# THE EFFECT OF APPLIED FERTILIZER AND OXYGEN DIFFUSION RATE ON THE GROWTH, YIELD AND CHEMICAL COMPOSITION OF PEAS

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# THE EFFECT OF APPLIED FERTILIZER AND OXYGEN DIFFUSION RATE ON THE GROWTH, YIELD AND CHEMICAL COMPOSITION OF PEAS

by

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## ABSTRACT


Growth of pea plants (Pisum sativum) and nutrient uptake were studied at a series of oxygen diffusion rates from 15 to 350 x $10^{-8}$gms/$cm^2$/min. and at three levels of applied fertilizer, low, medium and high. The same oxygen diffusion rates were maintained throughout the experiment.

At very low oxygen supply, soil fertility levels had little effect on growth, or on the number of peas produced. Increasing the rate of oxygen supply from 15 to 70 x $10^{-8}$gms/$cm^2$/min. increased growth and nutrient uptake at all fertility levels. High and medium fertilizer rates partially, but not completely, reduced the effects of low oxygen supply.

Oxygen diffusion rates above 70 x $10^{-8}$gms/$cm^2$/min. did not significantly increase growth, yield or nutrient uptake. Plants suffered from lack of oxygen if they were supplied at a rate less than 70 x $10^{-8}$ gm /$cm^2$ /min.

There was no consistent accumulation of nutrients in roots of plants growing under low oxygen supply. Roots of plants grown under oxygen stress were thicker, smaller and less fibrous than those where adequate supplies of oxygen were present.

The effects of short periods of oxygen deficiency on growth and nutrient uptake by peas, at different vegetative stages, and at three fertility levels, were also studied.

Short periods of oxygen deficiency just before blossoming and until peas were formed, caused a marked reduction in growth and yield, but did hot affect the mutrient uptake at high or normal fertility. At the low fertility level, nutrient uptake was lower in plants receiving inadequate oxygen. The effects of this treatment were partially alleviated at high fertility levels.

A reduction in the oxygen supply in the early stages of growth of pea plants had little effect on plant vigor or final yield. It was noted that 7 or 24 hours of low oxygen supply under conditions of this experiment had the same effect on reducing growth, dry matter production and seed yield.

## ACKNOWLEDGEMENT

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# I. INTRODUCTION

Many of the metabolic processes within higher plants are dependent on oxygen. Vital growth processes such as water absorption and nutrient uptake require energy from aerobic oxidation of a substrate or respiration (12). These processes and the resulting growth are limited by an inadequate oxygen supply.

It is the rate of supply of oxygen to the reducing surface of the root and not the absolute supply of oxygen in the soil air which is important in plant growth. Oxygen is supplied to plant roots mainly by diffusion down a concentration gradient from the atmosphere to the surface of the root. A convenient method of measuring the rate of diffusion using a platinum microelectrode devised by Lemon and Erickson (35) was used in these experiments.

This project was designed to study the relationship between plant growth and nutrient uptake, and oxygen supply.

Since the pore space occupied by air varies inversely with the moisture content of the soil, depth of water table was varied to obtain a series of oxygen diffusion rates. The garden pea plant, (Pisum sativum) which is sensitive to low oxygen supply, was studied over a range of oxygen diffusion rates from $15 \times 10^{-8}$ gm / cm$^2$/ min to over $300 \times 10^{-8}$gm /cm$^2$ / min.

The effect of fertility level under limited oxygen supply was also studied from the standpoint of growth and nutrient uptake in an effort to determine to what extent high fertility might alleviate a low oxygen supply. Three levels of fertilizer, low, medium and high which were obtained using inorganic fertilizers were compared over the entire range of oxygen diffusion rates.

The hypothesis that translocation rather than accumulation of nutrients is restricted by low oxygen supply (45) was also examined by comparing the nutrient content of the roots of plants growing under low oxygen supply to that of the plant parts above ground.

Under field conditions, plants are normally subjected to low oxygen supply only for short periods of time after heavy rains or flooding. The effect of low oxygen diffusion rates for 7 hours and for 24 hours on the growth of peas at eight stages of maturity was studied. The extent that fertility reduced the detrimental effects of short periods of low oxygen supply was also observed. Chemical composition of untreated plants and plants subjected to low oxygen diffusion rates for short periods were compared to determine if nutrient uptake was altered by short periods of low oxygen supply.

Although the water used to create low oxygen supply may influence plant growth, this method of producing oxygen deficiency closely simulates the method of low oxygen supply under field conditions.

# II. LITERATURE REVIEW

## 1. General Effect of Oxygen Supply on Plant Growth

There are many reports in the literature of the importance and the necessity of oxygen to plant growth. Sachs in 1860 obtained beneficial results by aerating his culture solutions. Oxygen supply may be critical with nutrieht solutions, since plants may extract the oxygen faster than it is dissolved in the solution (5).

Arike (3) in 1901 reported that the growth of lupine roots was more rapid in both soil and water cultures when a stream of air was passed through the culture media.

Free (21) suggested that there is a critical partial pressure of oxygen for normal or optimum growth, and a lower critical pressure below which there is no growth.

Loehwing (36) stated that continuoussoil aeration with moist air, increased size and growth rates of plants, but very rapid aeration had the opposite effect. He stated that excessive soil oxygen was possible under experimental conditions which might inhibit plant growth.

Arrington and Shive (5), Allison and Shive (1) and Knight (32) all stressed the importance of an ample supply of oxygen to the roots, and doubled or tripled yields by increasing the oxygen supply.

## 2. Requirement of Different Plant Species for Oxygen

Cannon (15) has shown that different species growing under the same conditions vary appreciably in their oxygen requirements. Peterson (40) suggested that species, such as salix found in soils saturated with water part of the year, were able to maintain root growth at low concentration of oxygen (.5 percent). However, other species such as soy beans and sugar beets, were sensitive to oxygen levels below 10 percent. Peterson also noted a difference in oxygen requirement with changes in temperature. More oxygen was needed at higher temperatures for an increased respiration rate. The effect of low oxygen was more pronounced at higher temperatures (13). Good aeration is necessary in hot weather.

## 3. Methods of Oxygen Absorption by Roots

It is not the absolute percent oxygen or the partial pressure that is important to plant growth, but the rate of delivering oxygen or oxygen diffusion rate, according to Free (21). Hutchins (30) also emphasized the importance of rate of movement of oxygen through the soil to the plant roots. Russell (43) believed that the evaluation of conditions at the interface between roots and soil system presents the greatest possibility of ascertaining the influence of soil aeration on plant growth. Active root surfaces are covered with a water film. Therefore, movement of oxygen from the atmosphere to the actively respiring cells of the plant involves diffusion through both gaseous and liquid phases. Under normal conditions, oxygen diffusion is down a concentration gradient from the atmosphere, to the soil atmosphere, to the water film around the cell, and then to the root cell wall and reducing region itself. Diffusion through the liquid phase is much slower than through the gaseous phase. Thickness of the water film around the root hair may be very important in determining the oxygen supply to the root. Low solubility of oxygen in water may also be a factor in lowering the supply of oxygen to the reducing surface of the root.

## 4. Effects of Low Oxygen Supply on Physiological Development

Low rate of oxygen supply has a marked effect on the physiological development of roots. Root branching, length, area of root surface and number of root hairs are all increased when deficient oxygen supply is increased (40). Root systems may vary in their structure, weight, extent, number, and orientation of their components, depending upon the chemical, and physical conditions under which they are grown (11). Anaerobic roots are devoid of root hairs and are slow growing (36). Under low oxygen supply there is a general reduction in the magnitude and rate of absorptive processes; resulting in a less vigorous top growth and pale foliage.

Sugar beet roots reflect the effect of poor aeration. Wiersma and Mortland (51) found that the length and shape of beets were related to oxygen diffusion rates. Under low oxygen diffusion rate, response to peroxide fertilization was obtained. The critical level of oxygen diffusion with sugar beets was reported as 20 to 30 x $10^{-8}$ gm/ sq. cm/ min. at the 4 inch depth. Smith and Cook (46) and Baver (8) noted a reduced yield of sugar beets under ample fertility because of poor aeration. The soil must be well aerated for good tapering roots. Aeration is particularly important for root crops. Maximum benefit from fertilizer may not be obtained without good aeration.

### 5. Oxygen Supply and Respiration

The question arises as to the function of oxygen in the physiological life of the plant which causes the observed responses to low rate of oxygen supply and beneficial results of good aeration. Respiration is an important process in plants, involving aerobic oxidation of a substrate releasing energy, carbon dioxide and water. Rate of respiration is a function, in part, of the oxygen supply and is limited under oxygen deficiency.

Respiration provides energy for endergonic reactions within plant cells. Therefore, respiration is essential to many of the basic reactions of the life of the plant.

### 6. Oxygen Supply and Nutrient Uptake

Nutrient uptake has been related to respiration. Conditions for maximum salt absorption and respiration coincide (47, 25). Maximum accumulation of electrolytes occurs under conditions which produce maximum aerobic respiration. Excised roots show little ability to accumulate electrolytes in the absence of aeration (47). Steward found that air was necessary for accumulation of bromide ion by potato tissue. A definite correlation was found between aerobic respiration and accumulation of potassium and bromide ions. Variables that affected rate of respiration also affected salt uptake. Steward Berry and Broyer (48) found 20 percent oxygen was maximum for the accumulation of potassium, whereas 3.8 percent oxygen permitted 70 percent efficiency in potassium uptake. Excised roots lost Potassium under partial oxygen prèssure of less than 1 percent but showed accumulation at 2.7 percent oxygen. Roots of most species studied, required as little as 0.5 percent oxygen for survival, but from 2 to 8 percent oxygen for maximum growth. Rate of oxygen supply was more important than oxygen content per se.

Danielson and Russell (18), using $Rb^{86}$ and moisture tensions up to 12 atmospheres, found that ion uptake was almost a straight line function of water content. Initial increases in oxygen concentration at each level of soil water resulted in increased $Rb^{86}$ uptake. Accumulation of $Rb^{86}$ by young corn was not significantly influenced by oxygen content above 10 percent oxygen. Both the critical oxygen level and the magnitude of the effect of oxygen on $Rb^{86}$ uptake decreased with increasing water tension.

Pepkowitz and Shive (39) emphasized the importance of oxygen and respiration for the absorption of all nutrients. They found 16 p.p.m. oxygen optimum for soy beans and 8 p.p.m. for tomatoes, and pointed out that oxygen might reach toxic levels. Respiration did not influence uptake of all ions equally.

Hoagland and Broyer (27) found that excised barley roots didn't accumulate nutrients in an atmosphere of nitrogen. Petrie (41), Arrington and Shive (5) stated that aeration of the root medium accelerated the absorption of salts.

Lawton (34) found that the percent K, N, Ca, Mg and P in the tissue was reduced under low oxygen levels in the order K-P-N-Ca-Mg. He also found that the percent of these nutrients increased in the plants by forced aeration.

It is the energy value of oxidation which is the factor most probably involved in ion uptake, according to Steward and Berry (48). The cells are kept in a high state of metabolism, supplying energy for ion uptake when aeration is satisfactory. The vital activity of growth with which ion uptake is associated, depends on oxygen supply.

Lundergardh and Burstrom drew a distinction between the absorption of cations and anions and concluded that respiration is especially concerned with anions. They suggested that anions require energy of respiration for absorption and that cations are absorbed passively. The cytochrome-cytochrome oxidase system functions in ion absorption. They suggested that a substance produced by metabolism acts as a carrier for anion absorption. Respiration may control ion absorption through the production of this carrier. They emphasized that it is the presence of anions which stimulates respiration and absorption. Lundegardh (37) suggested that it is the bicarbonate ion formed by respiration which plays a dominant role in ion uptake. A rise of carbon dioxide pressure in the solution increases the unequal absorption of anions over cations. Steward (47) speculated that respiration may supply ions for ionic balance and that respiration operates in an exchange of hydrogen or bicarbonate ions. There is no simple quantitative relationship between respiration and ion absorption but only a general parallelism. Systems which are actively accumulating ions use their carbohydrate supply rapidly; also showing the connection between ion accumulation and respiration.

7. Oxygen Supply and Water Uptake

There is a correlation between water uptake and respiration and aeration. L. C. Erickson (19) found that non aerated tomato plants showed a reduction of growth and water uptake. Hoffer (28) and Henderson (24) also pointed out the interrelationship between water uptake, oxygen supply, and respiration in the maintenance of favourable environment for corn roots. Kramer (33) stated that poor aeration caused poor water uptake, resulting in wilting and death of the roots. Bonner and Bandurski (12) have shown that water uptake is dependent on aerobic conditions. Increases in respiration for water absorption and osmotic work have been noted.

