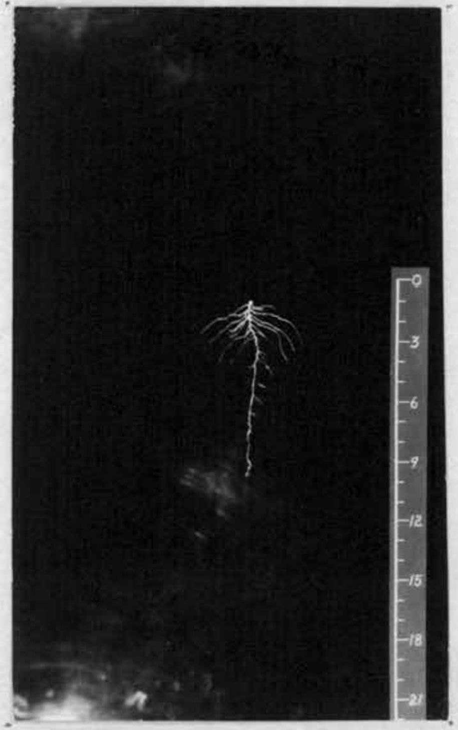
*Willamette



*Chehalis



*Melbourne



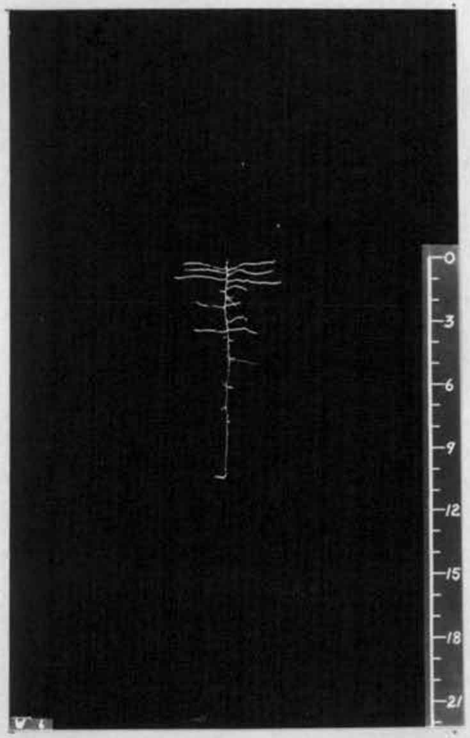
* Indicates soil type on which plants were grown

Plate XX

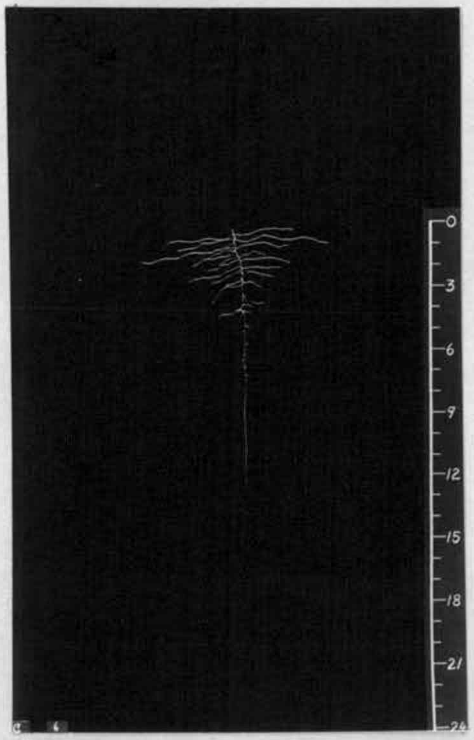
HAIRY VETCH

Root Development at 56 Days
on

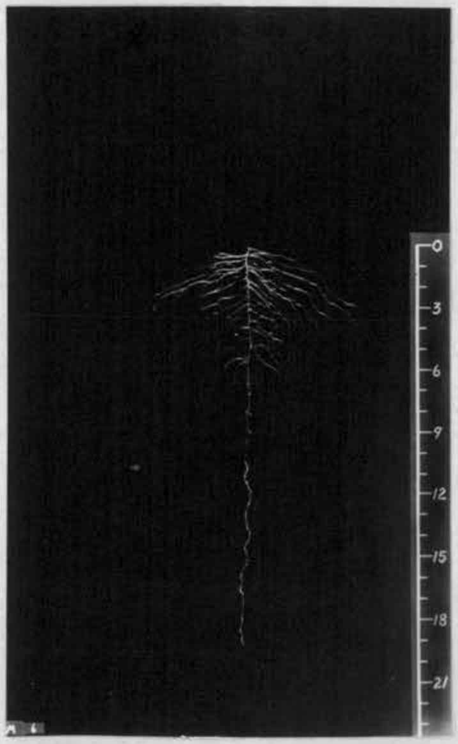
*Willamette



*Chehalis



*Melbourne



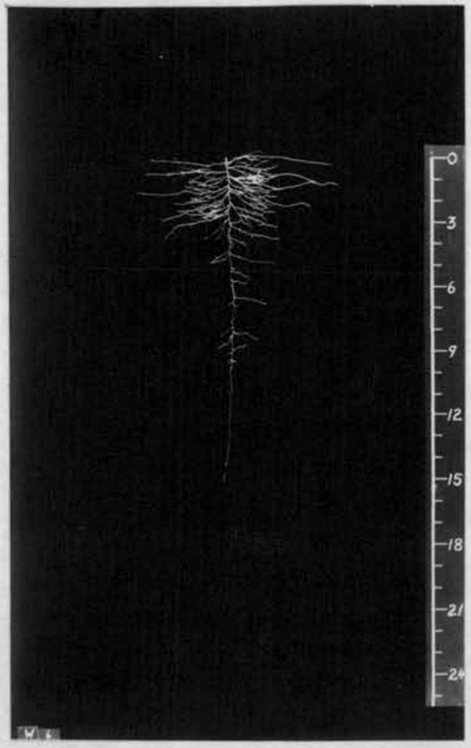
* Indicates soil type on which plants were grown

Plate XXI

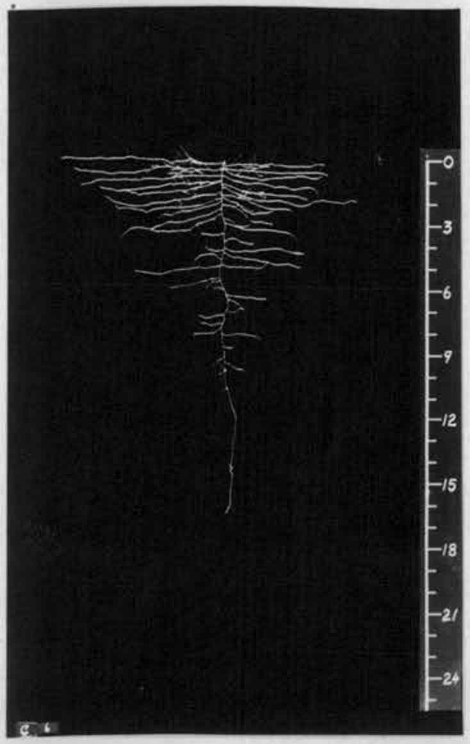
HAIRY VETCH

Root Development at 84 Days
on

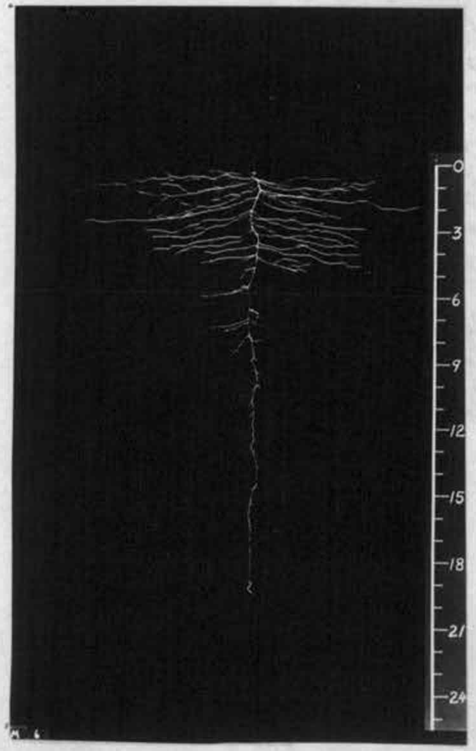
*Willamette



*Chehalis



*Melbourne



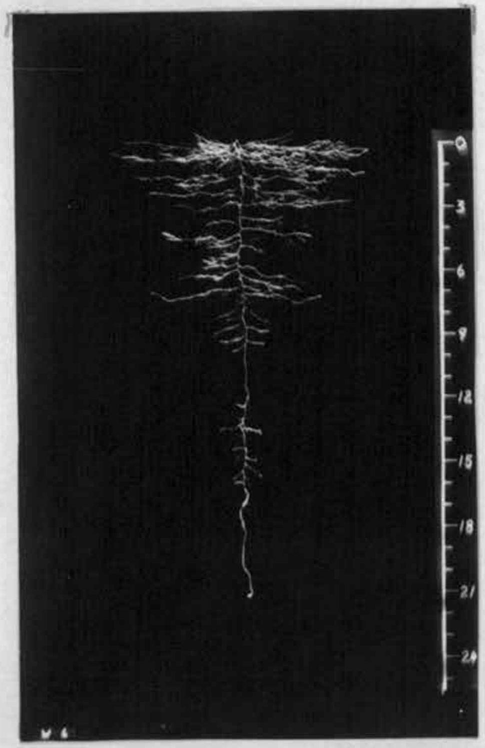
* Indicates soil type on which plants were grown

