The Pennsylvania State College

The Graduate School

Department of Agronomy

Relationship of Aerification, Irrigation, and Compaction to Phosphorus Penetration, Root Development, and Population Changes in a mixed Turf of Permanent Grasses

A thesis

by

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INTRODUCTION

Since the end of World War II, golf and other recreational activities requiring specialized fine turf areas have increased tremendously. This has, in turn, greatly increased the maintenance problems of the golf course superintendents and others involved in maintaining first rate playing conditions. Excessive compaction brought about by the increased play and the use of heavy modern maintenance machinery has increased the ever present but often unrecognized problems of soil physical condition manyfold. It has become common practice in many areas of the United States to install fairway watering systems. Improper management of systems, because of lack of knowledge of the proper use of water often has resulted in more damage than if no watering system were present at all.

There is no reason to doubt that under careful management the use of supplemental irrigation can be of great value in maintaining good turf quality. Unfortunately, it has been the common practice where watering systems are available, to overwater. This is not only detrimental to the turf, but also adds undue maintenance costs. Overwatering may have detrimental effects on turf quality in several ways. Under levels of high fertility, overwatering will result in a lush, succulent type of growth which generally is very susceptible to disease attacks. Overwatering may also be responsible for undesirable weed and crabgrass invasions as well as serving as a vehicle for the loss of soil nutrients through leaching. Rapid growth, through excessive watering, also requires that the turf be clipped more frequently, thus subjecting the soil to the compactive effects of heavy mowing machinery. It has long been observed that excessive watering tends to form a turf which is very shallow rooted and, therefore, incapable of surviving even under conditions of light drought.

Basically, many of the problems involved in fine turf maintenance revert back to the physical condition of the soil. Given the proper soil condition in the beginning, the golf course superintendent is faced with the problem of maintaining these soil conditions. Unfortunately, in most instances the desirable soil conditions already have been destroyed and the golf course superintendent must have some means, short of reconstruction, of restoring a better physical condition to the soil.

Proper soil physical condition involves several factors which, directly or indirectly, affect the ultimate turf quality and hence the playing conditions. Soil structure and texture undoubtedly determine the porosity of a soil, which in turn, plays an important role in the aeration and surface drainage. From a purely theoretical standpoint the ideal soil for turf would contain 50 percent solid material (mineral and organic content) and 50 percent pore space by volume of the total soil mass. Of this 50 percent pore space, one half would be occupied by soil air and the other one half by soil water. If any conditions arise which result in a decrease in total pore space and an increase in the solid portion of a given volume of soil, some degree of compaction has taken place. Compaction, in addition to reducing pore space may also cause the formation of a shallow impervious surface layer which will almost completely impede the penetration of water and result in loss of water by runoff. Under similar conditions on lower areas, water may pond on the surface for days at a time, forming anerobic conditions which may cause serious turf deterioration. Fundamental knowledge as to the exact nature and extent of compaction damage to turf quality is woefully lacking at the present time.

Plants, like animals, require oxygen in order to maintain life. Soil aeration is, therefore, of prime importance in the replenishment of soil oxygen and the removal of soil carbon dioxide and other gaseous materials which may become toxic if allowed to accumulate. The lack of adequate aeration may result in the formation of anerobic conditions which are not only detrimental to the plant directly, but may, in addition, retard the development of nitrification processes and the growth of desirable soil micro-organisms which are thought to play some role in the development of good structure.

Within the past ten years several types of aerating equipment have appeared on the commercial market under such names as Soilaire, Aerifier, and the Terforator. Unfortunately, many golf course superintendents looked upon these mechanical means of improving soil aeration as a cure all. There is no reason to doubt that such aerating machines have their place in any proper turf maintenance program, but it must be remembered that these devices are but one more of the many tools that can be of assistance in turf maintenance and should be regarded as such.

In recent years the various aerating machines have been given credit as aiding in the penetration of certain fertilizer elements as well as water and air, although at the present time there is no actual experimental data available to validate such an assumption. It seems quite reasonable that such penetration would take place purely through mechanical means, but it remains the task of the research worker to provide scientific proof that such a mechanical penetration does take place.

As additional experimental evidence is gathered regarding turf management, it becomes increasingly evident that we are confronted with a tremendously complex problem which cannot be solved by a few, simple experiments. At the same time, it must be realized that any future experimental work should be kept as simple as possible in order to better understand the basic fundamentals and thereby clarify the picture rather than add more confusion to an already confused situation.

This study was designed as a continuation and elaboration of earlier studies by Watson[25] in an attempt to find additional information on the physical effects outlined above on turf quality and maintenance practices. Basically, the work was conducted as a continuation of the work started by J. R. Watson, Jr. in 1947. The original plots used by Watson were retained and the basic treatments, with modifications, continued. During the summer of 1950 these modifications consisted primarily of an increase in the severity of the original compaction treatments with no change in the moisture treatments. In the spring of 1951, these plots were further modified by sub-dividing the original plots into aerified and non-aerified plots. At the same time applications of superphosphate at a high rate were applied in order to study the penetration of phosphorus on the aerified and non-aerified plots.

The methods of evaluation and techniques used in such evaluations will be found later in the text under the heading of Methods and Materials.

REVIEW OF LITERATURE

Literature dealing with soil compaction, moisture, and aerification as they affect turf quality, is limited. Scientifically acquired experimental data is almost totally unavailable. There are hundreds of articles appearing in our more popular periodicals dealing with these subjects, but they consist almost entirely of personal observations and opinions of the writers and have little or no scientific data to substantiate them.