## 8. Oxygen Supply and Biological Activitiy

Most biological reactions that occur in the soil require oxygen. Oxygen supply may also affect plant growth indirectly (49). Microbial activity in the soil is dependent on oxygen supply and may be limited under anerobic conditions. This might have far reaching effects on the release of nutrients from minerals, decomposition of humus, and structure of the soil, which in turn affects the aeration. Oxygen prevents the accumulation of toxic substances, such as ferrous and manganous ions, alcohols, aldehydes, hydrogen sulfide and nitrites by keeping them in the oxidized states.

Clements (17) and Cannon (13) reported increased germination, root penetration, respiration and transpiration by increased aeration.

## 9. Soil Management and Oxygen Supply

Realizing the importance of good aeration in crop growth, it becomes imperative that practices be incorporated in soil management to encourage good aeration of the soil. Baver (8) suggested that the composition of the soil air depends upon the texture, structure, organic matter, water level, and climatic factors such as temperature, pressure, wind, and rain. A part of the favourable affects of minimum tillage have been ascribed to an improvement in soil air - water relations.

## 10. Fertilization and Oxygen Supply

Chang and Loomis (16) suggested the use of fertilizer to partially overcome the detrimental effect of poor physical structure and aeration. Shive (44) found that under low oxygen tensions, plants used oxygen from nitrates. He concluded that absorption of nitrates and ammonia are exact opposites at different oxygen tensions. He suggested the use of nitrate fertilizer under low oxygen tensions but emphasized that soils will hot respond to fertilizer if oxygen is deficient. Arnon (4) compared the effects of utilization of ammonia and nitrate on the growth of barley under low oxygen tensions. Lack of oxygen may be partially offset by adequate nitrate supply. He concluded that since the nitrate ion is absorbed as such, only nitrate ions already absorbed would be useful in alleviating oxygen deficiency.

Hamner (23) found a marked increase in the respiration rate from the applidation of nitrates to tomatoes at low oxygen supply rates, provided that the initial carbohydrate supply was high. Only 30 percent of the energy in the reduction of nitrate to ammonia was used in the reaction. The rest of the energy would be available for metabolic activity.

The extent that fertilization may alleviate inadequate oxygen supply merits more research.

## 11. The Effect of Carbon Dioxide Accumulation in the Soil on Plant Growth

The accumulation of carbon dioxide has been studied as the source of trouble under anaerobic conditions. Parker (38) concluded from his work that carbon dioxide added to the soil didn't alter ion absorption. Free (20), however, observed that carbon dioxide bubbled through the culture solution, caused injury in several hours and death in a few days to buckwheat; whereas similar treatment with nitrogen, oxygen or air had no injurious effect. Knight (32) applied the same treatment to corn and obtained a better correlation of growth with the inverse of the carbon dioxide supply than directly with oxygen concentration. Chang and Loomis (16) stated that toxic concentrations of carbon dioxide were probably more common than limiting oxygen concentrations of 1 - 2 percent oxygen. Erickson (19) disputed this point. He found that aerating tomatoes with a gas containing 28.8 percent carbon dioxide limited growth but felt that growth responses under high carbon dioxide were due to low oxygen supply and not the carbon dioxide accumulation.

Henderson (24) found that excess carbon dioxide reduced the absorption of water much sooner than oxygen deficiency does. He interpreted that the large decrease in water uptake with high carbon dioxide concentration resulted from changes in the permeability of the protoplasm and increased resistance across the cell wall to passive absorption.

Loehwing (36) pointed out that roots were injured by the accumulation of carbon dioxide and that high oxygen tensions were required or carbon dioxide became toxic.

Symptons of carbon dioxide toxicity are slow root growth, inadequate absorption, short lived discolored foliage and delay or failure of the reproductive system. It is difficult to separate the effects of high carbon dioxide concentration from those of low oxygen concentration under poor aeration. This is fundamental, however, before the effect of either may be studied.

12. Methods of Measuring the Oxygen Supply in the Soil

Several methods have been developed to measure the oxygen supply in the soil. Hutchins (30) used an oxygen free chamber buried in the soil and determined the amount of oxygen that had diffused into the chamber after a given period of time.

Taylor (49) suggested that a soil parameter $\lambda$ should be used as a relative measure of the rate of diffusion of gases through the soil. $\lambda$ was calculated by a lab procedure which involved measuring the rate of diffusion through a porous core containing no oxygen.

Raney (42) measured the rate of diffusion of oxygen from the soil into a chamber, that was first flushed with nitrogen by measuring the oxygen concentration in the chamber with a Beckman oxygen analyser after a measured time of diffusion.

These methods suffer from the common fault of measuring the absolute amount of oxygen in the soil rather than the rate of supply of oxygen to the root hairs. Another problem is that the soil is disturbed in making measurements and this is sure to affect the diffusion rate.

Hoffer (28) suggested that the relative amounts of ferrous and ferric ions in the soil suggest the state of aeration. Potassium thiocyanate gives a red color with the ferric ion, indicating good aeration; whereas a blue color with potassium ferricyanide indicates an accumulation of ferrous ion and poor aeration.

Blake (9) suggested that the potassium content of the plant indicated the state of aeration since potassium uptake is related to the oxygen supply. He suggested that the oxygen supply was reduced by compaction since the potassium content was reduced in plants growing on the compacted soil.

Lemon and Erickson (35) have devised a method of measuring oxygen diffusion in the soil that simulates closely the conditions experienced by the plant roots. Under certain conditions, the electric current resulting from the reduction of oxygen at a platinum surface is controlled solely by the rate oxygen diffuses to the electrode.

A voltage of 0.8 volts applied across the 4 mm. platinum electrode and the standard calomel cell resembles the reducing surface of a root hair. Since the electrode surface is surrounded by water, diffusion is through a gaseous and liquid phase as it is in nature. Calculations from the current flowing through the microammeter give a very good measure of the rate of oxygen diffusion to the root hairs. This method has been used by Archibald (2), Lemon (35), Jackson (31), Bertrand, and Kohnke (11) with good correlation to crop responses.

Many studies of soil aeration have lost meaning because the absolute supply, and not the diffusion of oxygen was measured. A continuous supply of a gas mixture with a given oxygen concentration is not a valid method of study of the effect of oxygen supply to plants, since the plants may extract enough oxygen from a continual supply of a gas of low oxygen concentration for normal growth.

## III. EXPERIMENTAL STUDIES

### A. Constant Oxygen Diffusion Rate Experiments

(1) PURPOSE

These experiments were designed to study the effect of soil fertility levels and oxygen diffusion rates on growth and nutrient uptake by field peas.

(2) GREENHOUSE

This study was conducted in the Plant Science Greenhouse at Michigan State University, East Lansing, Michigan. Peas grown in Experiment I, from October, 1956, to January, 1957, suffered from low light intensities and poor temperature control. The temperature reached 80° F at times. However, during Experiment II carried out from February 1957 to May 1957, the temperature was maintained at, or below 60° F during the early growth period and the sunlight was more intense.

(3) SOIL

The soil used for this experiment was Oshtemo sand obtained from the Rose Lake Conservation Area in Clinton County, Michigan. The soil was passed through a quarter inch mesh screen to remove the coarse material. Oshtemo sand is low in fertility and therefore was adaptable to an experiment in which the fertility was to be controlled by added fertilizer. The soil test of the original unfertilized Oshtemo sand showed 55 pounds K20 and 24 pounds P205.

(4) SOIL CONTAINERS

Glazed tile nine inches in diameter was cut into 4, 8, 10, 12, 16, 20, 24 inch lengths and used as soil containers in Experiment I. The bottom of each tile was covered with cheese cloth and three tile of each length were placed upright in galvanized metal trays 3" deep.

Because of some difficulty in obtaining the roots from glazed tile, galvanized stove pipe eight inches in diameter was used in Experiment II for soil containers. The sides of the pipe were sealed with a non-hardening pipe fitting cement. It was also concluded from Experiment I that a narrower range of container heights might provide a more critical study. Six heights of 4, 6, 8, 10, 12, 14 inches were used, with 4 replications of each fertilizer treatment at each container height in Experiment II.

(5) FERTILIZER

Three fertility levels were established by mixing $NH_4NO_3$, KCl and $Ca(H_2PO_4)2$ thoroughly with the soil. In Experiment I, the fertilizer was mixed with the whole soil mass. In Experiment II the fertilizer was limited to the top 6 inches of soil. The fertility levels for Experiment I and II are shown in Table I. The fertility level was found to be too high in Experiment I. and was reduced in Experiment II.

TABLE I

Fertilizer Added for Low, Medium and High Fertility Levels

| | EXPERIMENT I | | | EXPERIMENT II | | |
|---|---|---|---|---|---|---|
| | $NH_4NO_3$ | $P_2O_5$ | $K_2O$ | $NH_4NO_3$ | $P_2O_5$ | $K_2O$ |
| | Pounds per acre added | | | | | |
| LOW | 50 | 100 | 50 | 25 | 50 | 25 |
| MEDIUM | 200 | 400 | 200 | 100 | 200 | 100 |
| HIGH | 400 | 600 | 400 | 200 | 400 | 200 |

Fertilizer rates were applied on a weight basis and expressed in terms of pounds per acre, assuming that an acre to a depth of six inches weighs two million pounds.

(6) OXYGEN DIFFUSION LEVELS

The galvanized pans were filled with distilled water to a depth of two inches and this level was maintained throughout the experiments by adding distilled water. The percent pore space filled with air; and thus the oxygen diffusion rate depends on the height of the soil container when the water level is kept constant in the trays. A range of oxygen diffusion rates were thereby established and the plants were also subirrigated.

The oxygen diffusion rates at a depth of three inches in the soil in soil containers of different heights for Experiment I and II are shown in Table II. The oxygen diffusion rates to electrodes at the depths of 8, 12, 16 and 20 inches are also shown in Table II. Rank statistical analysis of these rates revealed the diffusion rate in the four and eight inch containers in Experiment I and in the four, six and eight inch containers in Experiment II were significantly lower at the one percent level than all containers of greater height. Diffusion rates in four inch containers were significantly lower than in those six inches tall. Similarly diffusion was significantly lower in the six inch container than in the eight inch container. Diffusion in the eight inch container was significantly lower than in the ten inch tall container and diffusion in the ten inch container was significantly lower than in the

TABLE II

Oxygen Diffusion Rates

## EXPERIMENT I

| Container Height | Gms $O_2 x10^{-8}/cm^2/min./$ at 3" Low | Medium | High |
|---|---|---|---|
| 4" | 14.6 | 15.6 | 15.9 |
| 8" | 69.6 | 67.2 | 54.5 |
| 10" | 272 | 288 | 302 |
| 12" | 330 | 342 | 364 |
| 16" | 380 | 372 | 358 |
| 20" | 387 | 396 | 352 |
| 24" | 396 | 378 | 347 |

| Dist. of Electrode to water table | gms $O_2 x10^{-8}/cm^2/min$ diffusing Low | Medium | High |
|---|---|---|---|
| 2" | 15.0 | 21.0 | 23.4 |
| 6" | 52.5 | 48.0 | 54.0 |
| 10" | 330 | 336 | 318 |
| 14" | 408 | 318 | 390 |

## EXPERIMENT II

Oxygen Diffusion at Three Inch Depth

| Container Height | Low | Medium | High |
|---|---|---|---|
| | gms $O_2 x10^{-8}/cm^2/min$ | | |
| 4" | 15.6 | 14.8 | 15.6 |
| 6" | 51.0 | 37.2 | 49.9 |
| 8" | 78.6 | 69.6 | 68.4 |
| 10" | 286 | 246 | 302 |
| 12" | 328.8 | 364.4 | 310.8 |
| 14" | 414 | 303.0 | 243.0 |

twelve inch container at the five percent level. However, no significant difference in diffusion rates were obtained between twelve, sixteen, twenty and twenty-four inch containers or in the twelve or fourteen inch containers. It is of interest to note there was no significant difference between the oxygen diffusion rate in containers of the same height with different fertility levels. The oxygen diffusion rate tended to increase in the 8, 10, 12 and 14 inch containers of Experiment II during the experiment, but this trend was not statistically significant. The oxygen diffusion rate decreased with depth or increased as the distance of the electrode from the water table increased.

(7) INDICATOR CROP

Garden peas were used as an indicator crop, since they are known to be sensitive to low oxygen diffusion rates and are adaptable to greenhouse production. Seeds of the 1956 crop of the variety "Green Seeded Perfection" were obtained from the Horticulture Department at Michigan State University. The seeds were treated with spergon dust to prevent rot. Twelve seeds were planted at a depth of one inch in each container on October 23, 1956 for Experiment I and on February 15, 1957 for Experiment II. The soil in the containers was watered uniformally from the top until emergence. After emergence was almost complete, distilled water was added to the bottom trays to a depth of two inches. Moisture was thus supplied by sub-irrigation throughout the experiment.

(8) REPLICATION

In Experiment I three replicates of the container at each of the seven heights for each fertility level were used. Experiment II involved eighteen combinations of three fertilizer levels and six container heights. With four replicates of each fertility level and container height, a total of 72 containers were set up.