Plate XXII

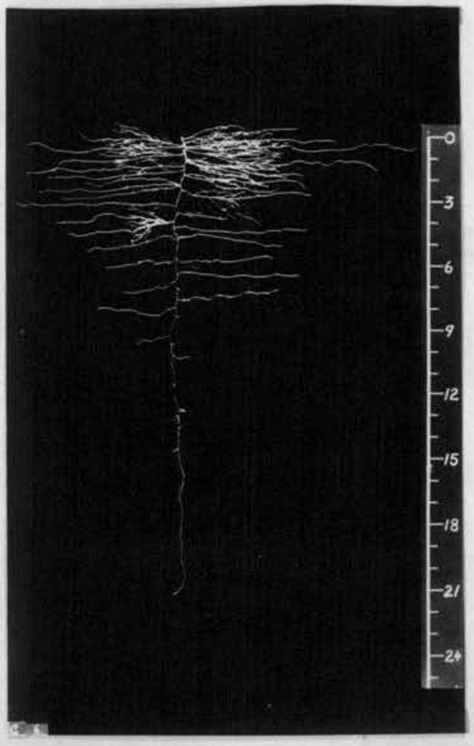
HAIRY VETCH

Root Development at 112 Days
on

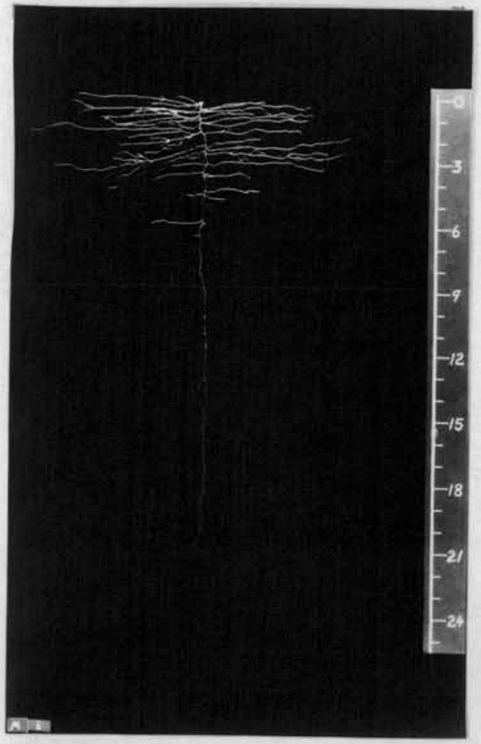
*Willamette



*Chehalis



*Melbourne



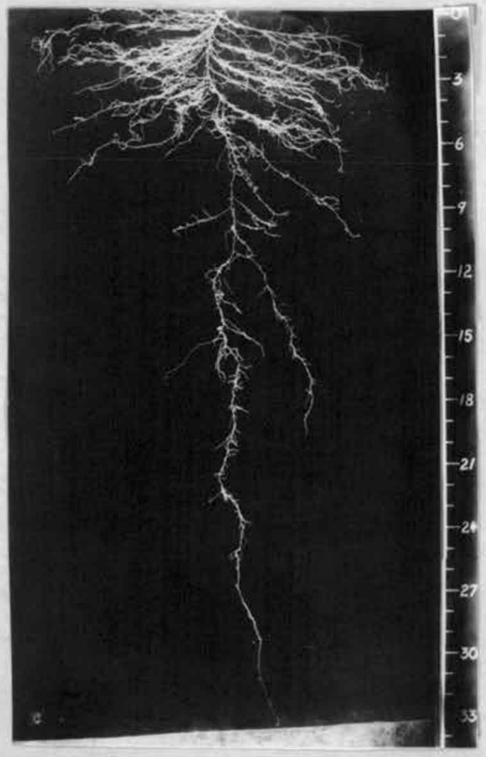
* Indicates soil type on which plants were grown

Plate XXIII

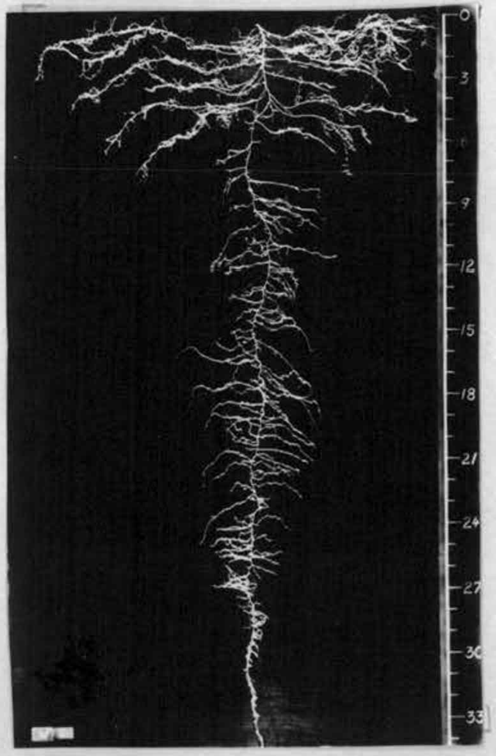
HAIRY VETCH

Root Development at 168 Days
on

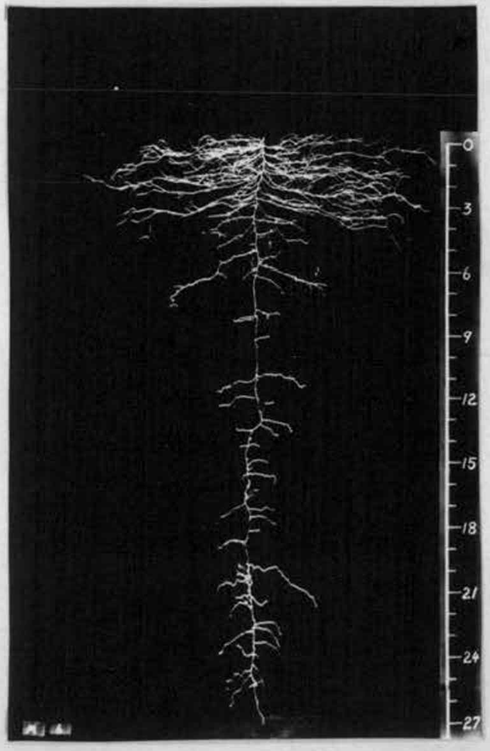
*Willamette



*Chehalis



*Melbourne



* Indicates soil type on which plants were grown

TABLE 15

HAIRY VETCH
ROOT DEVELOPMENT AND TOP GROWTH * IN
WILLAMETTE CLAY

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams **	.0118	.0158	.0538	.0800	.2340
Length of roots in inches	6.50	10.50	13.25	21.50	33.00
Weight of tops in grams **	.0086	.0260	.0626	.0803	.5700
Length of tops in inches	1.50	1.75	2.00	2.25	10.50
Lateral spread in inches	0.70	4.50	10.50	14.00	24.00
Zone of root concentration in inches from surface	0-2.00	0-3.50	0-4.00	0-9.00	0-11.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 16

HAIRY VETCH
ROOT DEVELOPMENT AND TOP GROWTH* IN
CHEHALIS CLAY LOAM

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams**	.0118	.0304	.0720	.0876	.2396
Length of roots in inches	7.00	12.25	17.75	20.50	34.50
Weight of top in grams**	.0118	.0370	.0648	.1166	.930
Length of top in inches	1.40	2.25	2.25	2.50	12.00
Lateral spread in inches	1.00	5.00	15.50	22.00	24.00
Zone of root concentration in inches from surface	0-2.00	0-2.50	0-3.00	0-8.00	0-12.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 17
HAIRY VETCH
ROOT DEVELOPMENT AND TOP GROWTH* IN
MELBOURNE CLAY

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams**	.0234	.0530	.0754	.0810	.1050
Length of roots in inches	8.00	19.00	19.25	20.00	27.00
Weight of top in grams**	.0186	.0328	.0588	.0648	.4030
Length of top in inches	1.00	1.50	2.75	2.75	8.00
Lateral spread in inches	2.00	7.00	17.00	20.00	24.00
Zone of root concentration in inches from surface	0-2.00	0-2.50	0-4.00	0-5.00	0-8.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 18

NUMBER OF LATERAL ROOTS PER THREE-INCH SECTION OF TAPROOT AT DIFFERENT DEPTHS AND AT SUCCESSIVE STAGES OF HAIRY VETCH

Soil type	Willamette clay					Chehalis clay loam					Melbourne clay				
Age of plants (days)	28	56	84	112	168	28	56	84	112	168	28	56	84	112	168
Depth of section (inches)	Number of laterals per section														
0- 3	24	27	30	30	33	24	27	24	27	26	29	30	32	33	31
3- 6		12	18	18	18		11	12	15	17		14	15	15	25
6- 9		9	9	12	9			9	16	10			12	12	10
9-12			9	9	10			6	9	12			6	8	12
12-15				16	10				6	16				5	17
15-18				12	14					15					20
18-21					16					17					15
21-24					13					18					14
24-27					7					18					14
27-30					6					19					12
30-33					4					10					

Common vetch (Vicia sativa L.)