Turf of a quality that will meet present day playing conditions is affected by many factors. The more important of these are physical soil condition, soil reaction, fertility, disease, and management practices. Among these factors none is more important than the physical condition of the soil. In turn compaction and moisture play an important role in the physical condition of the soil and the ultimate turf quality. Watson[(25)] found that moisture alone exerted more detrimental influence on turf quality over a three year period than did compaction alone. He found that under conditions of high moisture, bentgrass tended to increase at the expense of the Kentucky bluegrass and the red fescue. Watson[(25)] also found that compaction tended to increase the clover population at the expense of the permanent grasses. Smith and Cook[(18)], working with a pot experiment on sugar beets, involving compaction, aeration, and water, concluded that excessive compaction alone was more detrimental than excessive water alone. Watson[(25)], Smith and Cook[(18)], agree that the interaction of moisture and compaction together produce more injurious effects than either alone.

Alderfer and Robinson[1], working on pastures, report that maximum compaction occurs in the upper inch of the soil profile despite the high organic content usually found in this area under pasture conditions. This thin layer prevents the infiltration of water and causes runoff, even though excellent soil structure may exist below this one inch layer. Sokolovsky[19] agrees that this compacted layer generally forms in the upper inch and prevents water infiltration. He is also of the opinion that under irrigation there may be a breakdown of aggregation in the surface which leads to crust formation. Crust formation results in unfavorable air and water relations for plant growth. Cole[6], has shown that under high rates of irrigation, puddling of the surface may take place. The presence of a compacted layer at a greater depth, as is often the case in hardpans and certain artificial soils, would materially affect drainage.

Poor drainage is closely associated with poor aeration. Welton and Carroll[29] have pointed out the importance of adequate drainage in maintaining the proper air-water relationships. Musser[15], Welton, Carroll, and Wilson[30], and Watson[25] have emphasized that compaction and excessive water are primary factors contributing to poor aeration and drainage. Musser[16], Welton and Carroll[29] have also pointed out the importance of aeration and drainage in the development of adequate root systems. Watson[25] has shown that high moisture content in the upper two inches of the soil layer (due to poor drainage or high water tables) tend to develop very shallow root systems which cannot persist under conditions of slight drought. Numerous workers, using corn, barley, wheat, and sugar beets, have shown that compaction, by reducing aeration, may hinder root development. It has also been shown that an increase in the ratio of tops to roots is associated with soil compaction.

Workers have suggested that the presence of compacted layers in the soil may hinder the nutrient supplying power of the soil. Smith and Cook[18] found that severe soil compaction did not restrict the growth of sugar beets as much if excessive amounts of nutrients were supplied. Hubbell and Gardner[12] have shown on two New Mexico soils that soil compaction materially reduces the soil micro-organism population. Thus, soil compaction may influence the growth of the turf grasses as a result of its effect on the nutrient supplying ability of the soil organisms.

Cannon[4] has shown that the absorption of nutrients by plants is the result of an energy consuming process of the protoplasm for which oxygen is needed constantly. Cannon[4] also points out that the carbon dioxide given off during plant respiration may accumulate under conditions of poor aeration and dilute the oxygen supply to a critical value. In poorly aerated soils ferric iron may be reduced to the ferrous state and become toxic to plant growth, if allowed to accumulate. Adequate soil aeration, therefore, is necessary for the replenishment of soil oxygen, the dissipation of carbon dioxide and other gaseous substances, adequate nutrient uptake, adequate root development, and proper drainage.

The use of aerification as we now know it in turf management is of recent introduction. It is well known that adequate soil aeration is necessary for proper plant development. Hubbell and Gardner[12], Clements[5], Cannon and Free[4], and numerous other investigators have studied air and water relationships with crops other than established turf. Kramer[13], has shown the effect of aeration on plant-soil water relationships.

Considerable literature is available on the migration and penetration of phosphorus as influenced by water, but at the present time there is no material available on aerification and phosphorus penetration. Midgley[15], Crawley[7], Alway[2], Hockensmith[11], and others report that there is very little, if any, movement of phosphorus downward even under heavy rainfall and heavy applications of phosphorus fertilizer. Brown[3], reports that superphosphate does not move more than three inches downward on acid soils and seven inches downward on alkaline soils in a period of sixteen years. Robinson and Jones[17], in leaching North Welsh soils, found that naturally occurring phosphates do not materially move downward, but that phosphate applied dressings show considerable downward movements under the normal rainfall of Wales. Ulrich, Jacobson, and Overstreet[23], using radioactive phosphorus, report that 20 percent of the phosphorus applied penetrated three inches in eleven days when four inches of irrigation were applied over that period. They further stated that 11.5 percent of the phosphorus applied penetrated five inches in eleven days under the same irrigation treatment.

Stephenson and Chapman[20], are of the opinion that the direction of movement of phosphorus is governed by the direction of water movement. The form in which phosphate is carried need not necessarily be that of inorganic phosphorus in true solution. Soil organic forms, as well as organic and inorganic colloidal forms, might move readily with soil water. They further point out that there are indications that a more rapid penetration is effected through a few heavy applications of phosphorus rather than through numerous light doses. Wander[24], reports that under any cropping system which maintains a high soil organic matter content, there will be a higher rate of phosphorus penetration than on a soil having low organic matter content, because there is less fixation of the superphosphate. He found that by the addition of organic materials to the soil, phosphorus penetration could be materially increased down to twelve inches, but that no noticeable increase could be found beyond that depth.

METHODS AND MATERIALS

The site of this experiment was an established turf area on the campus of the Pennsylvania State College. The area consisted of 25,000 square feet of a well established turf population composed of Kentucky bluegrass (Poa pratensis), red fescue (Festuca rubra vars, genuina and fallax), and bentgrass (Agrostis palustris and A. tenuis). The soil of the area is a Hagerstown silt loam of good fertility and gentle rolling topography. This soil has excellent surface and subsoil drainage.

General maintenance of the area.