(9) PLANT MEASUREMENTS

Individual emergence dates were noted for all replicates. The dates for the first plant to emerge, one-half of the plants to emerge and ten plants to emerge were recorded for each container. The height of the plants was taken as a measure of growth. Individual height measurements were taken at two day intervals in Experiment I and three day intervals in Experiment II. Measurements were made from the soil to the top of the highest unfolded leaf.

In Experiment I, the plants were thinned to 8 per container on November 17, the 25th day of the experiment, and to 4 plants per container on December 6, the 44th day of the experiment. On March 22, 1957, the 35th day of the experiment, the plants in Experiment II were thinned to three per container. All samples were dried, ground, and stored for chemical analysis.

The plants were mature and the pods well filled at the time of harvest on January 17, 1957, 86 days after planting in Experiment I and on May 15, 1957, the 89th day of Experiment II. Green and dry weights of the above ground plant parts and dry weights of the roots were determined as a measure of total growth. A method was devised for obtaining the roots by washing the sand through a ¼ inch screen, leaving the roots suspended on the screen. The metallic containers in Experiment II enabled much easier separation of the roots from the soil than the tile of Experiment I.

Yield was also measured in Experiment II in terms of green and dry weights of the peas, and the number of pods and peas.

Duplicate samples from each container height and each fertility treatment of roots and tops were dried, ground and stored for chemical analysis.

## (10)SOIL MEASUREMENTS

The platinum microelectrode method designed by Lemon and Erickson (34) and modified by Van Doren (50) was used to obtain the oxygen diffusion rate in each pot. Determinations were made every third day during growth of the first experiment and every third week of the second experiment. There was little change of oxygen diffusion rate during Experiment I. Readings were taken less often in Experiment II to avoid compaction and to reduce the number of holes in the soil, which might alter the oxygen diffusion rates.

Five elctrodes were inserted in the soil of each container to a depth of three inches and were used to obtain initial and five minute current readings when 0.8 volts were applied across the electrode and silver chloride standard cell.

Three permanent electrodes were also inserted to a depth of 20, 16, 12 and 8 inches in the 24 inch containers of Experiment I and the oxygen diffusion readings were measured with these electrodes every third day.

The current readings were corrected to a conductivity reading of 200 micro mhos. A large variation of conductivity was caused by different moisture content and salt concentration with the different treatments.

In Experiment I, growth was very poor in the 16, 20 and 24 inch containers with medium and high fertilizer rates. Soluble salt readings were made on the soil of all containers on January 15 and are shown in Table III.

Rapid soil tests were made for Nitrogen, Phosphorus, Potassium and Calcium at the end of Experiment I. Results are shown in Table IV. It is obvious that the high and medium fertilizer rates were too high particularly in the 16, 20 and 24 inch containers where the moisture content was low and there was little leaching of the salts or dilution of the solution .

Moisture content at the 3 inch depth of all tiles at the end of Experiment I was determined. Results are shown in Table V.

TABLE III

Conductivity Readings (mhos x $10^{-8}$) of the Soils in Experiment I at each of the Three Fertility Levels and Seven Container Heights

| Container Height(inches) | Fertility Level Low | Medium | High |
|---|---|---|---|
| 4 | 45 | 52 | 52 |
| 8 | 58 | 62 | 68 |
| 10 | 80 | 94 | 140 |
| 12 | 72 | 150 | 225 |
| 16 | 85 | 300 | 500 |
| 20 | 130 | 220 | 530 |
| 24 | 170 | 420 | 440 |

TABLE IV

Rapid Soil Test Results of Soils at the End of Experiment I at each of the Three Fertility Levels and Seven Container Heights

| Container | Low | | | | Medium | | | | High | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Height | $NO_3$ | P | K | Ca | $NO_3$ | P | K | Ca | $NO_3$ | P | K | Ca |
| 4 | 140 | 3.0 | 28 | 210 | 50 | 3.5 | 82 | 320 | 100 | 8 | 144 | 800 |
| 8 | 75 | 2.3 | 139 | 320 | 467 | 5 | 92 | 320 | 388 | 8.0 | 64 | 320 |
| 10 | 233 | 3.0 | .57 | 800 | 217 | 4.0 | 122 | 507 | 370 | 18.0 | 184 | 1200 |
| 12 | 323 | 1.7 | 300 | 800 | 367 | 4.0 | 300 | 800 | 400 | 10.3 | 137 | 1470 |
| 16 | 400 | 1.3 | 71 | 1000 | 400 | 3.7 | 300 | 933 | 400 | 9.7 | 418 | 1600 |
| 20 | 400 | 2.0 | 133 | 1325 | 400 | 5.3 | 218 | 1333 | 400 | 17.3 | 632 | 1600 |
| 24 | 400 | 2.0 | 96 | 1025 | 332 | 5.3 | 101 | 1200 | 270 | 21.7 | 717 | 1600 |

TABLE V

Average Percent Moisture at the Three Inch Depth of the Seven Container Heights at the End of Experiment I.

| Container Height (inches) | % Moisture |
|---|---|
| 4 | 25.3 |
| 6 | 24.8 |
| 10 | 20.7 |
| 12 | 15.9 |
| 16 | 10.0 |
| 20 | 6.4 |
| 24 | 3.9 |

(11) CHEMICAL ANALYSIS

Analysis for Nitrogen, Phosphorus, Potassium, Calcium and Magnesium was made on the root and top samples taken during the experiments. The total Nitrogen content was determined by the Kjeldahl procedure. In preparation for analysis for the Phosphorus, Potassium, Calcium and Magnesium one gram samples were wet ashed with nitric and perchloric acids and the ash dissolved in 0.1 N HCl and diluted to fifty ml. Phosphorus in the ash solution was determined colorimetrically by the molybdenun blue method using amino-naphthol-sulfonic acid as the reducing agent. Color intensity was measured with a Coleman colorimeter using light having a wavelength of 540 mu. Potassium in the ash solution was determined using the Perken Elmer and calcium and magnesium using the Beckman D.U. spectrophotometer. Adjustments of the Beckman Spectrophotometer are shown in Table VI.

TABLE VI

Adjustments of the Beckman Spectrophotometer for the Determination of Calcium and Magnesium

| | Ca | Mg |
|---|---|---|
| W L (mu) | 422.7 | 285.2 |
| Filter | Blue | Blue |
| Phototube resistor | 2 | 2 |
| selector | .1 | .1 |
| Slit width (mm.) | .01 | .15 |
| Photomultiplier sensitivity | full | full |
| Photomultiplier zero depression | 1 | 1 |

## B. Effect of Short Periods of Low Oxygen Diffusion Rate on Growth and Nutrient Uptake

PURPOSE

These experiments were designed to study the effect of short periods of low oxygen diffusion rates on growth of peas. A comparison was also made of oxygen stress on growth under low and high fertilizer treatments.

### (a) EXPERIMENT III

(1) CONTAINERS

Fifty glazed tile, eight inches in diameter and twenty-four inches in length were used as containers. The tile were placed in tins ten inches in diameter and thirteen inches tall. The containers were filled within eight inches of the top with silica sand and the top seven and one-half inches was filled with Oshtemo sand. The soil and silica sand were packed uniformally in the tile as they were filled.

(2) DESIGN OF EXPERIMENT

The experiment consisted of fifty containers. Twelve seeds of "Green Seeded Perfection" peas were planted on February 14, 1957 in each container and later were thinned to three plants per container. On February 26th after emergence was almost complete equal amounts of Shive's nutrient solution was supplied to each pot.

Periodically during the growth period plants in the five containers were subjected to low oxygen diffusion rates. The water level in these containers was raised to a depth of thirteen inches. By capillary rise and surface watering the pore space was filled with water and the roots subjected to low oxygen tension. The water was drained from the containers after seven hours with two of the containers and after twenty-four hours with the other three. Ten containers were left untreated. The plants were subjected to low oxygen tension on sunny days when the transpiration rates were high.

(3) PLANT MEASUREMENTS

Height measurements every third day were taken as a measure of growth. Yield records were obtained at the end of the experiment, including green and dry weight of peas and tops, number of pods and individual peas.

(4) CHEMICAL ANALYSIS

Analyses for nitrogen, phosphorus, potassium, calcium and magnesium of untreated and treated plants whose growth was most affected by the treatment were compared. The same methods of analysis used in section A were used in this experiment.

EXPERIMENT IV

Experiment IV was designed to study the effect of short periods of low oxygen tension on peas growing under low and high fertility levels.

Galvanized stove pipes 24 inches long and 8 inches in diameter were used as containers, which were placed in tins similar to Experiment III.

Oshtemo sand was packed uniformally in the containers and the top 6 inches of soil was fertilized with low and high rates used in Experiment II as shown in Table I.

"Green Seeded Perfection" peas were again grown as the indicator crop. Twelve peas were planted per container on March 6, 1957, and later thinned to four plants per pot.

The plants were subjected to low oxygen tension by the same method described in Experiment III. Two pots at each fertility level were treated at the time of blossoming and two pots at each fertility level were left untreated.

Growth and yield of plants were measured as in Experiment III and chemical analysis of treated and untreated plants was made on samples taken at time of harvest on May 21, 1957.

# IV RESULTS and DISCUSSION

## Part A

### (1) GROWTH

Fertilizer rates were too high in Experiment I as shown by soluble salt tests (Table III) and soil tests (Table IV). This condition severely limited growth particularly with high and medium fertilizer rates and with 16, 20 and 24 inch containers. With shorter containers the salt concentration was reduced by leaching or dilution from the higher moisture content. The rate of growth and the total height of plants at the low fertility level were greater with increases in oxygen diffusion from $14.6 \times 10^{-8}$ gm / $cm^2$/min in the 4 inch container. There was no significant difference between the height of plants with oxygen diffusion rates above $330 \times 10^{-8}$ gm/$cm^2$/min.

Growth in the 24 inch container was probably less than in the 16 and 20 inch containers because of the low moisture content (4 per- cent) from inadequate subirrigation, and does not reflect the effect of oxygen diffusion rate.

Growth in the 4 inch containers with oxygen diffusion rate of about $15 \times 10^{-8}$ gms/$cm^2$/min. was very much less than growth in the other containers. The plants looked unhealthy at time of harvest. The lower leaves were chlorotic and in many cases had dried and dropped.

At the time of sampling on November 17, the roots in containers where oxygen diffusion rate of $15 \times 10^{-8}$ gms $O_2/cm^2/min.$ were maintained in the 4 inch containers were beginning to rot. This root rot appeared more prevalent with the high fertilizer treatment than with the low or medium fertilizer treatment. When samples were taken on December 6, the roots of the containers with oxygen diffusion rates of $15 \times 10^{-8}$gm/ $cm^2/min.$ were black with no lateral root development. With higher rates of oxygen diffusion there was more lateral root development when plants receiving low and medium fertilizer rates were compared with those having high fertilization. Root development at the high fertilizer levels was restricted by the high salt concentration.

Growth in Experiment I may have been limited by low sunlight intensity and also by high temperatures. However, the growth was definitely limited by oxygen diffusion rates below $70 \times 10^{-8}$gms $O_2/cm^2/min.$

More adequate fertility levels and increased sunlight promoted much better growth in Experiment II. Greenhouse temperature was also maintained at 60 $^{\circ}$F during early growth. In Table I in the appendix, data of height measurements are presented at three day intervals for the entire experiment. In Table VI height measurements of plants are shown at four stages of growth. Statistical values from the analysis of variance of the March 17 growth measurements show that the fertilizer rate caused a significant increase in growth (at the 1 percent level). Medium and high fertilizer rates produced an increase in growth over low fertilization at all container heights with the exception of when the oxygen diffusion rate of $15 \times 10^{-8}$ gms/$cm^2/min.$ was maintained.

TABLE VII

The Effect of Fertilization and Oxygen Diffusion Rate on Plant Height at Different Stages of Growth

| DATE | March 17 | April 1 | April 22 | May 7 |
|---|---|---|---|---|
| No. of days after planting | 30 | 44 | 65 | 80 |
| Oxygen Diffusion Rate | | HIGH FERTILITY | | |
| 15.6 | 8.4 | 23.1 | 37.5 | 36.4 |
| 49.9 | 9.6 | 27.1 | 58.2 | 61.9 |
| 68.4 | 8.8 | 25.2 | 67.8 | 74.7 |
| 302 | 8.6 | 24.2 | 65.8 | 82.4 |
| 310.8 | 7.6 | 19.0 | 54.0 | 75.6 |
| 243 | 7.7 | 22.0 | 55.7 | 84.7 |
| | | MEDIUM FERTILITY | | |
| 14.8 | 8.6 | 21.7 | 37.2 | 36.9 |
| 37.2 | 8.7 | 24.5 | 58.3 | 62.1 |
| 69.6 | 9.0 | 28.1 | 73.3 | 84.8 |
| 246 | 9.0 | 24.9 | 68.4 | 89.8 |
| 364.4 | 8.9 | 25.9 | 70.7 | 95.3 |
| 303.0 | 9.1 | 21.6 | 57.7 | 80.7 |
| | | LOW FERTILITY | | |
| 15.6 | 6.0 | 11.3 | 19.9 | 20.6 |
| 51.0 | 7.0 | 13.8 | 27.9 | 31.2 |
| 78.6 | 6.7 | 13.5 | 32.2 | 40.4 |
| 286 | 6.8 | 14.4 | 34.8 | 44.8 |
| 328 | 7.0 | 15.1 | 38.6 | 50.7 |
| 414 | 6.3 | 12.6 | 31.2 | 41.4 |
| LSD.05 | 1.72 | 5.3 | 7.5 | 8.3 |
| LSD.01 | 2.2 | 8.6 | 9.9 | 11.0 |

Similarly April 1 differences in growth were due to fertilizer rates and not to oxygen diffusion rates.