28 days

Similar to hairy vetch and Austrian winter peas, the lateral growth of common vetch was most advanced in Melbourne clay. Data on Plant XIV and in Tables 19, 20, and 21 show only a difference of one-half inch in depth of penetration. Depths were 8.75, 8.75, and 8.25 inches respectively in Willamette, Chehalis, and Melbourne soils. Early planting of the crop is credited for the advanced growth in the Melbourne clay.

56 days

Distinguishing characteristics of the root system appeared at this age. The roots appeared to be slightly coarser than those of hairy vetch but finer than roots of Austrian winter pea.

As shown by Plate XV and the data in Tables 19, 20, and 21, the roots had penetrated 18 inches in Melbourne clay, and 15 inches in Willamette clay, and 15 inches in Chehalis clay laom. Apparently the advanced growth during the first 28 days accounted for the greatest growth in Melbourne clay at this age.

No second order roots were formed.

Nodules appeared on the upper laterals in all three soils types.

84 days

At this age it was observed that the laterals on common vetch, as shown in Plate XXVI, are more evenly distributed and carry farthest down on the taproot than those on any other legumes observed. Tables 19, 20, and 21 show that roots grew 3.25 inches deeper and exhibited more lateral growth in Willamette clay, than either of the other two soils.

The tops weighed more than the roots on plants grown in Melbourne clay, while in Willamette clay and Chehalis clay loam the roots were slightly in excess.

Cotyledons were still attached at this age.

112 days

In comparing the length of the roots in Tables 19, 20, and 21, the effects of soil structure are rather definitely shown. In Chehalis clay loam the roots grew from 21 to 28 inches, from 24.25 to 28 inches in Willamette clay, and from 21 to 23 inches in Melbourne clay. Improved structure and greater fertility of Chehalis clay loam over the other two soils are possible causes for this advanced growth of the roots. A review of Tables 23, 24, and 25 shows the amount of available phosphorous to be greater in the lower regions of Willamette and Chehalis soils than in the Melbourne clay. More organic matter in the upper 12 inches accounts for the improved soil structure and, consequently, more profuse root growth in this regions.

The tops weighed more than the roots in all soils except Melbourne clay.

168 days

Plate XVIII and the data found in Tables 19, 20, and 21 indicate that root development in Chehalis clay loam was decidedly greater than root growth in Willamette clay or Melbourne clay. The depth of penetration was 43, 34, and 35.50 inches respectively in the above-mentioned soils. Lateral spread reached 25, 22, and 22 inches on soils in the order names.

Plate XVIII shows the large feeder roots appearing in the lower portions of Willamette and Chehalis soils with none appearing in Melbourne clay. Abundance of more soluble plant nutrients in the former soils appears to be most influential on this increased root growth.

The distribution of lateral roots per three-inch section of taproot, shown in Table 22, indicates the same general influence of soil compaction on the distribution;

namely , that the number of laterals per three-inch section of taproot in the soil profile is inversely proportional to the degree of soil compaction shown in Tables 23, 24, and 25

The tops weighed more than the roots in all soils. The top-root ratio was 3.34 in Willamette clay, 3.39 in Chehalis clay loam, and 6.12 in Melbourne clay.

An average top growth from Tables 19, 20, and 21 shows that in 168 days the tops grew 10 inches while the roots penetrated 37.50 inches for all three soils. The most top growth occurred between 112 and 168 days. Increasing temperatures and length of day were undoubtedly responsible for this advanced growth.

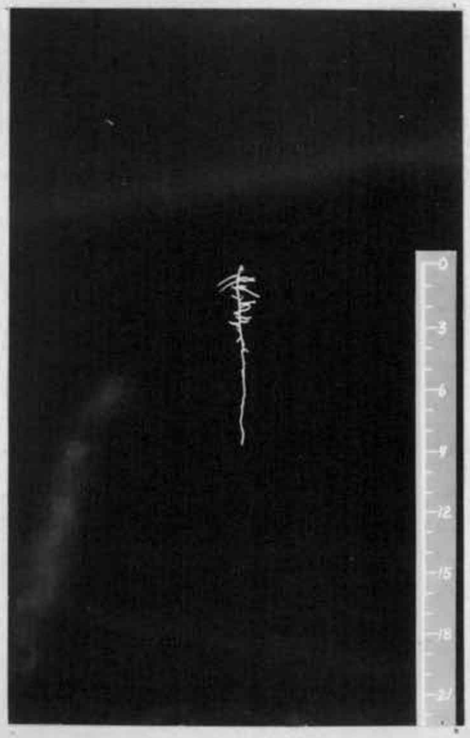
Globose nodules appeared at the tip of the taproots in Willamette clay and Chehalis clay loam at depths of 34 and 43 inches respectively. In Melbourne clay nodules were found at 24 inches. Along with the pore space date found in Tables 23, 24, and 25, the appearance of nodules on roots at these depths indicate that all three soils are rather well aerated.

Plate XXIV

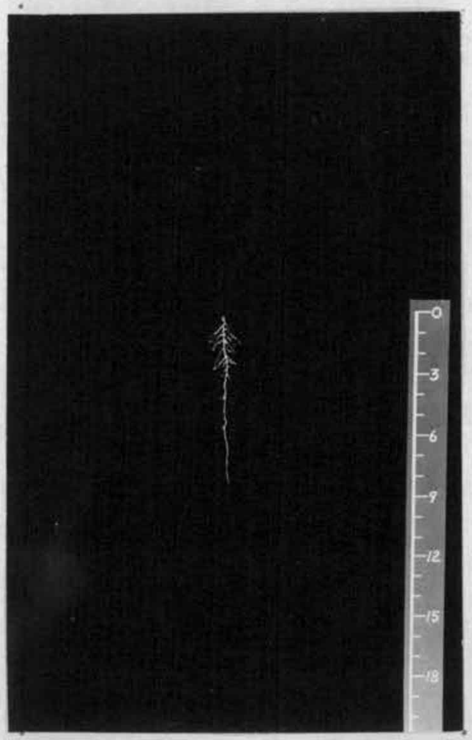
COMMON VETCH

Root Development at 28 Days
on

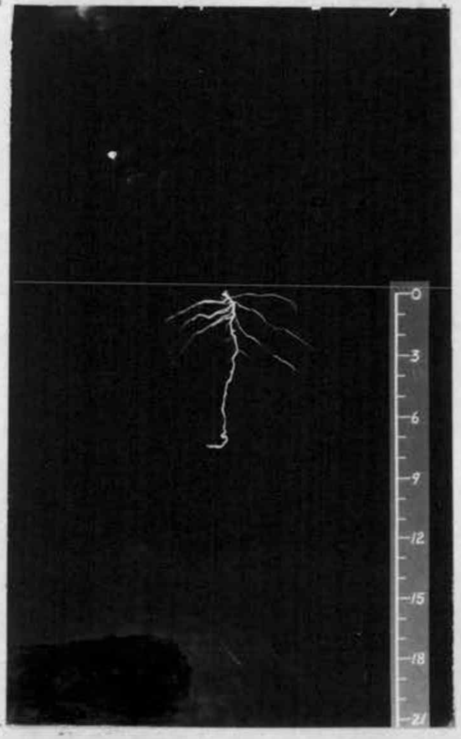
*Willamette



*Chehalis



*Melbourne



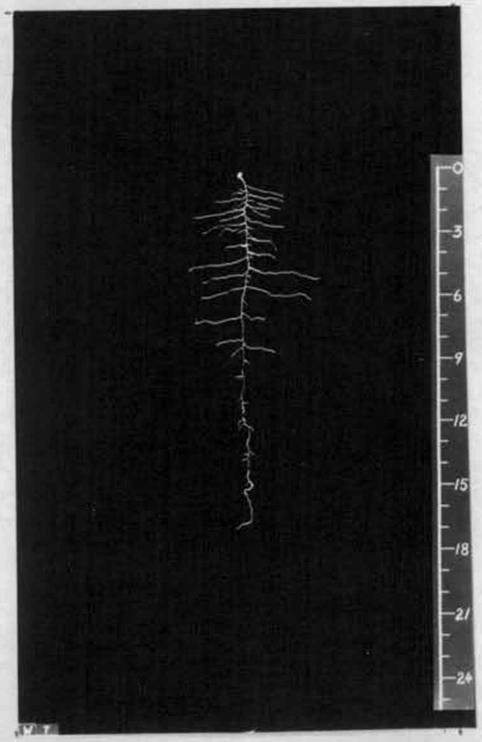
* Indicates soil type on which plants were grown