As far as possible the general maintenance practices of the area were very similar to the practices in common use on most of our golf courses. Throughout the course of the experiment the area was clipped at ½ inch, the frequency of clipping being determined by the rate of growth of the grass. Experimental evidence in the past has indicated that clipping to ½ inch may have detrimental effects on the Kentucky bluegrass and red fescue population, at the same time benefitting the bentgrass population; but in view of the fact that this has become common practice on most of our golf courses today it was felt close clipping was justifiable. A high level of fertility was maintained through regular fertilizer applications in the spring and fall. spring and fall of 1950 fertilizer was applied at a rate to pr and three-quarter pounds of organic nitrogen (milorganite), pound of inorganic nitrogen (Ammonium Sulphate), one and or of P_2O_5 (Superphosphate) and one and one-half pounds of K potash) per 1000 square feet. In the spring of 1951 fertilizer was provided at a rate to provide one and one-half pounds of organic nitrogen (milorganite and uramite), one-half pound of inorganic nitrogen (Ammonium Sulphate), one pound of K_2O (muriate of potash), and four pounds of P_2O_5 (Superphosphate) per 1000 square feet. Composite samples of the entire area were taken at regular intervals for soil reaction determination. The pH of the area was maintained at approximately 6.5 to 6.6.

Experimental design

The design used in this experiment was a modified split plot. In 1950 there were four levels of moisture and five levels of compaction with three replications. Compaction treatments were superimposed and at right angles to the moisture treatments in order to give all possible combinations of compaction and moisture. The individual plots were 18 by 20 feet. The compaction and moisture treatments were randomized within each block.

In 1951 a third factor, aerification, was introduced into the experiment. Aerification treatments were applied by dividing the compaction-moisture plots in half in the direction of the compaction applications. This resulted in compaction and aerification running in one direction and at right angles to the moisture treatment. Compaction and moisture, therefore, became the main plots and aerification the sub-plots. This again gave all possible combinations of compaction, moisture and aerification. The individual sub-plots were 18 by 10 feet.

Treatments

Compaction: A rather wide range of compaction treatments were applied in order to obtain definite and easily distinguishable levels of compaction. The application of a pressure of 62 pounds per square inch (the maximum used in this experiment) was sufficiently high to exceed the pounds per square inch delivered by our heaviest turf maintenance equipment.

The compaction treatments employed and the symbols used to denote these treatments throughout the course of this text are as follows:

(1) No. - No compaction applied.

(2) Lt 1X - Approximately 15 P. S. I. applied once each week.

(3) Lt 2X - Approximately 15 P. S. I. applied twice each week.

(4) H 1X - Approximately 62 P. S. I. applied once each week.

(5) H 2X - Approximately 62 P. S. I. applied twice each week.

The compaction treatments were applied by the use of two cylindrical hollow steel rollers. Sufficient weight in the form of concrete blocks was added to the weight tray of one of these rollers in order to meet the requirements of the Lt 1X and Lt 2X treatments. The second roller was filled with concrete and sufficient concrete blocks were added to the weight tray to meet the requirements of the H 1X and H 2X treatments. The rollers were pulled by a standard Ford tractor.

Before attempting to evaluate the effect of compaction on the turf it was necessary to experimentally show that differences in levels of compaction existed. Several methods, namely volume weights, penetrometer readings, and X-ray spectrometer determinations were used to determine compaction. These methods and their results will be discussed in more detail later in the text under the heading of Preliminary Investigations.

Moisture: The moisture levels to be used in the experiment were of such a nature as to cover practically any moisture situation found in nature. This necessitated a wide range of moisture applications. The moisture applications were made by the use of 100 foot pipes drilled and tapped every three feet and equipped with short throw nozzles. The short throw nozzles gave a uniform nine foot throw allowing a total area of nine feet by one hundred feet to be irrigated at any given time. Inasmuch as the plots were 18 feet wide it required two settings of the pipe to cover a 5 plot series of 20 by 18 feet plots.

The moisture levels employed and the symbols used to denote these treatments throughout the course of this test are as follows:

(1) Dry - No supplemental irrigation applied. The only moisture available during the growing season was that supplied by natural rainfall.

(2) A.N. - As Needed: Supplemental irrigation was applied only in sufficient amounts to maintain a healthy green color and promote normal growth. During the growing season the average soil moisture content was maintained at approximately 15 to 18 percent. The wilting point of this soil is approximately 9 percent.

(3) F. C. - Field capacity: Supplemental irrigation was applied in sufficient amount to maintain a soil moisture content of approximately 24 percent which is the field capacity of this soil. (Field capacity being defined as the amount of water held in the soil twenty-four to forty-eight hours after the soil had been saturated.)

(4) Sat. - Saturated: Supplemental irrigation was applied in sufficient amounts to keep the soil in a moisture condition approaching saturation. The total water holding capacity of this soil is approximately 49 percent. Due to the excellent surface and subsurface drainage of this soil it would have required almost continuous irrigation to maintain saturation. The average moisture content of the soil under this treatment was, therefore, approximately 38 percent, which is approximately 78 percent saturation.

In an effort to maintain the above moisture levels as closely as possible several methods of determining when to irrigate were used. The dry treatments, of course, did not receive any irrigation and, therefore, did not constitute a problem. On all moisture levels, periodic samples were taken and analyzed in the laboratory for moisture content. The addition of water to the As Needed plots was determined entirely by observing the condition of the turf and mentally correlating these observations with the prevailing weather conditions.

Water applications at the proper time on the field capacity and saturation plots constituted much more of a problem than did the other moisture levels. Watson,[25] primarily through trial and error, found that Lark soil moisture tensiometers were best suited for this purpose. The Lark tensiometer is a soil moisture indicator making use of a porous ceramic cup and a vacuum gauge connected together with a tube in such a way that the system can be completely filled with water. The entire system is filled with water and the porous cup placed in the plant root zone and allowed to come to equilibrium with the soil. If the soil has a high moisture content there will be no water movement between cup and the soil and the vacuum gauge will register zero. However, as the moisture content of the soil drops below the moisture content of the porous clay cup there will be a movement of water from the cup to the soil. This will create a vacuum and will be registered as a rise on the vacuum gauge.