Pea plants do not measurably respond to low oxygen diffusion levels during early stages of growth under conditions of this experiment.

However, the analysis of variance of height measurements made on April 22 revealed a significant difference in growth due to both fertilizer and oxygen diffusion rate. The growth of pea plants which received the medium and high fertilizer treatment was significantly greater than the growth where the low rate of fertilizer was applied at all oxygen diffusion rates.

The fertilizer partially overcame the limiting oxygen diffusion rates. However, growth was significantly increased with increasing oxygen diffusion rates from 15 to 70 x $10^{-8}$gms $O_2/cm^2$/min. with the medium and high fertility levels. With all fertilization levels, growth was significantly lower, with oxygen diffusion rates lower than 70 x $10^{-8}$gm/$cm^2$/min. The fertilizer partially alleviated the oxygen deficiency.

Again it was noted on May 7 that differences in growth were due to both fertilizer and oxygen diffusion rates. Rate of growth was very much lower at low oxygen diffusion rates at all fertility levels in later stages of growth. After April 22, there was very little growth at any of the fertility levels in containers where oxygen diffusion rates were below 70 x $10^{-8}$gms/$cm^2$/min. With higher oxygen diffusion rates the plants continued to grow till May 7. Growth-time curves for high, medium and low fertilizer rates respectively, are shown in Fig. I, II and III. Data in Fig. IV show the variation of growth with oxygen for the medium

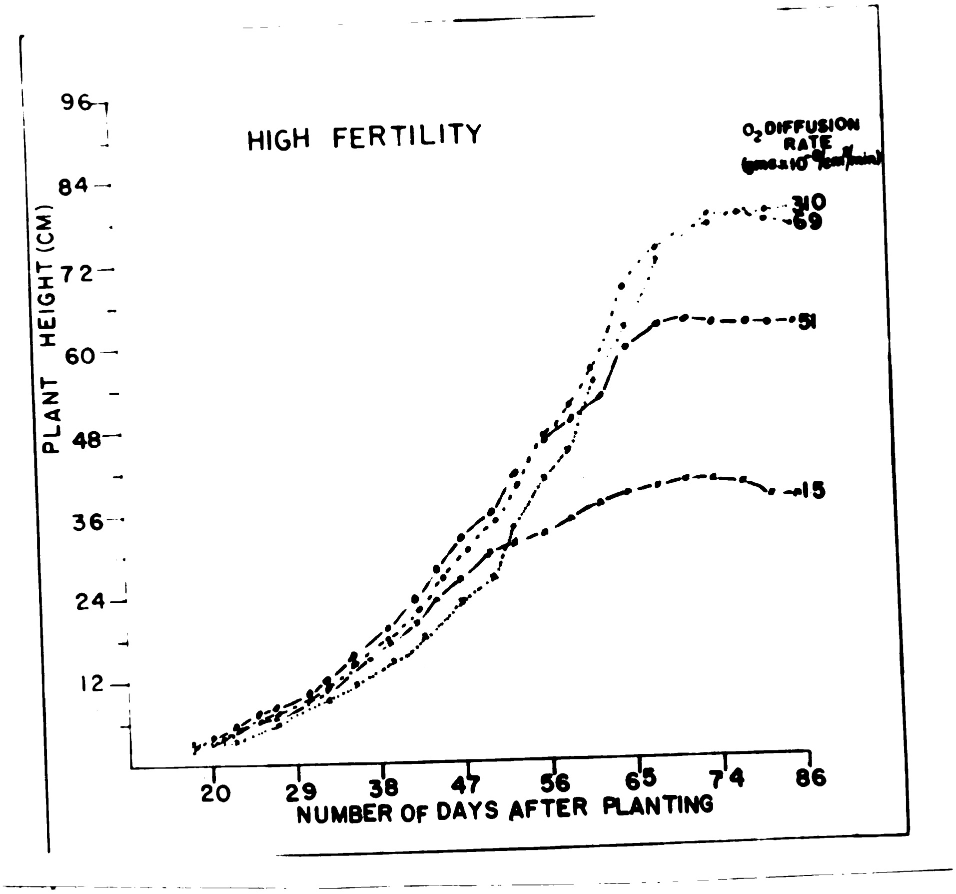


FIGURE I - The effect of oxygen diffusion rate at high fertility on the growth of pea plants.

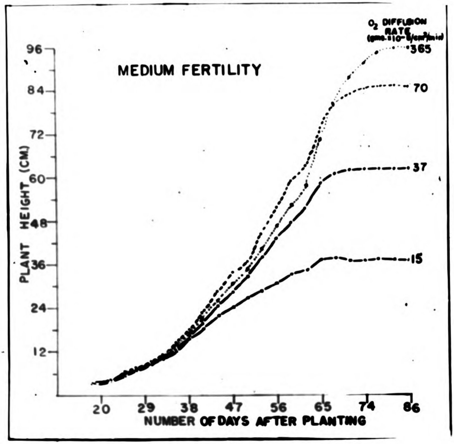


FIGURE II - The effect of oxygen diffusion at medium fertility on the growth of pea plants.

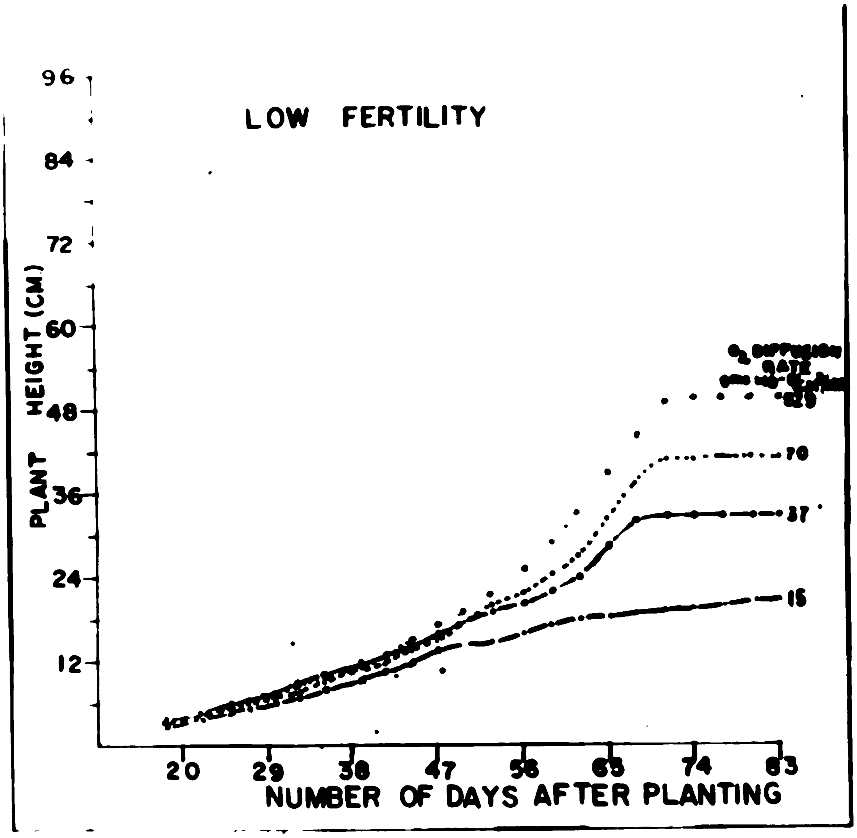


FIGURE III - The effect of oxygen diffusion rates at low fertility on the growth of pea plants.

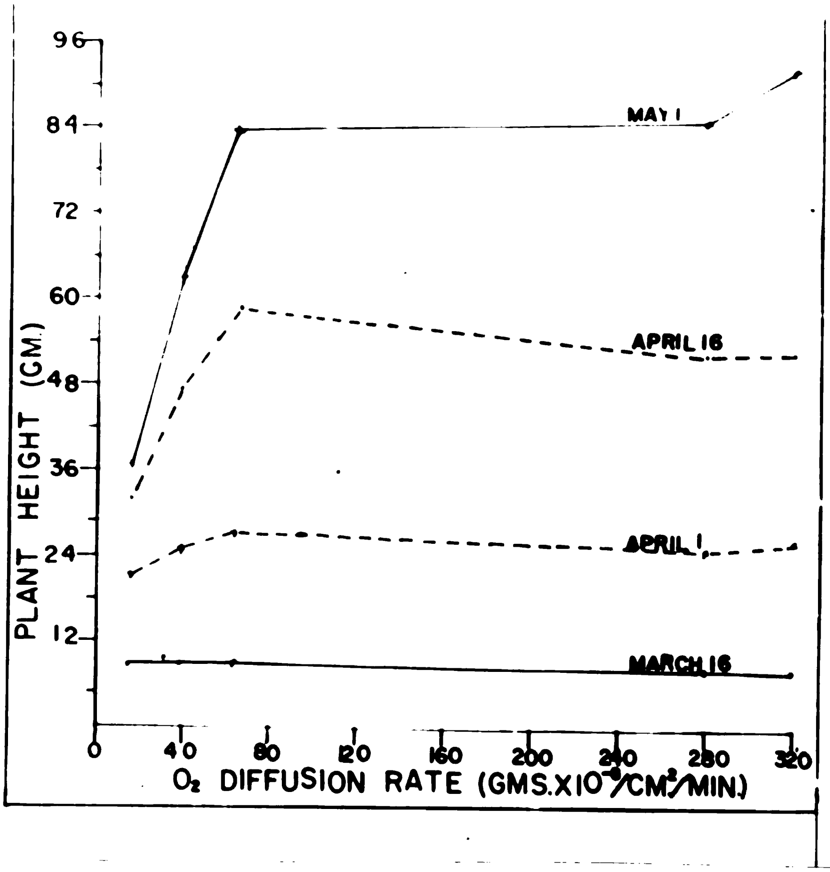


FIGURE IV - The effect of oxygen supply on the growth at four stages of development at the medium fertility rate.

fertilizer level at four stages of growth. These graphs show clearly that the oxygen diffusion rate has a much greater influence on the later stages of pea growth than on early stages of plant development. It was not until 45 days from the time of planting that differences in growth appeared because of different oxygen diffusion rates at medium and high fertilization and 53 days at the low fertilizer rates. Growth was limited by low fertility as well as low oxygen diffusion rates and the effect of low oxygen diffusion did not show until later stages in growth than it did when there was adequate fertilizer. An increase in oxygen diffusion rates above 70 x $10^{-8}$gms $O_2/cm^2$/min had little influence on growth.

Plates I, II and III show the effect of increasing oxygen diffusion rates in Experiment II on the height and general vigor of plants at high, medium and low fertilization respectively. Growth was very much reduced by low oxygen diffusion rates at all fertilizer rates. Plants in the short pots had a lack of vigor, leaves were chlorotic and dry. Colors in plates IV and V show the pale foliage and discoloration at low diffusion rates. Plates VI and VII show the effect of increased fertilization on growth at oxygen diffusion rates of 15 and 70 x $10^{-8}$gm/$cm^2$/min respectively. Even at low oxygen diffusion rates, high fertilization increased growth. But high and medium fertilizer rates increased growth considerably more at oxygen diffusion rates of, or greater than, 70 x $10^{-8}$gms/ $cm^2$/min.

Plates VIII, IX and X show root development at high, medium and low fertility levels respectively at the six container heights of


PLATE I - The effect of oxygen diffusion rate on growth and vigor of pea plants at high fertility rate in Experiment II.


PLATE II - The effect of oxygen diffusion rate on growth and vigor of pea plants at medium fertility rate in Experiment II.


PLATE III - The effect of oxygen diffusion rate in growth and vigor of pea plants at low fertility rate in Experiment II.