Plate XXV

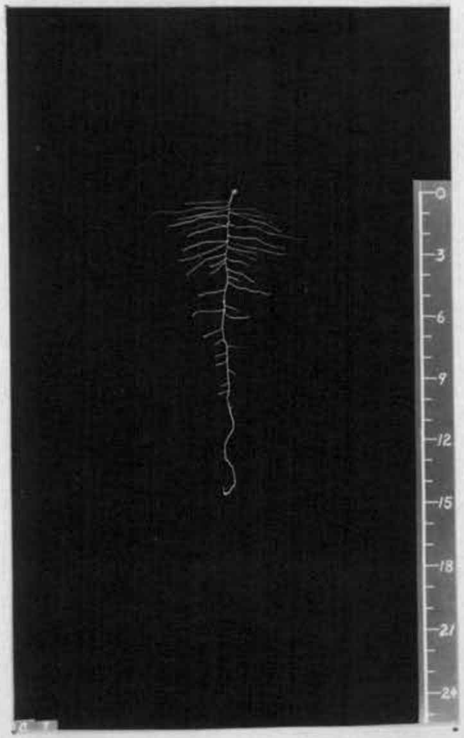
COMMON VETCH

Root Development at 56 Days
on

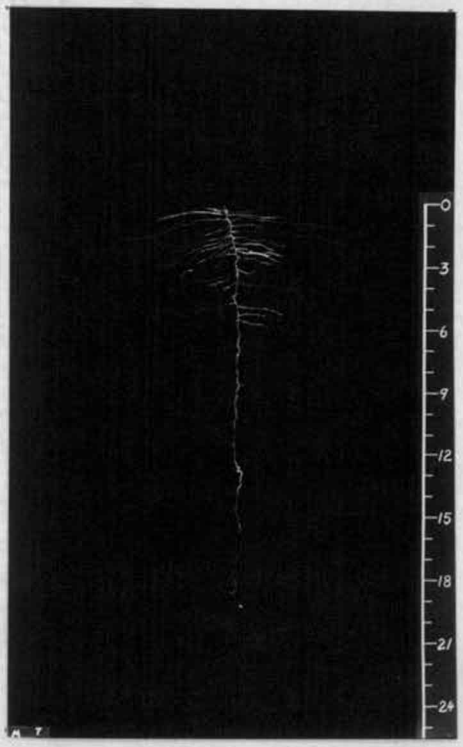
*Willamette



*Chehalis



*Melbourne



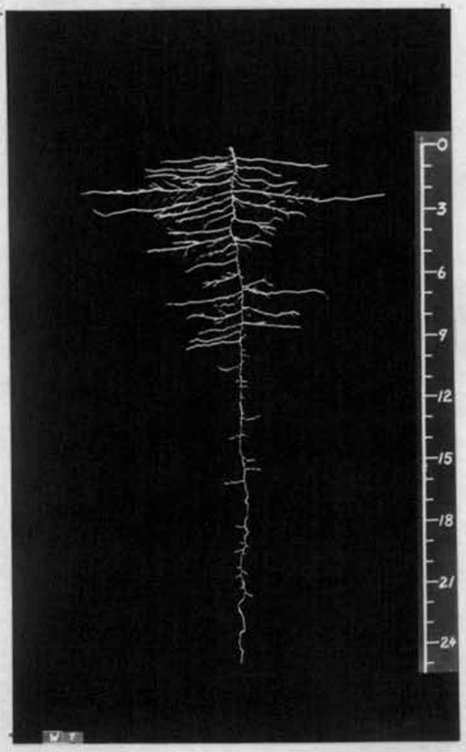
* Indicates soil type on which plants were grown

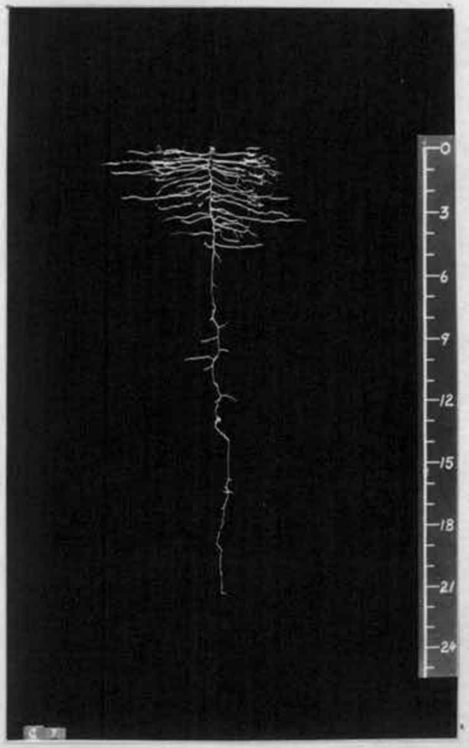
Plate XXVI

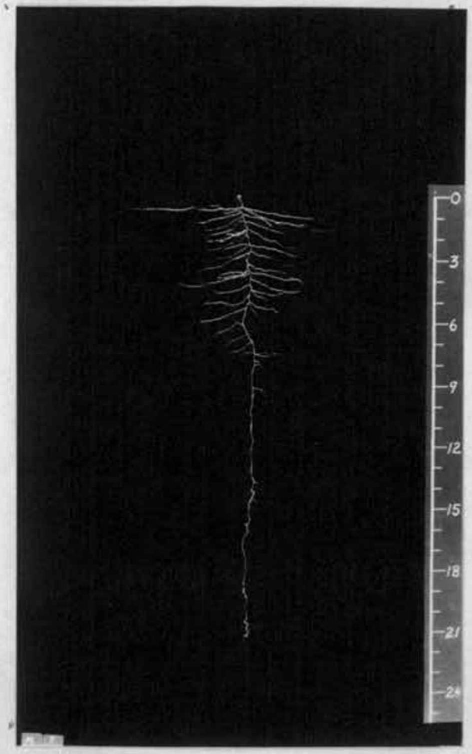
COMMON VETCH

Root Development at 84 Days
on

*Willamette	*Chehalis	*Melbourne







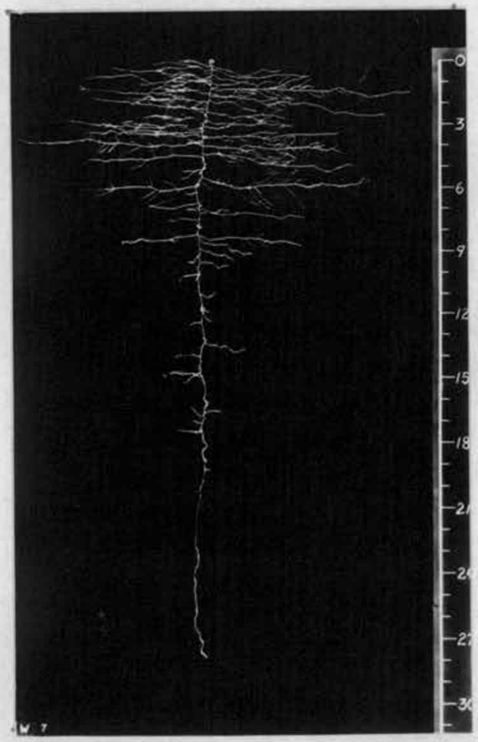
* Indicates soil type on which plants were grown