Tensiometers are limited in use and a thorough knowledge of their operation must be understood if they are to be used successfully. The maximum tension cannot exceed one atmosphere. When the potential of the soil water exceeds one atmosphere, air will enter the system and the tensiometer becomes inoperative. It has been found that the tension increases rather slowly as water is removed from wet soil so that a substantial fraction of the available water has been used by the time the tensiometer gauge approaches one atmosphere. Beyond this point the soil moisture tension rises rapidly. The limitation in range of the tensiometer, therefore, is not serious in this study inasmuch as it covers the optimum moisture range.

One serious drawback of the tensiometer, however, is that there is considerable hysteresis effect. A soil that is being wetted has a different soil moisture content at the same gauge reading from that of the same soil being dried. This obstacle was overcome in some degree through constant observation and anticipation as to the proper time for irrigation.

It was impossible to keep an accurate record of the amount of water applied under the various moisture levels. Unfortunately, the water line supplying the area also supplied several of the women's dormitories on the campus and severe fluctuations in the water pressure occurred throughout a twenty-four hour period. Financial aid was not available to supply pressure valves and other equipment necessary to maintain constant pressure.

Rainfall data for the growing seasons of 1950 and 1951 are given in the following table to indicate how much water was received by the dry plots.

Rainfall in Inches

Month	1950	1951
April	1.95	2.92
May	4.10	2.93
June	2.20	5.71
July	4.31	1.71
August	2.57	1.52
September	2.00	1.47
October	3.89	1.94

It should be pointed out in regard to the above rainfall data that total rainfall is a very poor criteria of the moisture conditions that prevailed over a monthly period. Rainfall distribution is of much more importance. For example, in August of 1951 the total rainfall was 1.52 inches, but of this total, 1.16 inches fell in a twelve hour period and no more rain fell for twenty-two days. Similarly in September of 1951, 1.01 inches of a total 1.47 inches fell in a twelve hour period and no more rain fell for twenty-six days. With this additional information it becomes apparent that drought conditions existed on the dry plots the greater part of these two months. Rainfall in 1950 was much more evenly distributed than it was in 1951. The As Needed plots received approximately one to two inches of supplemental irrigation per month during the growing season. Supplemental irrigation on the field capacity plots averaged approximately fifteen inches per month and the saturated plots approximately forty inches per month. These amounts varied considerably with changes in weather conditions, i.e., distribution of rainfall, temperature, evaporation index.

Aerification: Aerification treatments were applied to the area May 1, 1951. The original 18 by 20 foot compaction-moisture plots were sub-divided in half, one half being aerified, the other half continuing to receive the compaction treatments only. All plots continued to receive the same moisture treatment they had received in the past. This arrangement gave all possible combinations of compaction, moisture and aerification.

Aerification was done with West Point Lawn Products Aerifier model FC equipped with 3/4 inch spoons and Flexipress. Additional weight, in the form of concrete blocks, was added to the Aerifier in order to get a maximum penetration of 5 inches. The area was gone over three times.

Immediately following aerification, the spring application of fertilizer was applied by use of a tractor drawn Gandy spreader. The soil cores brought to the surface by the Aerifier were then broken up by dragging the area with a steel mat. This also served to distribute the fertilizer more thoroughly and undoubtedly resulted in the mechanical movement of some of the fertilizer down the Aerifier holes.

Methods of Evaluation

The effects of compaction, moisture and aerification were evaluated by five major criteria. They were:

(1) Ecological changes in the population of the permanent species. (Kentucky bluegrass, red fescue and bentgrass)

(2) Invasion of crabgrass, clover and other weeds, including *Poa annua*.

(3) Root quantities and distribution.

(4) Phosphorus penetration.

(5) The severity of natural disease infection.

Ecological changes: The changes in the population of Kentucky bluegrass, red fescue and bentgrass were determined by use of the inclined point quadrat. Population counts were taken in the fall of each year and were taken in the exact manner as taken by Watson[25] on these plots in previous years. This was done in order to permit comparison of results over the entire period of the two experiments.

All inclined point quadrat counts were based on five settings (50 needles) per individual sub-plot. Calculations of the percent of the various permanent species present were made directly from the number of times the individual species (Kentucky bluegrass, red fescue and bentgrass) were hit in comparison to the total number of hits on all species found in the turf. The percent of total permanent species was used as a base of 100 for the determination of the individual species.

Crabgrass, clover and other weeds: In making the point quadrat count, records were also kept on the individual weed species counts so that the percentage of total species that was crabgrass, clover, etc., could also be determined. In addition, crabgrass counts were made by use of a double X line quadrat. In this procedure the actual number of plants occurring under the lines were recorded.

Clover determinations were made with the point quadrat as described above and visual observations of the estimated percent of the total plot area covered by clover were also made. This was done by estimating how many square feet of the total plot area was covered by clover and converting these figures to percent area. All other weeds, including Poa annua, dandelion, buckhorn, Poa trivalis, leafy spurge, etc., were grouped under miscellaneous weeds and determined from the point quadrat counts.

Root quantities and distribution: Root samples were taken in September with a one and five-eighths inch plugger at one inch intervals to a total depth of six inches. Nine samples were taken at each one inch interval for each sub-plot. These samples were taken to the laboratory and each individual sample hand washed. The washed roots were dried overnight at a temperature of 105° C and weighed on a torsion balance. Calculations were made of the percent roots found in the upper two inches of the total six inch layer and of the percent roots in the lower four inches of the total six inch layer.