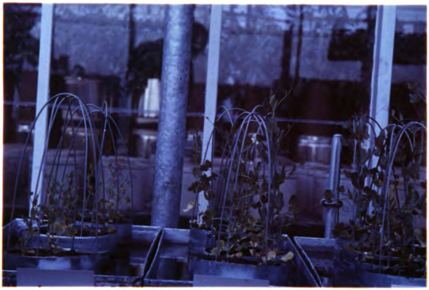

PLATE IV - The effect of fertility on color and vigor of pea plants at oxygen diffusion rates of 15 x $10^{-8}$ gms/$cm^2$/min.

LOW MED. HIGH

PLATE V - The effect of fertility on color and vigor of pea plants at oxygen diffusion rates of 70 x $10^{-8}$ gms/$cm^2$/min.

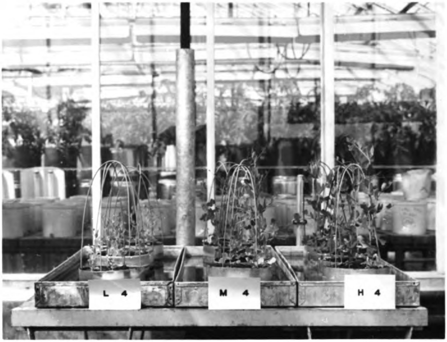


PLATE VI - The effect of fertilization on growth of pea plants at oxygen diffusion rate of $15 \times 10^{-8}$ gms/cm$^2$/min.


PLATE VII - The effect of fertilization on growth of pea plants at an oxygen diffusion rate of $70 \times 10^{-8}$ gms/cm$^2$/min.

PLATE VIII - The effect of oxygen diffusion rate (container height) on root development and nodule formation at high fertilization.

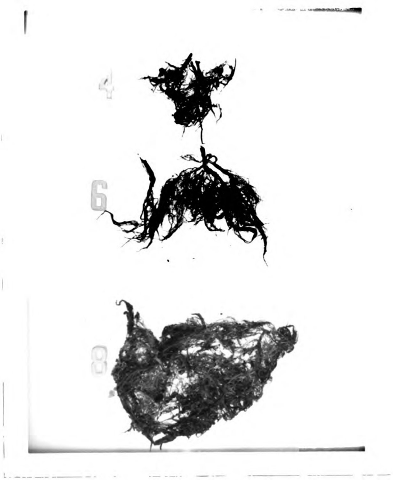


PLATE IX - The effect of oxygen diffusion rate (container height) on root development and nodule formation at medium fertilization.

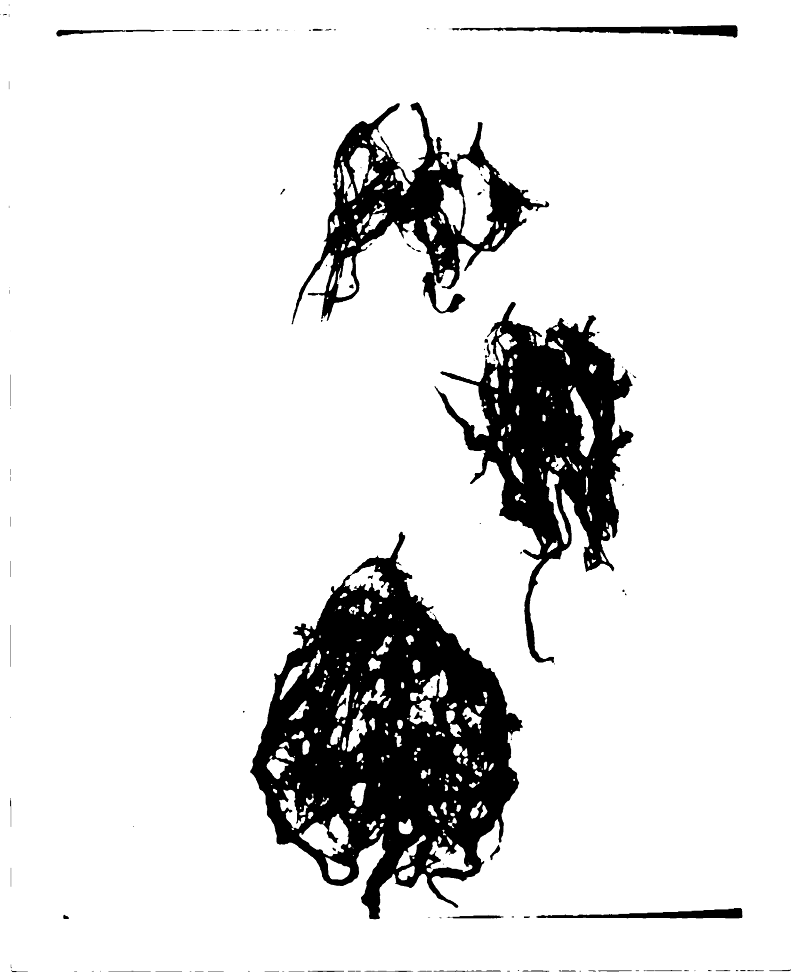

PLATE X - The effect of oxygen diffusion rate (container height) on root development and nodule formation at low fertilization.

Experiment II. Under low aeration, roots were much thicker with a marked reduction in lateral root development. There were no nodules in roots in the four inch containers and very few on roots of six inch containers. However, under ample aeration, nodule formation was very profuse, particularly under high and medium fertilization. In the taller containers the root system was much longer and more fibrous with finer roots which more thoroughly explored the soil mass. In all cases, the root system extended almost to the water table and there abruptly stopped. Lack of a well developed root system explains in part reduction in top growth due to poor aeration.

(2) YIELDS

Green and dry weight of tops and dry weight of roots are shown in Table VIII.

It is unfortunate that so many of the plants grown at the medium and high fertilizer levels failed to mature. With the low fertilizer treatment the green and dry weights of the tops increased with increasing oxygen diffusion rates from $15 \times 10^{-8}$gms $O_2/cm^2$/min to $350 \times 10^{-8}$gm.

In all cases the green and dry weights of the tops were lowest with oxygen diffusion rates of $15 \times 10^{-8}$gms/$cm^2$/min. There was little difference in yield between fertilizer levels at this low oxygen diffusion rate. However at $70 \times 10^{-8}$gms/$O_2/cm^2$/min there was an increase in green and dry weights with increasing fertilizer. The detrimental effect of

TABLE VIII

Average Yield Per Pot (4 plants) in Experiment I expressed as Green and Dry Weight of Tops and Dry Weight of Roots in gms.

| Oxygen Diffusion Rate $gms/cm^2/min.$ | Green Weight Tops | Dry Weight Tops | Dry Weight Roots |
|---|---|---|---|
| | HIGH FERILITY | | |
| 15.9 | 2.70 | 0.84 | - |
| 54.5 | 55.8 | 7.56 | 1.43 |
| 302 | 35.6 | 4.43 | .95 |
| 364 | 24.9 | 3.21 | .35 |
| | MEDIUM FERILITY | | |
| 15.6 | 3.6 | 0.90 | - |
| 67.2 | 23.0 | 3.80 | 0.80 |
| 288 | 24.4 | 4.20 | 1.00 |
| 342 | 34.1 | 5.07 | 1.31 |
| 372 | 32.0 | 4.19 | 1.24 |
| | LOW FERTILITY | | |
| 14.6 | 3.20 | 1.63 | - |
| 69.6 | 18.1 | 3.90 | 1.55 |
| 272 | 22.1 | 4.81 | 1.65 |
| 330 | 28.6 | 5.28 | 1.71 |
| 380 | 31.2 | 5.36 | 1.44 |
| 387 | 32.5 | 5.08 | 1.26 |
| 396 | 26.0 | 4.58 | 1.11 |

low oxygen diffusion rate was reduced by high fertility at oxygen diffusion rates of 70 x $10^{-8}$gms $O_2/cm^2/min$.

The weight of roots followed the same trend as the tops. With low and medium fertilization the root weight increased with increasing oxygen diffusion rates up to about 350 x $10^{-8}$gms/$cm^2$/min. The decrease in root and top weights in containers of heights greater than 16 inches high was likely due to low water supply rather than the oxygen diffusion rate.

Yield data from Experiment II are shown in Table IX.

The number of pods, number of peas, green and dry weights of peas and tops, and dry weight of the roots were significantly higher with high and medium fertilization than with the low level, with the exception of oxygen diffusion rates less than 70 x $10^{-8}$ gms $O_2/cm^2/min$. The influence of oxygen diffusion rate and fertility on the weight of peas is shown graphically in Figure V.

Yields were significantly lower with the lowest oxygen diffusion rate than all yields with all other oxygen diffusion rates with medium and high fertilization. Yield was increased significantly with each increase in container height with high fertilization with the exception of the 12 inch container. Similarly with the medium fertilizer level the yield was increased significantly in most cases with increasing container height up to 12 inches. The yield with the 14 inch container was significantly lower than that from the 12 inch container.

At the low fertility level the yield tended to increase with increasing oxygen diffusion rates with container heights up to 12 inches.

TABLE IX

Average Yield Per Pot (3 plants) Experiment II

| Oxygen Diffusion Rate $gmsO_2x10^{-8}/cm^2/min.$ | No. Pods | No. Peas | G.Wt. Peas gms. | D. Wt. Peas gms | G.Wt. Tops gms. | D.Wt. Tops gms. | D.Wt. Roots gms. |
|---|---|---|---|---|---|---|---|
| | | | High Fertility | | | | |
| 15.6 | 3 | 2.0 | 5.09 | 0.2 | 7.86 | 3.72 | .48 |
| 49.9 | 9.5 | 28.7 | 16.70 | 4.62 | 39.76 | 9.92 | 2.31 |
| 68.4 | 14.5 | 84 | 44.71 | 11.52 | 89.33 | 18.39 | 3.82 |
| 392. | 20 | 131 | 67.82 | 16.35 | 156.14 | 27.21 | 4.84 |
| 310 | 17.8 | 112.8 | 44.3 | 9.35 | 133.42 | 22.41 | 3.65 |
| 243 | 22.0 | 143.5 | 54.0 | 11.32 | 163.64 | 28.51 | 4.83 |
| | | | Medium Fertility | | | | |
| 14.8 | 3.0 | 7.25 | 2.90 | 0.89 | 8.82 | 2.65 | .72 |
| 37.2 | 9.7 | 24.25 | 11.57 | 3.10 | 25.26 | 6.22 | 1.76 |
| 69.6 | 11.8 | 54.0 | 28.87 | 7.72 | 66.82 | 14.70 | 3.39 |
| 246 | 16 | 106 | 53.90 | 11.26 | 127.61 | 24.06 | 4.60 |
| 364 | 24 | 155 | 55.63 | 11.22 | 169.5 | 29.38 | 4.80 |
| 303 | 17.8 | 117 | 38.47 | 7.40 | 118.62 | 22.23 | 4.67 |
| | | | Low Fertility | | | | |
| 15.6 | 2.3 | 2.8 | 0.52 | 0.14 | 2.76 | .93 | .66 |
| 51.1 | 3.0 | 11.0 | 4.63 | 1.13 | 8.33 | 2.10 | 1.67 |
| 78.6 | 4.5 | 25.3 | 13.04 | 3.05 | 22.06 | 4.38 | 2.64 |
| 286 | 5.8 | 29.5 | 14.59 | 3.19 | 27.98 | 5.33 | 2.77 |
| 328 | 6.0 | 33.3 | 18.05 | 4.04 | 35.65 | 6.73 | 2.78 |
| 414 | 5.0 | 25.5 | 13.29 | 2.91 | 19.14 | 4.10 | 2.89 |
| LSD .05 | 3.5 | 21.9 | 7.40 | 2.30 | 19.22 | 3.14 | 0.93 |
| LSD .01 | 4.65 | 29.0 | 9.81 | 3.05 | 25.43 | 4.24 | 1.23 |

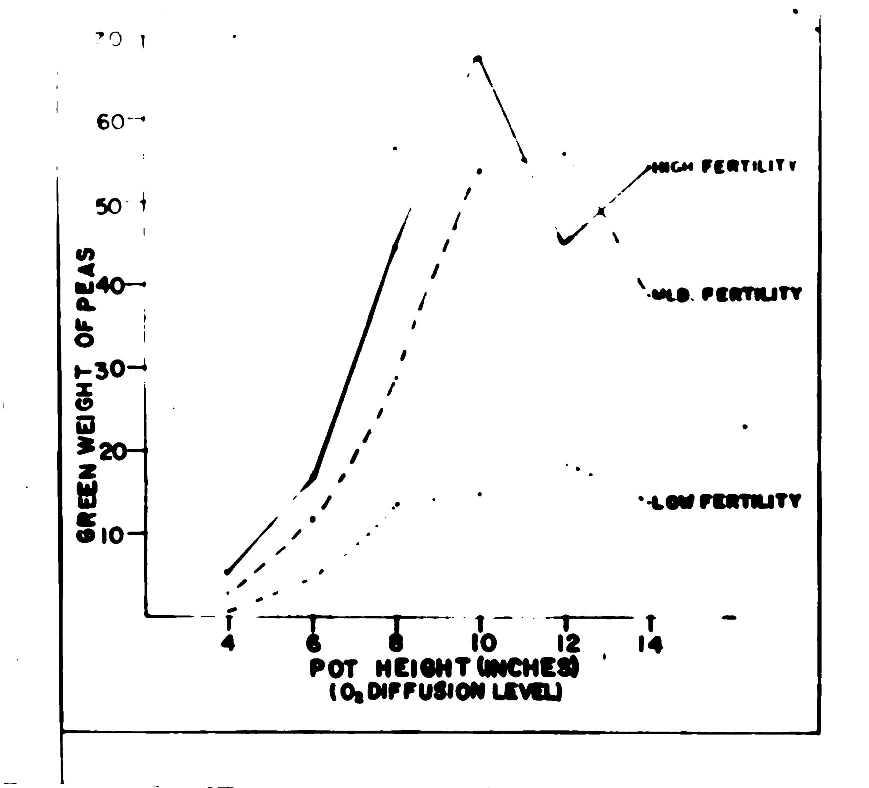


FIGURE V - The effect of fertilizer rate and oxygen diffusion rate (Pot height) on the green weight of peas.