Plate XXVII

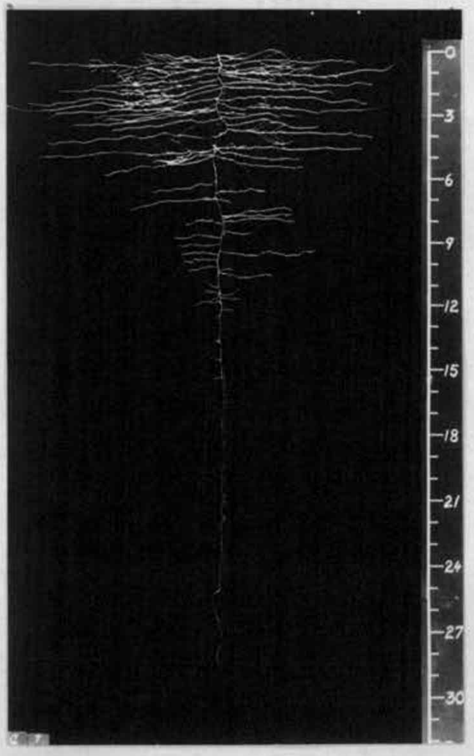
COMMON VETCH

Root Development at 112 Days
on

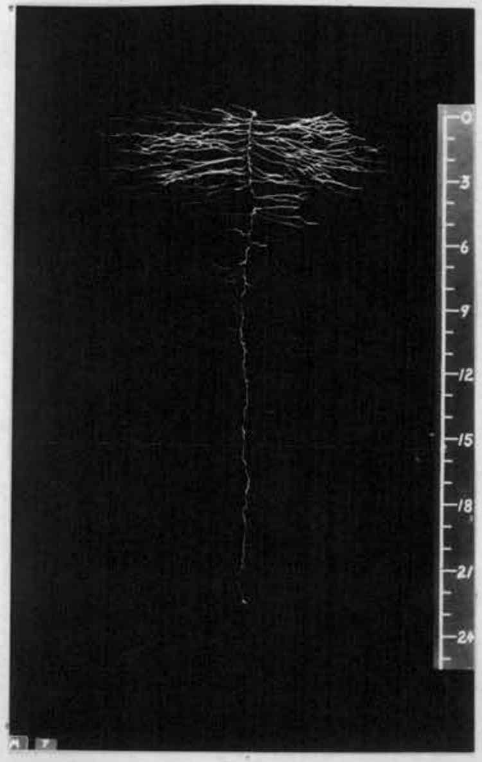
*Willamette



*Chehalis



*Melbourne



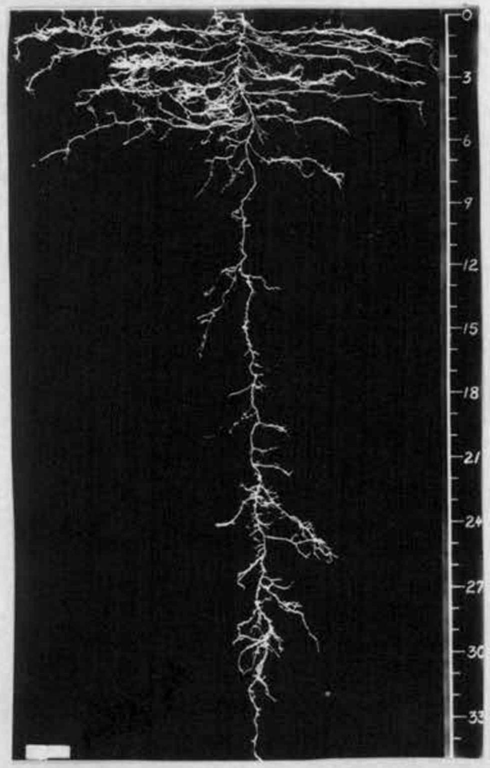
* Indicates soil type on which plants were grown

Plate XXVIII

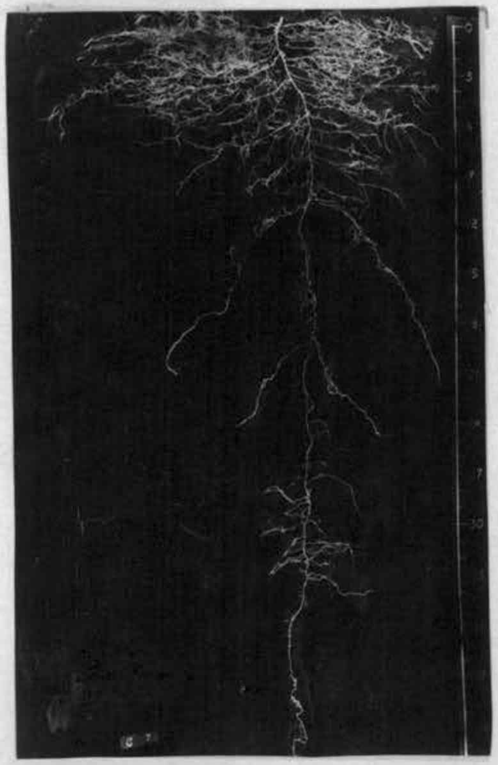
COMMON VETCH

Root Development at 168 Days
on

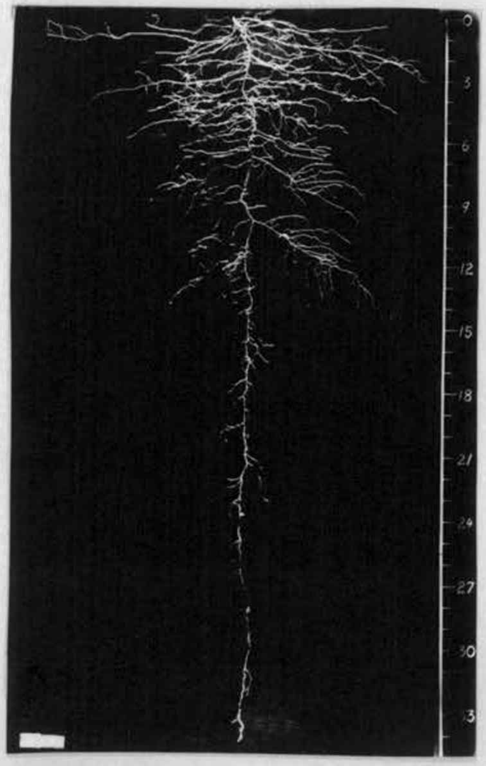
*Willamette



*Chehalis



*Melbourne



* Indicates soil type on which plants were grown

TABLE 19

COMMON VETCH
ROOT DEVELOPMENT AND TOP GROWTH* IN
WILLAMETTE CLAY

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of Observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams**	.0260	.0446	.0926	.1006	.2902
Length of roots in inches	8.75	16.75	24.25	28.00	34.00
Weight of top in grams**	.0124	.0472	.0900	.2450	.9700
Length of top in inches	1.25	2.25	2.25	2.25	10.00
Lateral spread in inches	1.25	6.50	18.00	21.50	25.00
Zone of root concentration in inches from surface	0-3.00	0-4.00	0-4.50	0-8.00	0-10.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 20

COMMON VETCH
ROOT DEVELOPMENT AND TOP GROWTH* IN
CHEHALIS CLAY LOAM

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams**	.0124	.0448	.0670	.1100	.4602
Length of roots in inches	8.75	15.00	21.00	28.00	43.00
Weight of top in grams**	.0100	.0328	.0564	.1366	1.561
Length of top in inches	1.50	2.00	2.50	2.75	11.00
Lateral spread in inches	1.50	4.00	10.00	11.00	25.00
Zone of root concentration in inches from surface	0-3.00	0-3.00	0-3.75	0-5.00	0-12.00

* Data based on a representative plant
** Weight after being dried at 112° C. for 24 hours

TABLE 21

COMMON VETCH
ROOT DEVELOPMENT AND TOP GROWTH* IN
MELBOURNE CLAY

Month of Observation	Nov.	Dec.	Jan.	Feb.	April
Age at time of observation	28 days	56 days	84 days	112 days	168 days
Weight of roots in grams**	.0326	.0390	.0446	.0822	.2300
Length of roots in inches	8.25	18.00	21.00	23.00	35.50
Weight of top in grams**	.0284	.0418	.0478	.0556	0.7340
Length of top in inches	1.25	1.50	2.00	2.50	10.00
Lateral spread in inches	.90	7.00	13.00	16.00	22.00
Zone of root concentration in inches from surface	0-1.50	0-6.00	0-7.50	0-8.00	0-12.00

* Data based on a representative plant
** Weight after being dried at 105° C. for 24 hours

TABLE 22

NUMBER OF LATERAL ROOTS PER THREE-INCH SECTION OF TAPROOT AT DIFFERENT DEPTHS AND AT SUCCESSIVE STAGES OF COMMON VETCH

Soil type	Willamette clay					Chehalis clay loam					Melbourne clay				
Age of plant (days)	28	56	84	112	168	28	56	84	112	168	28	56	84	112	168
Depth of section (inches)	Number of laterals per section														
0- 3	22	25	27	27	26	23	23	25	28	29	31	29	27	30	33
3- 6		10	12	15	14		9	8	11	16	14	15	17	18	20
6- 9		9	9	9	8		5	4	11	14		6	11	12	10
9-12		8	9	12	9			6	6	10			8	10	8
12-15		9	16	9	15			4	5	8			6	11	13
15-18			15	6	16			3	3	11				9	15
18-21			8	6	10					14				6	12
21-24					12					16					14
24-27					14					10					8
27-30					14										
30-33					10										
33-36					10										

EXPERIMENTAL RESULTS (cont.)

Physical and Chemical Properties of the Soils On Which Root Observations Were Made

Willamette Clay

General Description:

Willamette clay is considered one of the best old valley filling soils. It is fairly well drained and shows a mature profile.