Phosphorus penetration: Soil samples for phosphorus determination were taken in mid June 1951, approximately six weeks after aerification and application of the fertilizer. Samples were taken with an Oakfield soil testing tube at one inch intervals to a total depth of six inches. Ten randomized, one square foot areas were chosen on each individual plot and ten soil samples taken from each one square foot area. It was felt that by using this method of sampling rather than by taking 100 completely randomized samples, the effect of aerification would not be as highly diluted. By taking ten samples within a given square foot, there was a higher probability that some Aerifier holes would be hit.

The soil samples were taken to the laboratory and extracted by the method described by Truog[22]. The extracted phosphorus was then analyzed by the Deniges Stannous-Reduced Phosphomolybdic blue color method as adpated to photoelectric measurements by Jackson and improved by Truog and Meyer[21].

Disease infection: During the summers of 1950 and 1951 it was not necessary to take disease records because of the complete absence of disease. During the winter of 1950 there were several areas of the plots heavily infested with snow mold. It was felt this was due primarily, to the formation of drifts over certain areas of the plots and was not influenced by any of the treatments applied. Individual plot records, therefore, were not taken.

Preliminary Investigations

Determination of Compaction

INTRODUCTION

As indicated under Methods and Materials it was necessary to show experimentally that actual differences existed under the various compaction treatments before any discussions of the effects of compaction could be undertaken. Three methods of compaction measurements were studied and correlations between the methods were made. This involved the use of penetrometer readings, volume weights, and X-ray spectrometer data.

Volume weight determinations are, at the present time, the most generally accepted manner of evaluating compaction. The somewhat stony nature of the soil on the experimental area offered a serious disadvantage to this type of determination. It was felt, however, that if sufficient samples were taken the more stony ones could be eliminated and a reasonable degree of reliability attained.

The soil penetrometer offered the simplest method of evaluating compaction. Penetrometer readings are also influenced by the presence of stones, but the ease of obtaining penetrometer readings was such that any hits occurring on stones were not recorded. The density of plant stems and roots may also influence penetrometer readings.

Preliminary investigations by Watson, Jefferies, and Musser(26) indicated that the Geiger counter X-ray spectrometer could be successfully used to determine compaction. This technique involved the recording of the intensity of the 1010 quartz line as recorded by the X-ray spectrometer. The assumption was made that the more compacted the soil was, the more tightly the quartz particles would be pushed together and the higher would be the intensity of the 1010 quartz line.

PROCEDURE

Penetrometer: A Rototiller Soil Penn-o-trometer was used to take penetrometer readings. Twenty-five stone free hits were taken on each individual plot. These readings were taken in June of 1951. In all probability maximum compaction for the season had not occurred at that early date but it was necessary to take such readings when time permitted.

Volume weights: Volume weights were taken with a volume weight tube having a volume of 242.13 cubic centimeters. These determinations were very difficult to make because of the stony nature of the soil. Approximately 60 percent of the samples were discarded because of the presence of stones. Enough samples, however, were taken to give six usable samples per plot. The samples were removed to the laboratory, dried, weighed, and the volume weight calculated.

Geiger counter X-ray spectrometer: Samples were taken in triplicate from each individual plot with a Hoer Soil Profile sampler. These samples were sized to approximately one-half by one by two inches and immediately coated on both sides with a four to one amyl acetate-collodian solution and allowed to harden. This coating was applied to hold the sample together and to facilitate handling. This coating had no effect on the action of the X-ray spectrometer pattern.

Quartz was used as the indicator mineral and the 1010 or secondary quartz line determined. Four determinations of this line were made at intervals on each sample, giving a total of twelve determinations for each plot. These readings were averaged to determine the average intensity of the quartz line for each plot.

RESULTS

Penetrometer: Table XLIII of the appendix shows the penetrometer readings. Appendix Table XLIV shows the analysis of variance for penetrometer readings and indicates a high significance for compaction. This table also shows that aerification has a significant effect on penetrometer readings. Although the analysis of variance shows no significant effect of moisture on penetrometer readings, Figure 1 does show a definite trend. In this respect it should be pointed out that penetrometer readings were taken June 1st. At this time no supplemental irrigation had been applied to the plots for approximately ten days because of frequent rains. Therefore all plots were at approximately the same moisture content and moisture had no significant effect on the penetrometer readings. Watson[25] in testing penetrometer readings taken in September has reported that moisture has a highly significant effect on penetrometer readings.

Figure 1 shows that as the moisture content of the soil increases there is an increase in compaction up to a point. In this experiment, this point occurred somewhere between the As Needed moisture level and field capacity. When compaction had reached its maximum at this point, there was a decrease in compaction with increasing moisture. Figure 1 also indicates that as compaction increased, the amount of penetration of the penetrometer probe decreased.