Differences were not nearly as great as with the medium and high fertilizers. Generally the 10 and 12 inch containers had significantly higher yields than the 4 inch containers. There was a decrease in yield of plants grown in the 14 inch containers over that of plants from the 12 inch containers.

Yield data, like that of growth measurements, emphasizes the importance of an ample oxygen supply to the plants for growth and reproduction. There seems to be a critical rate of oxygen supply below which the plant is unable to function. With peas this critical diffusion rate is 70 x $10^{-8}$gm/$cm^2$/ min.

Fertilizer partially overcame the effects of a low oxygen diffusion rate. This was particularly noticeable in the 6 inch containers. The green weight of the peas was 16.7 gms with high fertility and 4.63 gms with low fertility. Only under optimum oxygen diffusion conditions did the dry weight of plants grown under low fertility exceed that of plants from the high fertilizer treatment under restricted aeration. At very low oxygen diffusion rates (15 x $10^{-8}$gm. $O_2/cm^2$/min) high fertilization had no effect in increasing yields.

(3) CHEMICAL ANALYSIS

The chemical analysis of samples from Experiment 1 are shown in Table II in the appendix and of samples from Experiment I[I] in Table X.

The percent nitrogen, phosphorus and potassium generally was higher in samples with medium and high fertilizer treatments than with low fertilizer treatment. The calcium and magnesium was higher with low

TABLE X

Chemical Analysis of Samples from Experiment II

| Oxygen Diffusion gm x $10^{-8}$ $cm^2$/min | March 22, Tops N | P | K | Ca | Mg | May 15, Tops N | P | K | Ca | Mg | Roots N | P | K | Ca | Mg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | High Fertility | | | | | | | | |
| 15.6 | 3.69 | .40 | 3.17 | .61 | .09 | 2.37 | .25 | 1.17 | 4.52 | .33 | 2.24 | .32 | 0.40 | 2.20 | .30 |
| 49.9 | 5.34 | .66 | 3.83 | .75 | .09 | 1.36 | .24 | 1.27 | 3.06 | .25 | 1.72 | .29 | 1.32 | 3.43 | .45 |
| 68.4 | 5.02 | .69 | 3.70 | .78 | .11 | 1.64 | .26 | 1.07 | 2.57 | .21 | 2.03 | .51 | 2.14 | 3.14 | .52 |
| 302 | 4.80 | .54 | 2.98 | .88 | .14 | 2.71 | .31 | 1.52 | 1.80 | .18 | 2.05 | .72 | 2.38 | 2.82 | .51 |
| 310 | 4.71 | .48 | 2.66 | .71 | .11 | 2.41 | .32 | 1.99 | 2.05 | .20 | 2.13 | .78 | 2.53 | 3.19 | .52 |
| 243 | 4.82 | .49 | 3.21 | 1.02 | .17 | 2.59 | .34 | 2.72 | 2.02 | .20 | 2.33 | .77 | 2.25 | 2.67 | .56 |
| | | | | | | | Medium Fertility | | | | | | | | |
| 14.8 | 3.40 | .37 | 2.42 | .50 | .15 | 1.47 | .21 | 1.03 | 2.80 | .26 | 1.94 | .26 | 0.83 | 3.30 | .44 |
| 37.2 | 4.30 | .53 | 3.06 | .75 | .17 | 1.40 | .21 | 0.89 | 2.75 | .28 | 1.96 | .20 | 1.17 | 2.60 | .46 |
| 69.6 | 4.15 | .73 | 3.69 | .97 | .21 | 1.60 | .25 | 0.88 | 1.82 | .19 | 1.93 | .26 | 1.09 | 2.15 | .51 |
| 246 | 4.12 | .63 | 3.35 | .98 | .23 | 2.29 | .25 | 1.14 | 1.95 | .21 | 2.11 | .31 | 1.15 | 2.10 | .61 |
| 364 | 4.92 | .63 | 3.60 | 1.14 | .29 | 2.65 | .28 | 1.50 | 1.95 | .22 | 2.11 | .36 | 1.20 | 2.07 | .58 |
| 303 | 4.19 | .59 | 3.11 | 1.14 | .29 | 2.41 | .27 | 1.88 | 1.70 | .20 | 2.17 | .39 | 1.24 | 1.97 | .52 |
| | | | | | | | Low Fertility | | | | | | | | |
| 15.6 | 2.02 | .21 | 1.28 | .47 | .32 | 1.02 | .15 | 1.11 | 3.46 | .38 | 1.29 | .11 | 0.32 | 2.45 | .40 |
| 51.0 | 1.86 | .25 | 1.65 | 1.51 | .24 | 1.85 | .17 | 1.00 | 2.20 | .26 | 1.51 | .12 | 0.69 | 1.65 | .36 |
| 78.6 | 2.47 | .24 | 2.00 | 1.60 | .22 | 2.23 | .19 | 1.02 | 2.10 | .28 | 1.94 | .19 | 1.45 | 2.45 | .45 |
| 286 | 2.86 | .26 | 2.13 | 1.88 | .25 | 2.19 | .20 | 1.03 | 2.00 | .25 | 1.92 | .21 | 1.82 | 2.15 | .46 |
| 328 | 3.08 | .23 | 2.20 | 2.01 | .21 | 2.31 | .19 | 1.32 | 2.12 | .27 | 2.07 | .19 | 1.61 | 2.00 | .41 |
| 414 | 3.42 | .22 | 1.95 | 2.33 | .25 | 2.36 | .24 | 1.36 | 2.07 | .26 | 2.09 | .19 | 1.77 | 2.02 | .37 |
| LSD.05 | 0.33 | .05 | .25 | .15 | .02 | 1.27 | .04 | .67 | 1.30 | .04 | .21 | .18 | ..27 | .48 | .11 |
| LSD.01 | 0.46 | .06 | .34 | .22 | .03 | 1.69 | .05 | .89 | 1.52 | .05 | .28 | .24 | .36 | .59 | .14 |

fertilizer treatment than with high fertilizer in March 22 samples but this was not significant in the May 15 samples.

There was a definite effect of oxygen diffusion rate on plant composition. Nitrogen, phosphorous and potassium content tended to increase with increasing oxygen diffusion rates at all fertility rates and all sampling dates. This trend was more pronounced at low fertility levels than at high. The percent nitrogen phosphorus potassium in the March 22 samples was significantly lower at oxygen diffusion rates of 15 x $10^{-8}$gms/$cm^2$/min than at all other rates at medium and high fertilizer rates. Nutrient uptake was definitely reduced in early stages of growth by low oxygen supply. However, the nitrogen, phosphorus and potassium content was significantly higher in the high and medium fertilizer treatments than with low fertilization. The plants were able to take up more nitrogen, phosphorus and potassium if there was more available and thereby partially alleviated the lack of oxygen.

Nitrogen, phosphorus and potassium content of the May 15 root and top samples increased with increasing oxygen diffusion rates up to 70 x $10^{-8}$gms/$cm^2$/min. Above this rate of diffusion there was little correlation of nutrient content and oxygen diffusion rate. This would suggest that as with the growth and yield that the critical level of oxygen diffusion for peas is 70 x $10^{-8}$gm/$cm^2$/min.

Figure VI shows the general increase in nitrogen, phosphorus and potassium content with increases in oxygen diffusion rate and fertilizer rate. Calcium and magnesium tended to accumulate in the tops under low oxygen supply.

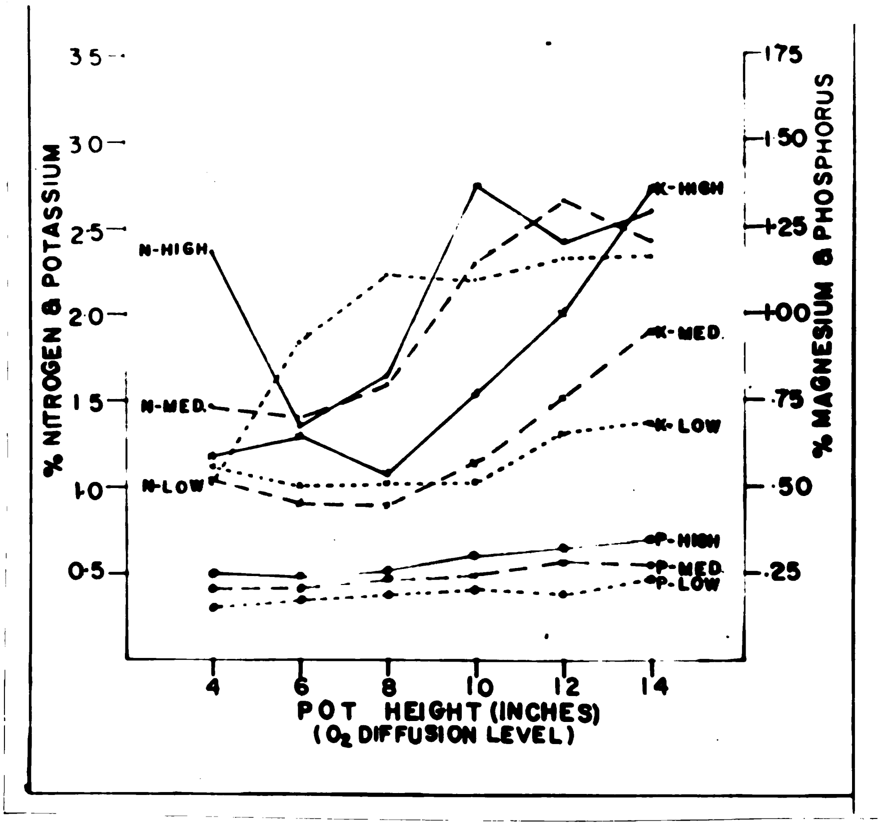


FIGURE VI - The effect of fertilizer rate and oxygen diffusion level (container height) on plant composition.

Comparison of root and top analysis showed a slight accumulation of nitrogen, phosphorus and potassium in the roots. There was no consistent accumulation in plants low in oxygen supply. Roots showed the same increases in nutrient content with increases in oxygen diffusion rates up to 70 x $10^{-8}$gms/$cm^2$/min. Oxygen supply affected nutrient uptake but did not appear to affect translocation. A smaller root system under low oxygen diffusion rates may partially explain the reduction in nutrient uptake at low oxygen supply.

The high fertilizer rates of Experiment I were reflected in the composition of all plant samples of the high and medium fertilizer treat0 ments of Experiment I. There was a very noticeable effect of increased diffusion rates on plant composition. The nitrogen and potassium content tended to increase with increased oxygen diffusion rate in all samples and the phosphorus and magnesium content increased in the samples taken when the plants were mature.

It seems apparent that nutrient uptake is dependent upon oxygen supply at all stages of growth. Differences in composition due to different oxygen diffusion rates were greater when the plants were mature.

## V RESULTS and DISCUSSION

### Part B

Figure VII shows the growth curve for plants in Experiment III. Stage of growth at which the plants were subjected to low oxygen diffusion rates is also indicated. Height measurements are presented in Table III in the appendix. The stage of growth at the time that the plants were subjected to low oxygen supply had a very marked effect on the final height of the plants. Plants subjected to low oxygen diffusion rates fifty-four days after planting, just before blossoming, were most affected by treatment. Treatment during pod formation while peas were forming also reduced growth. Treatment during early stages had little effect on growth. Average yields are shown in Table XI. There was a significant decrease in the number of pods, number of peas, dry weight of the peas and in the green and dry weight of the tops of plants subjected to 7 or 24 hours of oxygen deficiency 54 days after planting. Dry weight of the peas tended to increase with treatment at early stages of growth. This was perhaps due to earlier maturity.