It is one of the most representative general-purpose agricultural lands of the valley, and occupies the level, to rolling areas above the poorly-drained soils. Grain and legumes are the principal crops grown. The Willamette clay on which this study was conducted was in a good state of fertility.

Structure and Textures

Data in Table 23 indicate that the Willamette clay soil profile is comparatively mature with well-defined A, B_1, B_2, and C horizons.

The pore space data show that the tillage pan lies between 6 and 12 inches, actually it includes the zone between 8 and 13 inches. The foregoing experimental results show rather concisely that lateral roots in this region of the soil were much shorter and were less numerous per three-inch section of tap root. Undoubtedly, this high mechanical resistance of the soil makes root penetration more difficult.

The region from 12 to 18 inches directly below the tillage pan exhibits the best structure throughout the entire profile. It contains 26.8 percent non-capillary pore space, in comparison to 14.3 and 13.4 above and below this six-inch region. This improved structure may be accounted for by the increased animal and insect activities in this zone as well as the accompanying supply of organic matter in this region.

In the B_1 and B_2 horizons the downward movement of the finer soil separates is very well defined. Table 23 shows the greatest accumulation of colloidal material in the B_1 horizon, 24 to 30 inches; and the greatest clay accumulation from 36 to 42 inches which is classified in the B_2 horizon. From 42 inches downward these finer soil separates gradually decrease into the original parent material beyond 78 inches. Slight iron mottling is found in the B horizon. Review of the pore space data indicates that aeration may be insufficient due to the decreasing amounts of non-capillary pore space and organic matter.

Plant Nutrients:

Chemical analyses show the profile to have ample quantities of organic matter, nitrate nitrogen, and available phosphorus in the upper 24 inches of soil. Below this level the amount of organic matter decreases from 1.80 to 0.33 percent, and at from 60 to 78 inches only 0.02 percent is present.

The amount of nitrate nitrogen is highest between 24 and 30 inches; below this it drops from 34 ppm. to 12 ppm., and from 42 to 78 inches there is only 7 ppm. present.

Conversely, the available phosphorus supply is least between 24 and 30 inches, and gradually increases from 92 ppm. at 30 inches to 306 ppm. between the 72 and 78-inch section of the soil profile.

Willamette clay has the potentialities of supporting plant growth to a depth of 78 inches.

A pH from 6.0 to 6.4 was not considered a limiting factor in root growth.

Chehalis Clay Loam

General Description:

Chehalis clay loam is a good representative soil type of the Chehalis soil series. It is derived from alluvial materials deposited so recently that it has undergone very little modification since deposition.

It has excellent drainage except in winters when it is inundated by stream overflows.

TABLE 23

PHYSICAL AND CHEMICAL PROPERTIES OF
WILLAMETTE CLAY

Soil Depth Inches	Pore Space Total	Capillary	Non-capillary	Mechanical Analysis Sand	Silt	Clay	Colloid	Organic Matter percent	* NO_3 ppm	** Phos ppm	Acidity pH
A horizon											
0- 6	54.6	37.1	17.5	24.4	44.8	30.8	25.8				
6-12	53.3	40.0	14.3	18.8	48.4	32.8	26.4	2.60	28.0	204	6.0
12-18	63.6	36.8	26.8	17.4	48.2	34.4	30.8				
18-24	51.7	38.3	13.4	18.8	43.8	37.4	31.2	1.80	22.2	176	6.0
B horizon											
24-30	52.8	43.0	9.8	18.6	43.4	38.0	35.4	0.33	34.1	92	6.2
30-36	52.5	45.7	6.8	16.6	44.4	29.0	36.8				
B_2 horizon											
36-42	52.5	43.7	8.8	15.4	43.6	41.0	33.2	0.15	12.0	120	6.4
42-48	51.3	42.9	8.4	17.2	45.5	37.3	28.2				
48-54	52.4	44.4	8.0	18.6	47.2	34.2	27.2	0.13	6.8	182	6.6
54-60	53.2	44.0	9.2	19.4	51.4	29.2	23.4				
60-66	52.1	46.0	6.1	20.6	49.8	29.6	22.8	0.02	7.2	232	6.6
66-72	52.1	46.6	5.5	20.2	52.0	27.8	22.4				
72-78	53.6	45.4	8.2	20.6	51.8	27.6	21.2	0.02	7.0	206	6.6
C horizon											
Below 78											

* Nitrate nitrogen
** Available phosphorous

Chehalis clay loam is a deep, fertile soil and is considered one of the best all-purpose agricultural soil types in the Willamette Valley. The principal intertilled crops grown on it are hops, corn, potatoes, beets, berries, and truck crops. Small grains, fiber flax, alfalfa and clovers for hay and seed are also important.

Structure and Texture:

Chehalis clay loam has been recently deposited and exhibits a fairly constant structure throughout the entire profile. The texture, however, is somewhat different in that most of the coarser separates lie in the upper horizon and the finer separates are located in the lower portion of the profile.

Table 24 indicates that the most compact region of the profile lies between 12 and 18 inches with 11.2 percent non-capillary pore space, and 50.2 percent total pore space which is also the lowest.

This region is too far beyond tillage depth to be called the tillage pan, however, the effects of its compact nature on lateral growth and numerical distribution are shown as distinctly as the tillage pan regions of the Willamette and Melbourne soils.

The entire profile contains from 50.2 to 62.3 percent total pore space. To be most ideal these figures should be composed of one-half capillary and one-half non-capillary pore space. Although this isn't the case, the amounts of each are relatively constant throughout the profile.

The amount of colloidal material throughout the profile—17.5 percent in the upper 6 inches, 33.2 percent from 48 to 54 inches, and 29.6 percent from 72 to 78 inches—indicates some profile development taking place, and that there is an excellent supply of colloidal material available for crop production far beyond the 6 foot depth.

Plant Nutrients:

The chemical analysis in Table 24 shows that the soil has a good supply of organic matter, nitrate nitrogen, and available phosphorus from 0 to 60 inches. Between 60 to 78 inches the amount of organic matter decreases from 1.8 percent to 0.6 percent, and nitrate nitrogen decreases from 32 to 7 ppm. The zone of greatest phosphorus concentration lies between 24 and 30 inches with 400 ppm. The amount of available phosphorus above 24 inches is slightly over one-half as great, while a slight decrease is noted below the 30 inch level.

Of the three soils included in this study, Chehalis clay loam exhibits the greatest inherent fertility.

A pH range of 6.4 to 6.6 was not considered to be of any limiting importance in the growth of these legumes.

TABLE 24

PHYSICAL AND CHEMICAL PROPERTIES OF
CHEHALIS CLAY LOAM

Horizon Soil Depth Inches	Pore Space Total	Capillary	Non-capillary	Mechanical Analysis Sand	Silt	Clay	Colloid	Organic Matter Percent	* NO_3 ppm	** Phos ppm	Acidity pH
C horizon											
0- 6	52.1	35.6	16.5	46.0	31.0	23.0	17.5	2.60	41	230	6.4
6-12	51.7	36.1	15.6	48.0	28.0	24.0	17.5				
12-18	50.2	39.0	11.2	46.0	30.3	23.7	17.5	2.30	24	241	6.4
18-24	53.2	48.2	15.0	40.0	30.0	30.0	23.7				
24-30	52.8	38.4	14.4	30.5	34.3	35.2	25.2	2.40	25	400	6.4
30-36	57.7	40.4	17.3	20.2	39.3	40.5	29.7				
36-42	59.2	37.7	21.5	16.4	44.2	39.4	30.8	2.40	20	380	6.4
42-48	58.9	38.1	20.8	15.8	44.6	39.6	32.8				
48-54	62.3	39.3	23.0	14.6	44.6	40.8	33.2	1.80	32	380	6.4
54-60	61.5	40.0	21.5	15.8	43.4	40.8	33.2				
60-66	56.6	36.5	21.0	14.2	42.8	43.0	33.2	0.64	7	380	6.6
66-72	57.0	43.3	13.7	14.2	48.8	37.0	29.0				
72-78	57.0	43.5	13.5	16.2	46.6	37.2	29.6	0.60	7	375	6.6

* Nitrate nitrogen
** Available phosphorous

Melbourne Clay

General Description:

Melbourne clay is one of the most distinctly residual soils in Western Oregon. It has been developed from sedimentary rock—principally shale and sandstone.

This soil has a fairly high clay content and the profile is very shallow. Powers (21) states that from one-fourth to three-fourths of the top plow-depth soil has been lost by erosion.

Melbourne clay occupies the low rolling hills and the topography is fairly rough in some areas.

The principal uses of this soil are for the production of trees, small fruits, and grains, with a constantly increasing acreage being devoted to grass and to hairy vetch for seed.

The soil upon in which the root systems of the annual legumes were observed had been cropped to grain and vetch for the past 20 years.

Structure and Texture:

Table 25 shows the profile of Melbourne clay to very shallow and fairly mature.