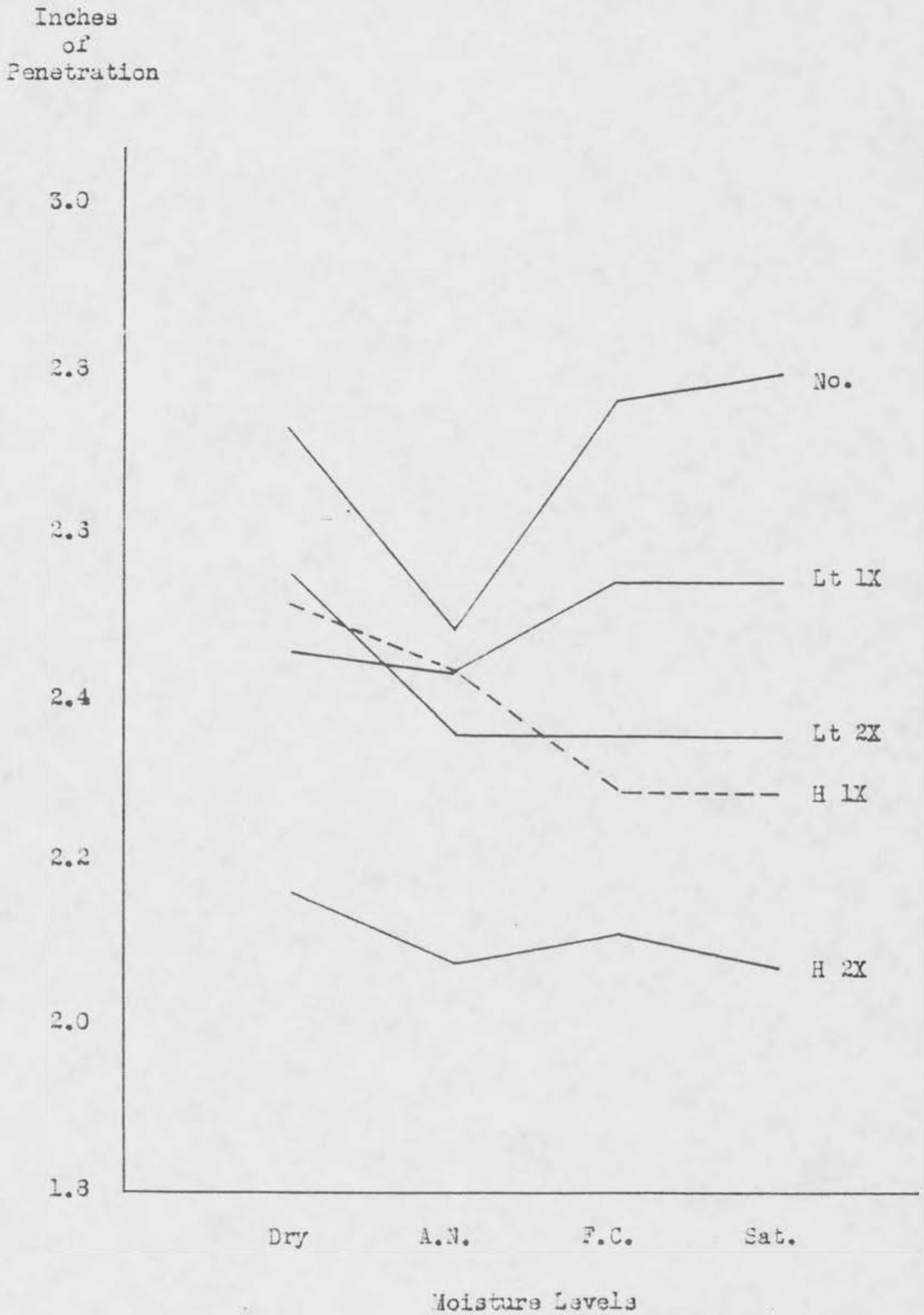

Fig. 1 Relationship between moisture and soil compaction as measured by the soil penetrometer, 1951.

Volume weights: Table XLII of the appendix shows the analysis of variance for volume weights and penetrometer readings, aerification treatments omitted. Because of the difficulty in taking volume weights, samples were taken only from the no compaction and H2X compaction levels at all moisture levels. In making a comparison of the individual analysis of variance for penetrometer and volume weights, it was necessary to use only data from the penetrometer readings which coincided to the volume weight data from the same plots. This explains the difference in the analysis of variance of penetrometer readings found in Table XLII and Table XLIII of the appendix.

The analysis of variance for volume weights (Table XLII) shows compaction to be highly significant. Moisture had no significant effect on the volume weight determinations. This was due to the fact that all plots had the same approximate soil moisture content at the time of sampling. The volume weight samples were taken in early September, shortly after a one inch rainfall. Figure 2 shows that as compaction increases there is a comparable increase in volume weight.

In order to compare volume weights and the penetrometer as a means of determining compaction, a simple correlation was run between penetrometer readings and volume weights. A highly significant correlation of -.7000***[1] was found to exist. That a negative correlation should be obtained is obvious. As compaction increases, the depth to

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1 * Denotes significance at 5% level ** Denotes significance at the 1% level *** Denotes significance at the .1% level

which the penetrometer probe penetrates will decrease. On the other hand, as compaction increases, volume weights will increase.

Geiger counter X-ray spectrometer: Data obtained by use of the X-ray spectrometer was found to be quite inconsistent and very unreliable. The data obtained was found to be almost inverse to that reported by Watson, Jefferies and Musser[26]. In most instances the plots receiving the heaviest compaction treatment (H2X) showed the lowest 1010 quartz line intensity and the plots receiving no compaction other than the normal maintenance practices showed the greatest 1010 quartz line intensity. It was felt that the data obtained had no value whatsoever and no statistical analysis was made. No explanation is at hand for the behavior of the samples in this particular experiment, but opinions of the writer will be expressed in the discussion that follows.