Low oxygen supply at certain stages of growth had an adverse effect on plant metabolism which resulted in lower yields and growth. The stage of growth of low oxygen supply was very important in determining the extent of this effect. Length of the low oxygen supply used in this experiment does not alter the extent of growth or yield. Shorter times

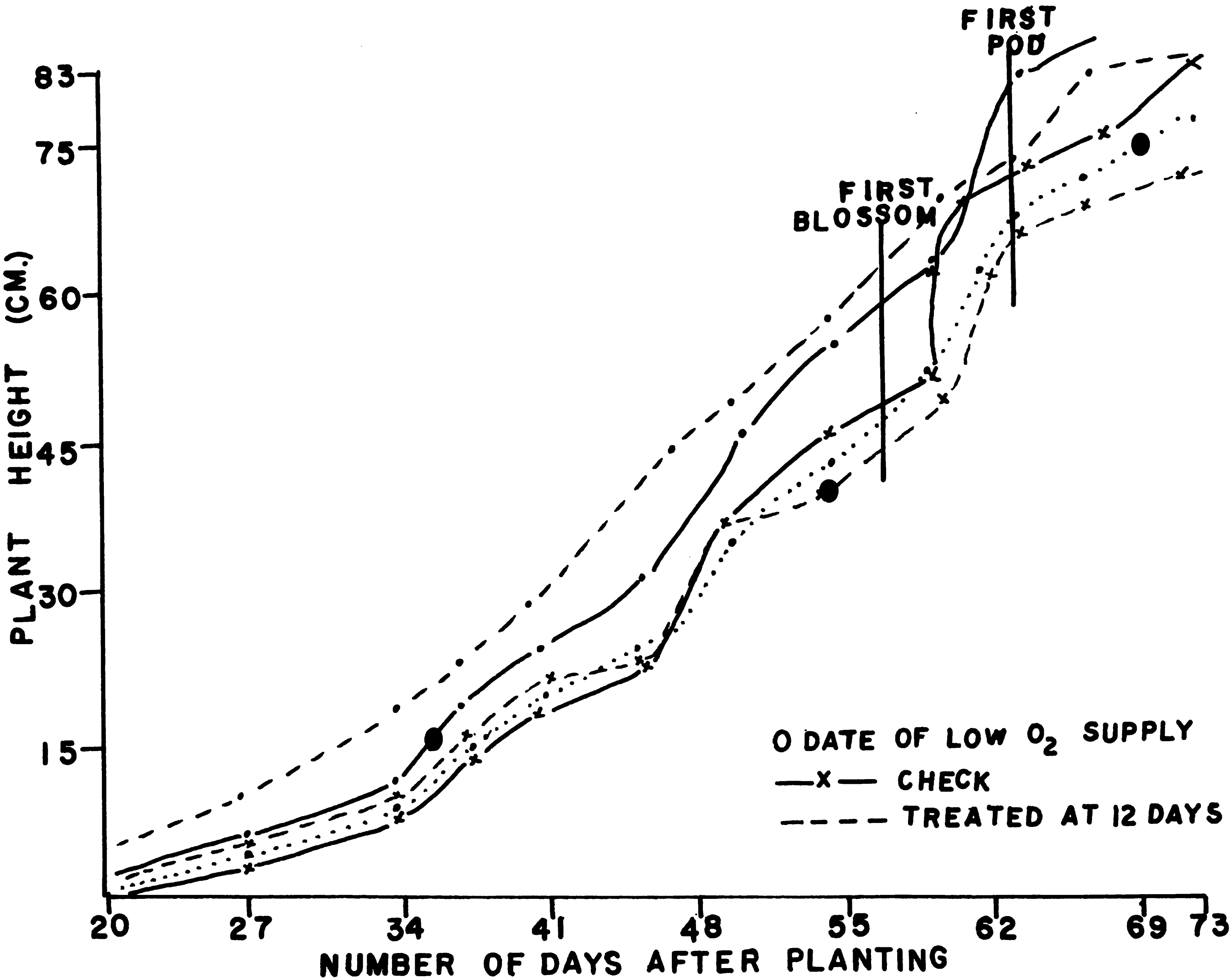


FIGURE VII - The Effect of Short periods of low oxygen supply at different stages of maturity in plant growth might give a different effect.

Comparison of the chemical analysis of samples of untreated plants and of plants most severely affected by short periods of low oxygen supply (treated 54 days after planting) are presented in Table XII . Treatment had no effect on plant composition. Oxygen plays other essential roles in the life of the plant besides nutrient uptake which effect yield and growth.

Table XIIIshows yields of treated and untreated plants at low and high fertilizer rates.

Plants were subjected to low oxygen supply at the time of blossoming. Treatment tended to reduce yields at low fertility levels and increase yields at high fertility. Differences are too small to be significant. It is difficult to understand why there is a reversal of effect of treatment at low and high fertility. Perhaps plants growing at high fertility were more vigorous at the time of treatment and were better able to withstand the low oxygen supply and growth was stimulated by the moisture. It does appear that at low fertility, short periods of oxygen deficiency was detrimental to growth andyields. High fertility may help the plant to overcome short periods of low oxygen supply.

The chemical analysis of treated and untreated plants at low and high fertility levels are shown in Table XIV. Nitrogen, phosphorus, potassium, calcium and magnesium were all lower with treated plants than untreated plants at low fertility. However at high fertility levels there was no reduction of nutrient uptake after treatment. The short period of low oxygen diffusion may have permanently disturbed the

TABLE XI

Experiment III

Average Yield - 3 Plants - 5 Pots

| | No. days after planting that plants were subjected to low oxygen diffusion | No. pods | No. peas | G.Wt. peas gm. | D.Wt. peas gm. | G.Wt. tops gm. | D.Wt. tops gm. |
|---|---|---|---|---|---|---|---|
| 1 | 12 | 8.6 | 57.2 | 20.49 | 4.23 | 110.62 | 19.6 |
| 2 | 14 | 10.2 | 61.4 | 19.42 | 3.92 | 117.40 | 21.0 |
| 3 | 27 | 9.6 | 57.4 | 20.08 | 4.08 | 105.49 | 20.02 |
| 4 | 36 | 10.6 | 64.6 | 25.17 | 5.12 | 134.76 | 22.3 |
| 5 | 43 | 10.0 | 62.8 | 21.48 | 4.29 | 131.5 | 21.1 |
| 6 | 54 | 7.0 | 42.0 | 15.6 | 3.20 | 82.6 | 14.3 |
| 7 | 69 | 8.6 | 49.4 | 13.36 | 2.66 | 108.0 | 19.52 |
| 8 | 71 | 9.6 | 56.0 | 17.04 | 3.46 | 100.4 | 19.04 |
| 9 | Check | 11.3 | 70.3 | 19.90 | 3.87 | 145.7 | 25.0 |
| | LSD .05 | 2.8 | 14.9 | 5.83 | 0.38 | 7.88 | 4.73 |
| | LSD .01 | 3.8 | 19.9 | 7.81 | 0.51 | 10.06 | 6.34 |

*

TABLE XII.
Chemical Analysis of Samples from Plants Affected by 7 or 24 Hours of Low Oxygen Diffusion Rate and Untreated Plants

| | N. | P. | K. | Ca. | Mg. |
|---|---|---|---|---|---|
| Treated | 1.26 | 0.25 | 1.58 | 1.46 | 0.52 |
| Untreated | 1.28 | 0.28 | 1.50 | 1.65 | 0.48 |

TABLE XIII

Average Yield - 4 plants - Experiment IV

Low Fertility

| | No. Pods | No. Peas | G.Wt. Peas | D. Wt. Peas | D.Wt. Tops |
|---|---|---|---|---|---|
| Subjected to low oxygen supply for 24 hours | 4 | 13.5 | 5.28 | 1.05 | 2.39 |
| Untreated | 4.5 | 16.5 | 8.0 | 1.77 | 3.91 |

High Fertility

| | No. Pods | No. Peas | G.Wt. Peas | D. Wt. Peas | D.Wt. Tops |
|---|---|---|---|---|---|
| Subjected to low oxygen supply for 24 hours | 7.0 | 29.5 | 8.41 | 1.65 | 11.0 |
| Untreated | 5.0 | 19.0 | 7.95 | 1.75 | 7.42 |
| LSD .05 | NS | 7.70 | NS | NS | NS |
| LSD .01 | | 14.13 | | | |

TABLE XIV

Chemical Analysis of Samples at the time of Harvest of Peas of Experiment IV.

Low Fertility

| | N. | P. | K. | Ca. | Mg. |
|---|---|---|---|---|---|
| Subjected to low oxygen supply | 1.98 | .17 | 0.90 | 1.97 | 0.36 |
| Untreated | 2.53 | .22 | 1.10 | 2.35 | 0.36 |

High Fertility

| | | | | | |
|---|---|---|---|---|---|
| Subjected to low oxygen supply | 3.13 | .33 | 1.80 | 2.30 | .23 |
| Untreated | 3.09 | .22 | 1.77 | 2.33 | .23 |

the metabolism of plants growing at low fertility levels so that their nutrient uptake and growth was reduced. More vigorous plants at high fertility levels maintained their normal nutrient uptake and in this case growth was stimulated by treatment. Fertilizer would appear to be very effective in overcoming low oxygen diffusion rates. Conclusive results can not be obtained from such a small experiment. More work should be done on this problem.

## VI SUMMARY

1. Nitrogen, phosphorus and potassium uptake by peas was increased by increasing oxygen diffusion rates up to $70 \times 10^{-8} gm/cm^2/min$ and then oxygen was no longer a limiting factor in nutrient uptake.

2. Growth and yields were also increased with increasing rates of oxygen diffusion up to $70 \times 10^{-8} gm/cm^2/min$. The same critical level of oxygen diffusion applied to both growth and nutrient uptake.

3. In early stages of growth, high fertility may alleviate oxygen deficiencies. Increasing fertilizer rate was more effective in increasing growth of young plants than increased oxygen diffusion rate when both oxygen and fertility supplies were low.

4. During the period of rapid growth until maturity, the growth and resulting yields were very closely related to oxygen supply. The pea plant was much more sensitive to oxygen deficiencies during the lasttwenty-five days of growth than during the first fifty days of growth.

5. Increased fertility level in part compensated for low oxygen supplies but did not completely overcome the oxygen deficiency.

6. Under almost anaerobic conditions, fertilizer did not increase growth or yield.

7. There did not appear to be a great accumulation of nutrients in roots in comparison to the tops at low oxygen diffusion levels.

8. Roots produced under low oxygen supply were much coarser with fewer lateral roots. The number of nodules produced was much less under low oxygen supply.

9. Short periods of low oxygen supply at certain periods of growth significantly reduced growth and yield. Pea plants were most sensitive to short periods of low oxygen supply from several days before blossoming until peas were set and developing. Short periods of low oxygen supply had little effect on the pea plant in the early stages of growth.

10. At normal and high fertility levels short periods of oxygen deficiency did not alter the nutrient uptake. At low fertility levels, nitrogen, phosphorus, potassium, calcium and magnesium content of treated plants was reduced.