The A horizon has been almost completely eroded away by the heavy winter rains which occur during the winter months. The upper 6 inches include this A horizon and the tillage depth, and it exhibits fair structure, although the non-capillary pore space is only one-third that of the capillary pore space. This condition is more acute in the region from 6 to 12 inches where the tillage pan is located.

This region is lowest in non-capillary pore space as well as total pore space. The high clay content in addition to this very compact condition appears to have a retarding effect upon the growth of the laterals as well as their numerical distribution per three inch-section of taproot even though the amount of organic matter is highest from 0 to 12 inches.

The regions below 12 inches exhibit increasingly good structure, ranging from 14.4 percent at 12 to 18 inches to 17.4 percent at 24 to 30 inches. Animal and insect borings are especially numerous in these regions, and they undoubtedly offset the effect of the increasing amounts of silt, clay, and colloids and the decrease of organic matter on soil structure. The mechanical analysis in Table 25 shows an increase in the amount of sand, and a marked decrease of the finer separates from 24 to 30 inches. This condition is caused by the outcroppings of the parent material which begin to appear at this depth. These fragments of hard sandstone greatly influence the course of roots growing through this region.

The solid parent material lies below 33 inches. Few roots ever penetrate this region except through crevices or larger openings in the rock.

Plant Nutrients:

The greatest amount of organic matter and phosphorus lie in the upper 6 inches of soil. Nitrate nitrogen is rather evenly distributed throughout the upper 24 inches. The lower part of the B_2 horizon is lowest in organic matter and nitrate nitrogen but contains 12.7 ppm. of phosphorus. The amount of available phosphorus present is exceedingly low.

The best part of the soil lies in the upper 12 inches. This region is fairly well supplied with organic matter and nitrate nitrogen.

A pH of 5.4 was not considered low enough to be harmful to the growing of the annual legumes observed in this study.

TABLE 25

PHYSICAL AND CHEMICAL PROPERTIES OF
MELBOURNE CLAY

Soil Depth Inches	Pore Space Total	Capillary	Non-capillary	Mechanical Analysis Sand	Silt	Clay	Colloid	Organic Matter Percent	* NO_3 ppm	** Phos ppm	Acidity pH
A horizon											
0- 6	50.2	38.6	11.6	25.8	31.5	42.7	36.7	2.10	20	19	5.4
B_1 horizon											
6-12	46.3	36.2	10.1	26.3	28.2	45.5	40.7				
B_2 horizon											
12-18	49.1	34.7	14.4	25.0	29.5	45.5	41.7	1.40	21	12	5.4
18-24	48.6	32.1	16.5	23.8	36.2	46.0	42.2				
24-30	59.1	41.7	17.4	30.0	27.8	42.2	28.0	0.77	6	13	5.6
C horizon Below 30											

* Nitrate nitrogen
** Availabe phosphorous

DISCUSSION OF RESULTS

Examination of the foregoing data shows that the root systems of the annual legumes included in this study grow to be rather extensive and deep-seated. Further consideration of the data also shows that soil type does exert some influence on root development.

The physical factors of the soil which appeared to influence root growth most were structure and texture. Aeration was not considered a limiting factor in root growth since all soils were well drained.

It was observed that root growth was most rapid, that the roots were longer and greater in diameter, and that the number of lateral roots per three-inch section of taproot was greater in the less-compact regions of the soil.

In zones of compaction, where the proportion of capillary pore space greatly exceeded that of the non-capillary pore space, the taproots appeared to be more distorted, smaller in diameter, and showed less growth than when they encountered the more porous regions of the soil. When the taproot intercepted an extra large non-capillary pore space as a worm cavity, it would curl around inside the space until the root tip, in its downward growth, penetrated the soil again. It was also noticed that roots tend to follow the path of the least resistance. Often when the root grew into a vertical insect burrow it would follow the mellow soil downward in preference to breaking into the undisturbed soil nearby. Weaver (38) and Miller (17) noted that roots grew more rapidly and exhibited more vigorous branching when they encountered these larger soil cavities. They suggest that aeration, greater fertility, and the fact that these areas are most deficient in moisture may be possible causes for the accelerated root growth. Results of this study would also indicate that soil areas with least soil compaction may also be a factor for increased root growth.

Results show that the physical and chemical properties of the soil are somewhat interrelated as to their effects upon the development of rooting systems, but that each appears to have a slightly different influence on the growing habits of the roots.

The data show rather distinctly that during periods when there is plenty of usable water for root growth that growth is most extensive in the more fertile regions of the soil, (referring to nitrate nitrogen and available phosphorous in this study). Although the results show that the physical properties of the soil; as structure and texture, influence the length and number of laterals, it is rather evident that the most general increased growth was in the most fertile soils.

These influences are rather easily compared in Chehalis clay loam soil, which is deep and shows excellent physical and chemical properties, with Melbourne clay which is a shallow, more compact hill soil having a heavy clay subsoil and showing little inherent fertility.

Lateral growth occurs quite naturally in these annual legume roots, and when adverse environmental conditions occur, as excessive soil compaction or a decrease in fertility, this growth is retarded due to increased mechanical resistance of the soil as well as nutrient deficiencies. On the other hand, a soil which possesses good structure and fertility is naturally more favorable to extensive root development. This aids in explaining the advanced growth of the laterals and the deepest penetration of the taproots in Chehalis clay loam.

Root systems grown in Willamette clay were slightly less extensive than those grown in Chehalis clay loam.

Weaver (35) noted that a limited degree of penetration of the rooting system caused a marked increase in the degree of lateral branching. No indication of such a condition was noticed on the roots on this study. Age of the plant undoubtedly plays an important part in this respect--the older plants being most subjected to such adverse soil conditions as obstructions or a shallow profile. Plants in this study were probably too young to show such results, since Austrian winter peas was the only crop which penetrated the C horizon of Melbourne clay.

Tables 6, 10, 4, 18, and 22 show that in all crops except for compact layers of soil the number of lateral roots per three-inch section of taproot gradually decreased with increasing depth; also that this number tended to increase with the age of the plant. Such a distribution is a natural one. No absolute reason was found to explain this numerical variability of the laterals at various soil depths. Doubtless, the mechanical resistance of the soil, the increase or decrease in the supply of plant nutrients, and the age of the plant are responsible for this variation.

Data also show that pH values increased with depth in all soils. The lower readings in the upper layers of soil doubtless were caused by leaching and by the greater absorption of basic materials by roots.

Although the physical and chemical factors of the soil appear to influence the development of roots in growing habits, the inherent characteristics of these seem to have the most influence on the type of root system which grows in the soil.

Of the particular legumes studied, crimson clover developed the finest and most compact root system, even though it had developed least at 168 days. Subterranean clover developed a slightly coarser type of root system with fewer second order roots; however, the growth was more extensive than the growth of crimson clover during the same period. Austrian winter peas showed greatest development under all conditions and had the coarsest root system of all of the cover crops observed. Hairy vetch produced a finer and slightly more intensive root growth than common vetch; however, common vetch grew slightly more in length and lateral spread in all soil types. Austrian winter peas, hairy vetch, and common vetch showed the quickest germination and root growth after seeding. Early establishment is especially desirable for crops used as winter cover in holding the soil against the forces of wind and water. The root growth of crimson clover and subterranean clover was not as prolific during the winter months. Apparently they make their greatest growth during the early spring when conditions are more favorable for crop growth.

The periods of most rapid root development and top growth occurred quite consistently among the crops during the first 28 days after seeding, and between 112 and 168-day periods of observation. During the first 28 days of growth, the averages of root penetration and top growth for the entire group were 7.05 and 1.21 inches respectively. Austrian winter peas, hairy vetch, and common vetch grew most rapidly during the first period; however, during the last period, between 112 and 168 days, subterranean clover made the most marked average root penetration in all three soils. Crimson clover developed the least in all respects after 168 days of growth.

A possible explanation for the advanced growth of the roots and tops during these two periods may be that during the late fall season, when these crops were planted, more favorable environmental conditions, as warmth, aeration, moisture, and the abundance of organic matter in the upper portion of the soil brought about quicker germination and increased the rate of growth. In addition, the greater day length and amount of sunshine were most favorable to the growth of the above-ground portions of the plants.

During the latter period, the increased day temperatures correlated with some loss of soil moisture undoubtedly were greatly responsible for the accelerated growth of the plants.