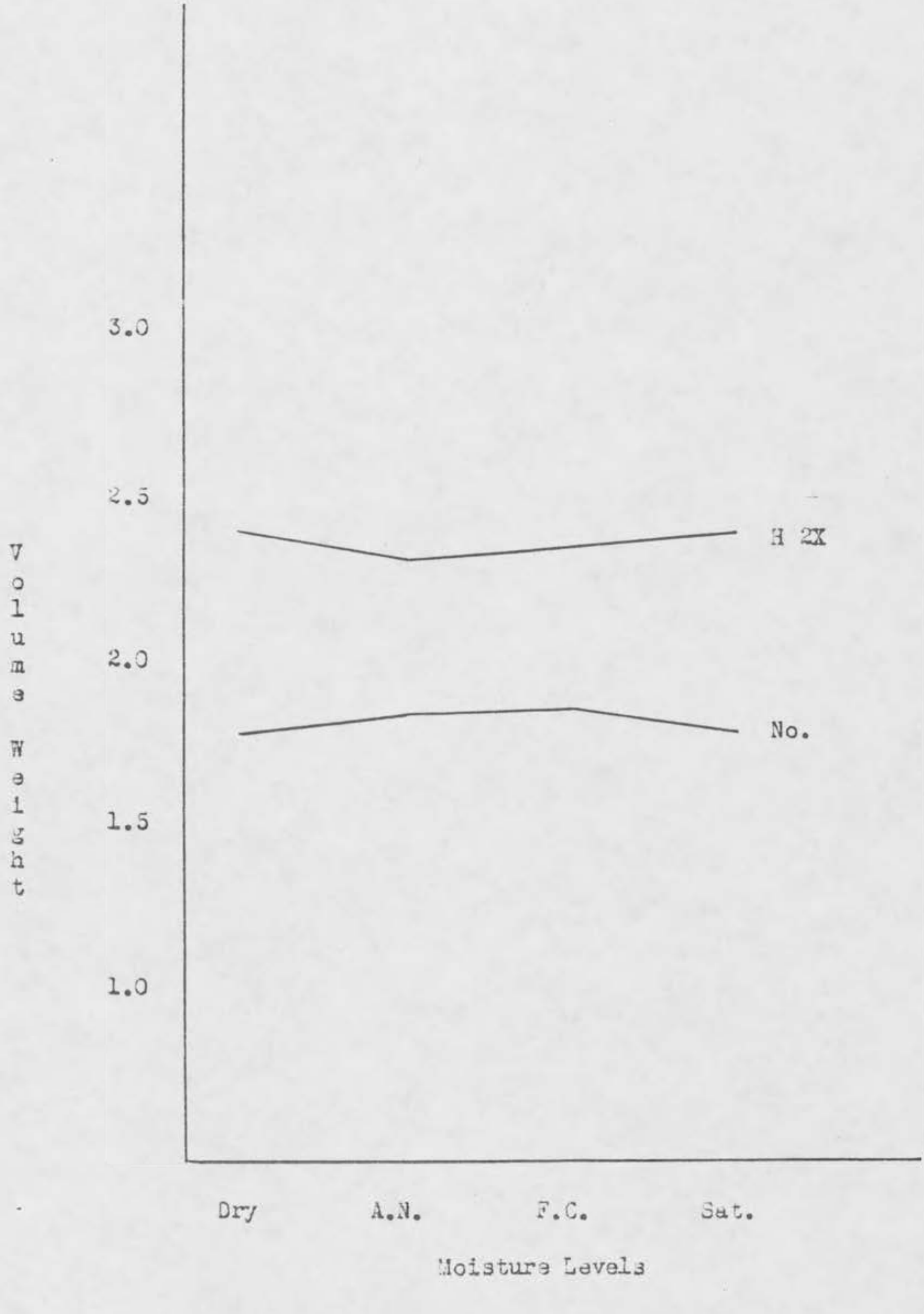


Fig. 2 Relationship between moisture and soil compaction as measured by volume weights, 1951.

DISCUSSION

Penetrometer results obtained in this investigation vary somewhat from those found by Watson(25). Watson(25) has shown that, as the moisture content of the soil increases, there is a straight line decrease in compaction (increase in penetrometer penetration) under any given compaction treatment. Weaver and Jamison(27), working with compaction caused by tractor tires, do not agree with this statement. They have shown that under a given compaction treatment there is an increase in compaction as the moisture content of the soil approaches field capacity. Maximum compaction occurs in this moisture range and with any further increases in moisture content there is a decrease in compaction. This is due, primarily, to the high amount of water in the soil, which is almost impossible to compress. The findings in this investigation confirm the findings of Weaver and Jamison(27).

Under soil conditions which permit the use of volume weight determinations, this method has become the most standard method for determining compaction. Despite the stony nature of the soil under investigation in this work, it was felt that sufficient samples were obtained to remove the undesirable samples. This conviction was upheld by the highly significant correlation that was found to exist between volume weights and soil penetrometer readings.

The Geiger counter X-ray spectrometer did not give consistent compaction measurements comparable to those obtained by volume weight determinations and penetrometer readings as reported by Watson, Musser and Jefferies(26). This may have been due to failure to obtain adequate samples to meet the requirements of the machine itself. The X-ray spectrometer requires that pit free samples approximately one-half by one by two inches be used. It is difficult to obtain proper samples with the Hoer Soil Profile Sampler, the tool used to take samples for X-ray determination. The stony nature of the experimental area increased the difficulties of sampling. Stones small enough to enter the sampler often caused the sample to break apart or crack when being removed from the sampler. Larger stones prevented the penetration of the sampler to the desired depth. Another difficulty arose in the coating of the samples to prevent breakage in handling. Because it was necessary to lay the sample down immediately after coating, differential drying took place and the sample often warped to some degree. The samples obtained in this investigation were, therefore, quite inconsistent.

The samples themselves became a further problem when placed in the X-ray machine. Pits in the samples caused by the presence of small stones in the sampler and the scraping of the sample against the ragged edge of the sampler caused considerable variations in the X-ray intensities. In many cases the X-ray was deflected from side to side in the soil pits causing false readings on the Geiger counter.

This discussion is not designed as a condemnation of the Geiger counter X-ray spectrometer method of soil compaction measurement, but rather is to point out some of the difficulties which must be overcome if this method is to be used successfully to measure soil compaction.

SUMMARY

It has been shown that a close relationship exists between penetrometer readings and volume weights. This relationship is shown by a highly significant negative correlation. As compaction increases, there is a decrease in penetrometer readings, but as compaction increases there is an increase in volume weights. This necessitates a negative correlation.

Statistical analysis showed compaction to be highly significant (1%) when compaction determinations were made with the penetrometer and volume weights. Moisture was not found to be statistically significant, but the interaction of moisture x compaction was found to be significant at the 5% level.