11. Oxygen deficiency for seven hours or twenty-four hours had the same effect on pea plants.

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TABLE I -- APPENDIX

Growth (cm) - Experiment II

| No. of days after planting / Oxygen Diffus. Level | 18 | 22 | 25 | 27 | 30 | 32 | 35 | 39 | 42 | 44 | 47 | 50 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HIGH FERTILITY | | | | | | | | | | | | |
| 4 | 2.3 | 4.2 | 6.0 | 6.5 | 8.4 | 9.9 | 13.2 | 16.9 | 19.6 | 23.1 | 25.7 | 29.0 |
| 6 | 2.8 | 4.8 | 7.0 | 7.7 | 9.6 | 11.2 | 14.6 | 18.9 | 22.9 | 27.1 | 31.6 | 34.8 |
| 8 | 2.8 | 4.2 | 6.4 | 7.1 | 8.8 | 9.8 | 13.1 | 16.6 | 20.0 | 25.2 | 29.2 | 33.6 |
| 10 | 2.8 | 4.3 | 6.0 | 6.7 | 8.6 | 9.8 | 12.6 | 16.4 | 19.7 | 24.2 | 26.7 | 32.1 |
| 12 | 2.7 | 3.7 | 5.5 | 5.7 | 7.6 | 8.5 | 10.8 | 13.4 | 15.8 | 19.0 | 22.2 | 24.4 |
| 14 | 2.8 | 3.7 | 5.6 | 6.2 | 7.7 | 8.9 | 11.8 | 14.4 | 17.7 | 22.0 | 25.4 | 28.6 |
| MEDIUM FERTILITY | | | | | | | | | | | | |
| 4 | 2.9 | 4.3 | 6.0 | 6.7 | 8.6 | 9.8 | 12.4 | 15.5 | 18.1 | 21.7 | 23.8 | 26.3 |
| 6 | 2.7 | 4.4 | 6.3 | 7.1 | 8.7 | 10.4 | 12.4 | 16.3 | 19.4 | 24.5 | 28.3 | 32.4 |
| 8 | 2.9 | 4.2 | 6.1 | 7.2 | 9.0 | 10.5 | 14.1 | 18.7 | 22.4 | 28.1 | 32.4 | 36.7 |
| 10 | 3.2 | 4.2 | 6.3 | 7.5 | 9.0 | 10.5 | 13.5 | 16.8 | 20.5 | 24.9 | 29.1 | 32.9 |
| 12 | 3.2 | 4.3 | 6.5 | 7.2 | 8.9 | 10.0 | 13.1 | 17.8 | 21.2 | 25.9 | 30.2 | 34.2 |
| 14 | 3.1 | 3.6 | 5.7 | 6.4 | 9.1 | 9.2 | 11.8 | 14.9 | 17.8 | 21.6 | 25.2 | 28.2 |
| LOW FERTILITY | | | | | | | | | | | | |
| 4 | 2.9 | 3.7 | 4.5 | 5.3 | 6.0 | 6.6 | 8.0 | 9.1 | 9.9 | 11.3 | 12.7 | 13.3 |
| 6 | 2.9 | 3.7 | 5.3 | 5.9 | 7.0 | 7.8 | 9.8 | 11.4 | 12.6 | 13.8 | 15.5 | 16.3 |
| 8 | 2.6 | 3.5 | 5.1 | 5.8 | 6.7 | 7.3 | 8.5 | 10.4 | 11.7 | 13.5 | 14.7 | 16.3 |
| 10 | 2.8 | 3.7 | 5.3 | 5.8 | 6.8 | 7.6 | 9.2 | 10.6 | 12.4 | 14.4 | 15.8 | 17.5 |
| 12 | 3.0 | 3.7 | 5.6 | 6.0 | 7.0 | 7.8 | 9.7 | 11.4 | 13.2 | 15.1 | 16.9 | 18.6 |
| 14 | 2.6 | 3.3 | 4.8 | 5.2 | 6.3 | 6.6 | 8.0 | 9.4 | 10.8 | 12.6 | 13.7 | 15.1 |

TABLE I - APPENDIX

Growth (cm) - Experiment II

| No. of days after planting / Oxygen Diffus. Level | 53 | 56 | 59 | 62 | 65 | 68 | 71 | 74 | 77 | 80 | 83 | 85 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HIGH FERTILITY | | | | | | | | | | | | |
| 4 | 30.3 | 32.2 | 34.1 | 36.2 | 37.5 | 38.5 | 39.1 | 39.1 | 37.5 | 36.4 | 36.3 | 34.3 |
| 6 | 40.4 | 44.7 | 47.8 | 51.2 | 58.2 | 61.2 | 62.2 | 61.7 | 61.9 | 61.9 | 61.8 | 61.3 |
| 8 | 38.8 | 45.6 | 51.2 | 56.6 | 67.8 | 71.2 | 74.7 | 75.6 | 75.3 | 74.7 | 74.3 | 75.0 |
| 10 | 37.2 | 41.4 | 48.4 | 52.9 | 65.8 | 74.2 | 80.4 | 82.6 | 82.5 | 82.4 | 82.7 | 82.6 |
| 12 | 28.5 | 33.2 | 39.8 | 44.8 | 54.0 | 60.9 | 70.4 | 74.8 | 75.3 | 75.6 | 76.3 | 76.6 |
| 14 | 33.2 | 39.3 | 44.2 | 49.3 | 55.9 | 69.3 | 75.0 | 81.8 | 83.9 | 84.7 | 83.7 | 82.2 |
| MEDIUM FERTILITY | | | | | | | | | | | | |
| 4 | 28.3 | 30.2 | 32.9 | 33.7 | 37.2 | 37.5 | 37.0 | 36.8 | 37.2 | 36.9 | 37.2 | 38.0 |
| 6 | 37.6 | 42.9 | 47.5 | 50.8 | 58.3 | 60.8 | 61.8 | 61.8 | 61.9 | 62.1 | 62.1 | 61.8 |
| 8 | 44.1 | 51.5 | 58.8 | 62.8 | 73.3 | 80.6 | 83.8 | 84.0 | 84.7 | 84.8 | 84.5 | 83.5 |
| 10 | 38.7 | 45.5 | 52.1 | 56.3 | 68.4 | 77.6 | 84.3 | 84.5 | 90.3 | 89.8 | 89.6 | 90.1 |
| 12 | 39.7 | 46.3 | 52.4 | 57.7 | 70.7 | 79.9 | 86.8 | 91.3 | 94.3 | 95.3 | 95.5 | 95.5 |
| 14 | 32.6 | 38.6 | 43.4 | 47.5 | 57.7 | 64.8 | 71.7 | 73.9 | 79.3 | 80.7 | 80.1 | 79.5 |
| LOW FERTILITY | | | | | | | | | | | | |
| 4. | 13.8 | 15.6 | 16.8 | 17.7 | 19.9 | 20.0 | 20.2 | 20.9 | 20.7 | 20.6 | 20.5 | 19.9 |
| 6 | 17.8 | 20.3 | 22.7 | 23.6 | 27.9 | 30.4 | 31.2 | 30.8 | 31.0 | 31.2 | 30.5 | 30.9 |
| 8 | 18.5 | 20.9 | 23.9 | 26.2 | 32.2 | 37.0 | 39.7 | 40.4 | 40.4 | 40.4 | 40.5 | 40.5 |
| 10 | 19.8 | 22.8 | 26.4 | 29.1 | 34.8 | 40.8 | 44.7 | 44.8 | 45.0 | 44.8 | 44.8 | 44.7 |
| 12 | 21.6 | 24.7 | 28.4 | 32.1 | 38.6 | 45.1 | 48.5 | 50.1 | 50.7 | 50.7 | 50.2 | 49.9 |
| 14 | 17.2 | 19.4 | 22.1 | 24.6 | 31.2 | 35.2 | 40.0 | 41.5 | 42.0 | 41.4 | 41.7 | 40.9 |

TABLE II - APPENDIX

CHEMICAL ANALYSIS, EXPERIMENT I

| Oxygen Diffus. | Nov.17 | | | | | Dec. 7 | | | | | Jan.17 Tops | | | | | Jan.17 Roots | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Level | N | P | K | Ca | Mg | N | P | K | Ca | Mg | N | P | K | Ca | Mg | N | P | K | Ca | Mg |
| | | | | | | | | | | HIGH | | | | | | | | | | |
| 4" | - | .59 | 2.60 | 0.45 | .13 | 3.58 | .24 | 2.72 | .67 | .15 | | .15 | 2.55 | .90 | .25 | | | | | |
| 8" | | | | | | 7.73 | .41 | 3.17 | .61 | .20 | 5.35 | .24 | 3.22 | 1.10 | .21 | 1.40 | .16 | .55 | .24 | .15 |
| 10" | | | | | | 7.50 | .32 | 3.15 | .54 | .23 | 6.54 | .24 | 4.44 | 1.34 | .29 | 1.22 | .14 | .76 | .24 | .15 |
| 12" | | | | | | | | | | | 5.70 | .23 | 2.78 | 1.84 | .28 | 1.51 | .10 | .81 | .26 | .18 |
| | | | | | | | | | | MEDIUM | | | | | | | | | | |
| 4 | 6.60 | .56 | 3.00 | .54 | .15 | 3.78 | .15 | 2.40 | .70 | .25 | 4.33 | .16 | 2.06 | 1.73 | .34 | | | | | |
| 8 | | .63 | 3.60 | .66 | .20 | 6.16 | .27 | 3.65 | 1.39 | .27 | 4.72 | .16 | 3.14 | 1.86 | .31 | 1.40 | .26 | .30 | .26 | .14 |
| 10 | | .50 | 3.75 | .96 | .25 | 6.28 | .26 | 3.50 | 1.70 | .38 | 4.19 | .17 | 3.67 | 1.74 | .29 | 1.37 | .093 | .39 | .24 | .11 |
| 12 | 7.64 | .50 | 4.00 | .89 | .27 | 6.52 | .29 | 3.38 | 1.92 | .38 | 4.08 | .20 | 3.96 | 1.68 | .25 | 1.30 | .12 | .55 | .35 | .10 |
| 16 | | .68 | 3.86 | 1.05 | .35 | 7.40 | .30 | 2.85 | 1.72 | .34 | 4.81 | .25 | 2.67 | 1.64 | .29 | 1.43 | .11 | .52 | .35 | .10 |
| 20 | | .67 | 3.00 | 1.03 | .31 | | | | | | | | | | | | | | | |
| | | | | | | | | | | LOW | | | | | | | | | | |
| 4 | 6.09 | .25 | 2.65 | .39 | .21 | 2.95 | .18 | 1.90 | .64 | .23 | 2.20 | .17 | 1.60 | 1.06 | .29 | . | . | . | | |
| 8 | 6.21 | .52 | 4.83 | 1.19 | .32 | 5.11 | .29 | 3.08 | 2.03 | .40 | 2.48 | .25 | 2.98 | 1.59 | .24 | .68 | .08 | .30 | .35 | .13 |
| 10 | 6.35 | .50 | 3.91 | 1.03 | .27 | 5.30 | .30 | 3.17 | 1.96 | .36 | 2.83 | .27 | 3.14 | 1.86 | .27 | .78 | .08 | .36 | .32 | .15 |
| 12 | 6.60 | .49 | 4.15 | 1.11 | .40 | 6.60 | .30 | 3.65 | 2.03 | .46 | 3.11 | .32 | 2.87 | 1.24 | .27 | .79 | .08 | .41 | .30 | .19 |
| 16 | 7.09 | .53 | 3.57 | 1.17 | .29 | 6.00 | .40 | 3.57 | 1.93 | .31 | 3.44 | .33 | 3.12 | 1.70 | .34 | .99 | .09 | .52 | .39 | .15 |
| 20 | 7.00 | .50 | 3.57 | 1.14 | .31 | 6.51 | .34 | 2.90 | 2.00 | .32 | 3.39 | .30 | 3.23 | 1.67 | .35 | .99 | .09 | .43 | .39 | .21 |
| 24 | 7.35 | .61 | 2.45 | 0.64 | .31 | 6.68 | .44 | 3.00 | 1.82 | .32 | 3.86 | .31 | 3.33 | 1.92 | .48 | 1.40 | .12 | .70 | .32 | .13 |

TABLE III - APPENDIX

Experiment III

Average Growth - 5 Plants

| No. days after planting | DAYS AFTER PLANTING | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | 18 | 26 | 28 | 33 | 36 | 39 | 45 | 49 | 54 | 59 | 61 | 63 | 66 | 68 | 70 | 75 |
| 12 | 6.0 | 9.8 | 11.5 | 18.4 | 23.1 | 29.0 | 42.8 | 49.2 | 56.8 | 68.6 | 71.9 | 74.4 | 80.0 | 81.6 | 82.2 | 81.8 |
| 14 | 5.8 | 10.5 | 11.6 | 17.8 | 22.4 | 29.1 | 43.4 | 52.0 | 58.2 | 70.9 | 74.7 | 77.0 | 84.2 | 85.8 | 86.5 | 86.5 |
| 27 | 4.9 | 9.0 | 10.6 | 16.2 | 21.1 | 26.7 | 38.5 | 47.8 | 53.8 | 64.1 | 69.7 | 75.3 | 79.5 | 81.1 | 81.5 | 81.8 |
| 36 | 3.4 | 6.2 | 10.3 | 11.5 | 18.1 | 23.5 | 31.1 | 45.6 | 54.4 | 63.4 | 77.1 | 80.5 | 83.1 | 87.3 | 89.4 | 90.6 |
| 43 | 2.8 | 5.6 | 9.7 | 10.4 | 16.0 | 20.8 | 27.1 | 43.4 | 50.8 | 58.6 | 71.6 | 75.5 | 77.0 | 81.7 | 83.0 | 85.0 |
| 54 | 3.0 | 5.8 | 9.6 | 10.6 | 15.7 | 20.3 | 25.9 | 36.6 | 42.6 | 51.2 | 61.7 | 67.0 | 67.4 | 71.6 | 72.8 | 74.0 |
| 68 | 3.0 | 5.7 | 9.4 | 10.5 | 15.5 | 19.8 | 26.0 | 36.4 | 43.8 | 54.2 | 64.0 | 69.3 | 71.3 | 76.4 | 78.2 | 77.2 |
| 71 | 2.7 | 5.1 | 8.9 | 10.0 | 14.7 | 18.7 | 24.6 | 35.4 | 41.6 | 51.2 | 61.4 | 65.7 | 67.8 | 75.5 | 76.3 | 77.1 |
| CHECK | 2.9 | 5.5 | 9.3 | 10.2 | 15.4 | 19.1 | 25.6 | 36.9 | 45.1 | 53.8 | 68.0 | 71.8 | 73.9 | 80.4 | 82.7 | 84.8 |

ROOM USE ONLY

Date Due

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