Results shown in Fig. I indicate that a marked increase in top growth occurred with an increase in day temperatures. It was also noted that soils with the greatest inherent fertility produced the most extensive root systems. In turn, these plants showed greater top development 168 days after seeding than plants which had developed less extensive

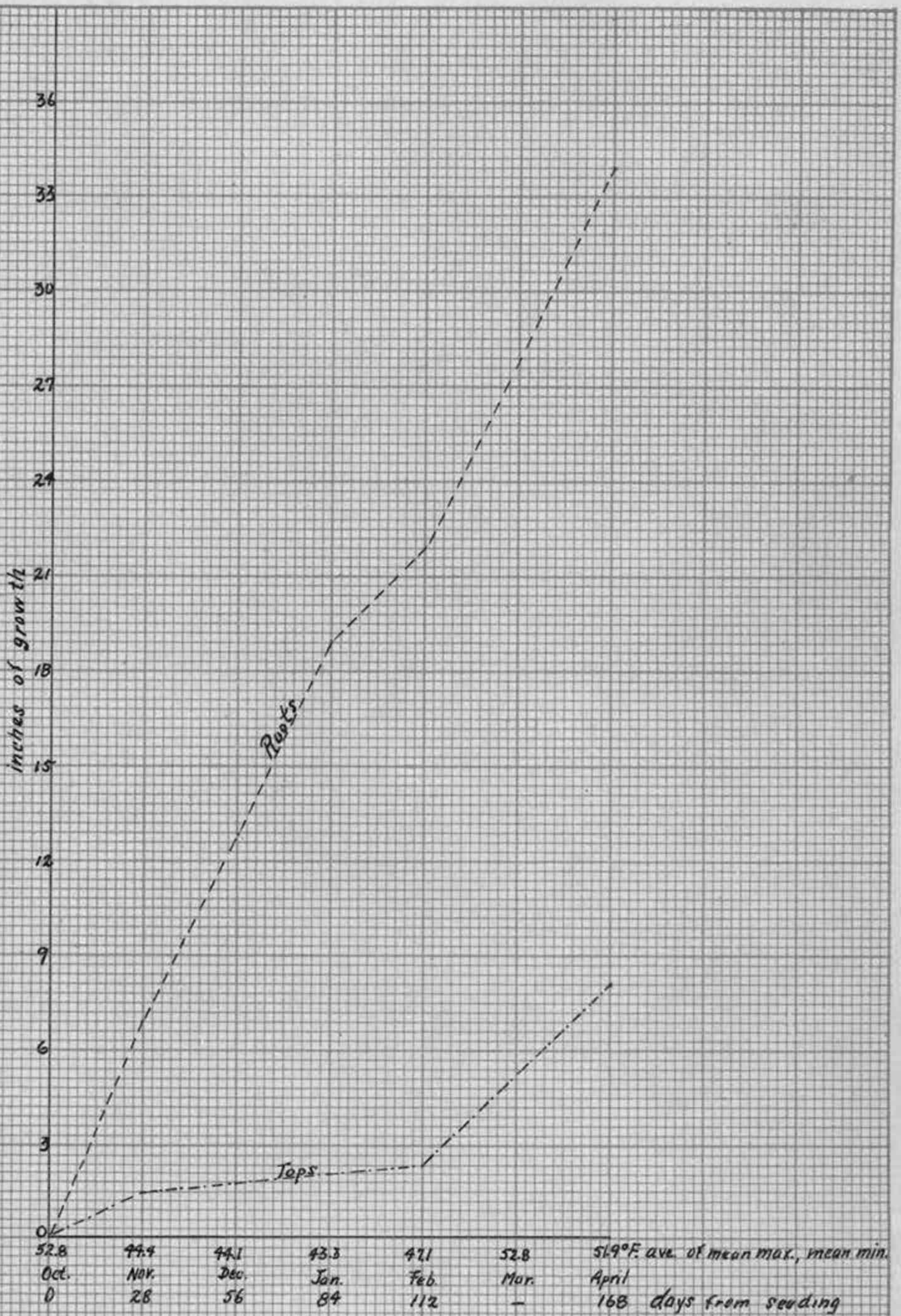


Fig. I A Graph Showing Comparative Top Growth and Depth of Root Penetration of Annual Legumes During Period of October 1940 to April 1941 root systems.

The young plants of all these crops go largely to root development during the winter months, so that top growth is comparatively slow at first. To be more specific, 112 days after seeding the rooting system of Austrian winter pea had penetrated 35 inches and showed a lateral spread of 21 inches in Chehalis clay loam, while the tops grew only 2.50 inches.

A possible explanation for this advanced growth may be one of heredity and environment. A plant is what it is because over a long period of time it has adapted itself to environment. These crops are winter annuals; it may be a natural tendency for them to sacrifice the early top growth for a rapid establishment of the rooting system. Necessarily, the underground portion of the plant must be well established in order to support the increased top growth and early maturity during periods of higher temperatures. Furthermore, the soil is warmer than the winter atmosphere, and it is, therefore, quite favorable for root growth. In contrast, the cooler temperatures, high humidity and the lack of sunshine above the surface during the winter months are most unfavorable for the top growth of plants.

The comparative weight of roots and tops was not so uniform as their growth. During the first three observation periods the weights of roots and tops varied somewhat with the soil type and the crops. With the exception of Austrian winter peas, hairy vetch, and common vetch grown in Melbourne clay at 112 days of age, all crops produced tops with greater weight than the roots at 112 and 168 days from seeding.

Turner (33) found that the barley and corn showed significant increases in the ratio of tops to roots with an increase of nitrates in the soil. He concluded that an increase in top ratio with an increase in nitrate may be explained on the basis of an increased use of carbohydrates in the tops, due to their combination with the nitrogen. This results in a decrease in the supply of carbohydrates for the roots, which may bring about a relative reduction in growth and in weight.

Results of this study indicate that depth of root concentration is governed to a greater extent by the inherent nature of the crop than by the physical or chemical properties of the soil. The depth of root concentration was not significantly different for any one soil type; however the individual crops showed some degree of variation.

The average depth of root concentration for each crop observed on the three soil types are as follows:

crimson clover, 7 inches

subterranean clover, 8 inches

Austrian winter peas, 10 inches

hairy vetch, 10 inches

common vetch, 10 inches

Although the soil types seem to have no effect on the zone of greatest root accumulation, the upper 12 inches in all three soils are most favorable to root growth since there is more soil porosity, more aeration, more organic matter, and a greater supply of soluble plant nutrients.

The depth to which roots penetrate, and their relative volume in the soil, especially in the upper portion, are important factors in determining the amount of organic matter a crop is capable of producing in the form of root residue. All five of the annual legumes included in this study produce root systems which would increase the amount of organic matter in the upper 12 inches of the soil; however, results indicate that Austrian winter peas, hairy vetch, and common vetch would be most productive in this respect.

The deep penetration of the roots into portions of the subsoil is most effective for increased soil aeration and drainage. Results show that Austrian winter peas are most suitable for the improvement of soil structure and aeration due to the coarse texture and the deeply-penetrating nature of the rooting system.

Nodulation was fairly abundant on the roots of all crops. Soil fertility appeared to have little effect on the numbers of nodules. It was observed, however, that during the period when the temperature increased the size of the nodules varied directly. This agrees with results found by Jones and Tisdale (14) in their work with annual legumes.

Nodulation on all crops occurred between 15 and 28 days after seeding.

SUMMARY

1. Crimson clover (Trifolium incarnatum), subterranean clover (Trifolium subterraneum), Austrian winter pea (Pisum arvense L.), hairy vetch (Vicia villosa), and common vetch (Vicia sativa L.) were observed periodically in order to determine the influence of soil type on root development.
2. Crops were seeded at standard rates on plots which had been previously fallowed one season.
3. The root systems were excavated from the soil by means of a stream of water under low pressure. This water was applied to the face of a trench which was dug 6 to 8 inches from the plant or plants to be removed.
4. Results of the study indicate that the structure and texture of the soil have a marked influence on the vertical growth of the roots, and that the lateral growth of the roots was most developed in the most fertile soils. It was also found that the number of lateral roots per three-inch section of taproot as well as lateral spread was least in the more compact regions of the soil profile.
5. Root and top growth were most marked in Chehalis clay loam, and they were least developed in Melbourne

clay. Plants grown in Willamette clay were slightly less developed than those grown in the Chehalis soil.

6. The top growth of these annual legumes is very slow during the early life of the plant since the young growth of these annual legumes is very slow during the early life of the plant since the young growth goes mostly to root development. A possible explanation for this condition is given.

7. Austrian winter peas, hairy vetch, and common vetch made the most rapid growth after seeding, and possess the most extensive rooting systems. It was apparent that crimson clover and subterranean clover develop the greater portion of their root systems during the early spring when day temperatures are on the increase. The weight of the tops also exceeded that of the roots during this later period.

8. Austrian winter peas and common vetch showed greatest capacity for root penetration. Their rooting systems were coarser than those of hairy vetch, crimson clover, or subterranean clover, and they were considered to be most effective in opening up the deeper channels of the soil for the improvement of soil aeration, drainage, and the addition of organic matter in the form of root residue.

9. The number of roots per linear inch decreased downward from the surface, and increased with the age of the plant.

10. The field of root study is one of opportunity, and there are yet many aspects to be studied pertaining to the ecological relations of roots.

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