In this investigation, the Geiger counter X-ray spectrometer was found to be quite unreliable as a method of measuring compaction. It is felt that the X-ray data was not complete and further work should be done with this machine before recommending or condemning it as a means of determining compaction.

RESULTS

Effects of Moisture, Compaction, and Aerification on the Total Percent of Permanent Species in the Turf Population

The average percentage of total population that is permanent species under the various moisture and compaction treatments in 1950 is shown in Table I of the appendix with the analysis of variance for the data. Table I shows that the percent permanent species was quite uniform under all compaction levels. The mean average percent permanent species under all compaction treatments in 1950 was 93.7 percent. The statistical analysis indicates that compaction had no significant effect at the five percent level on the percent permanent species. Table I of the appendix also shows a definite trend towards a decrease in percent permanent species as the moisture content increased. This trend is shown more clearly in Figure 3. Statistically, moisture had no significant effect at the five percent level on the percent permanent species present in the turf population in 1950. The interaction of moisture x compaction was not significant in 1950.

Appendix Table II shows the average percentage of the turf population that is permanent species at the various moisture, compaction, and aerification treatments in 1951. Appendix Table III shows the statistical analysis for this data. As in 1950, compaction had no significant effect on the percent permanent species. The mean average percent permanent species under all compaction treatments in 1951 was 95 percent. This was not a significant increase over the percent

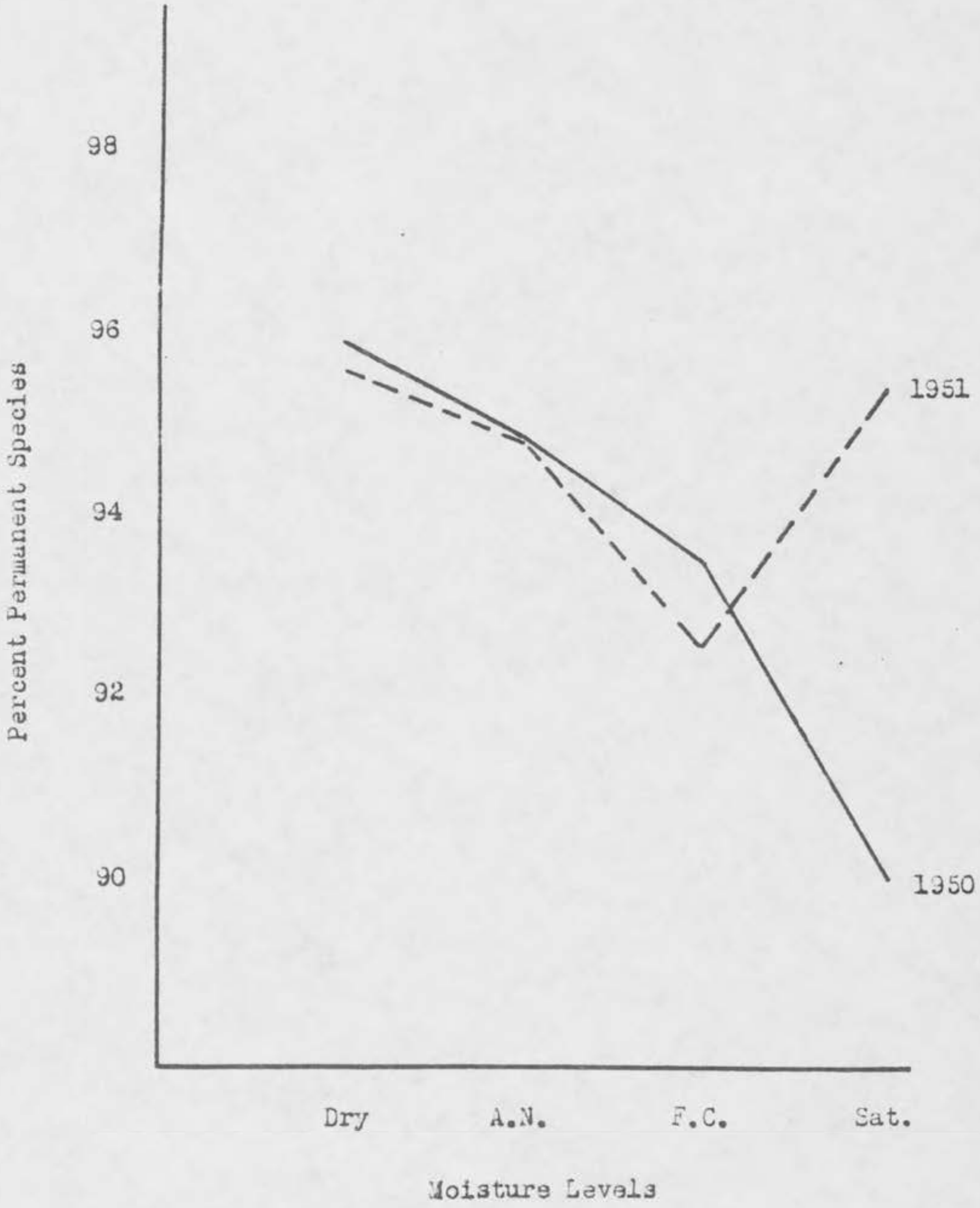


Fig. 3 Effect of moisture on the percent total species that is permanent species, 1950 and 1951.

permanent species determined in 1950. There was no significant effect due to moisture on the percent permanent species in 1951. The trend towards a decrease in percent permanent species with an increase in moisture content shown in the 1950 data was not found in the 1951 data (Figure 3). Aerification had no significant effect on the percent permanent species in 1951. Figure 4 shows a slight trend towards a decrease in percent permanent species due to aerification. This was probably due to an increase in weed population under Spring aerification.

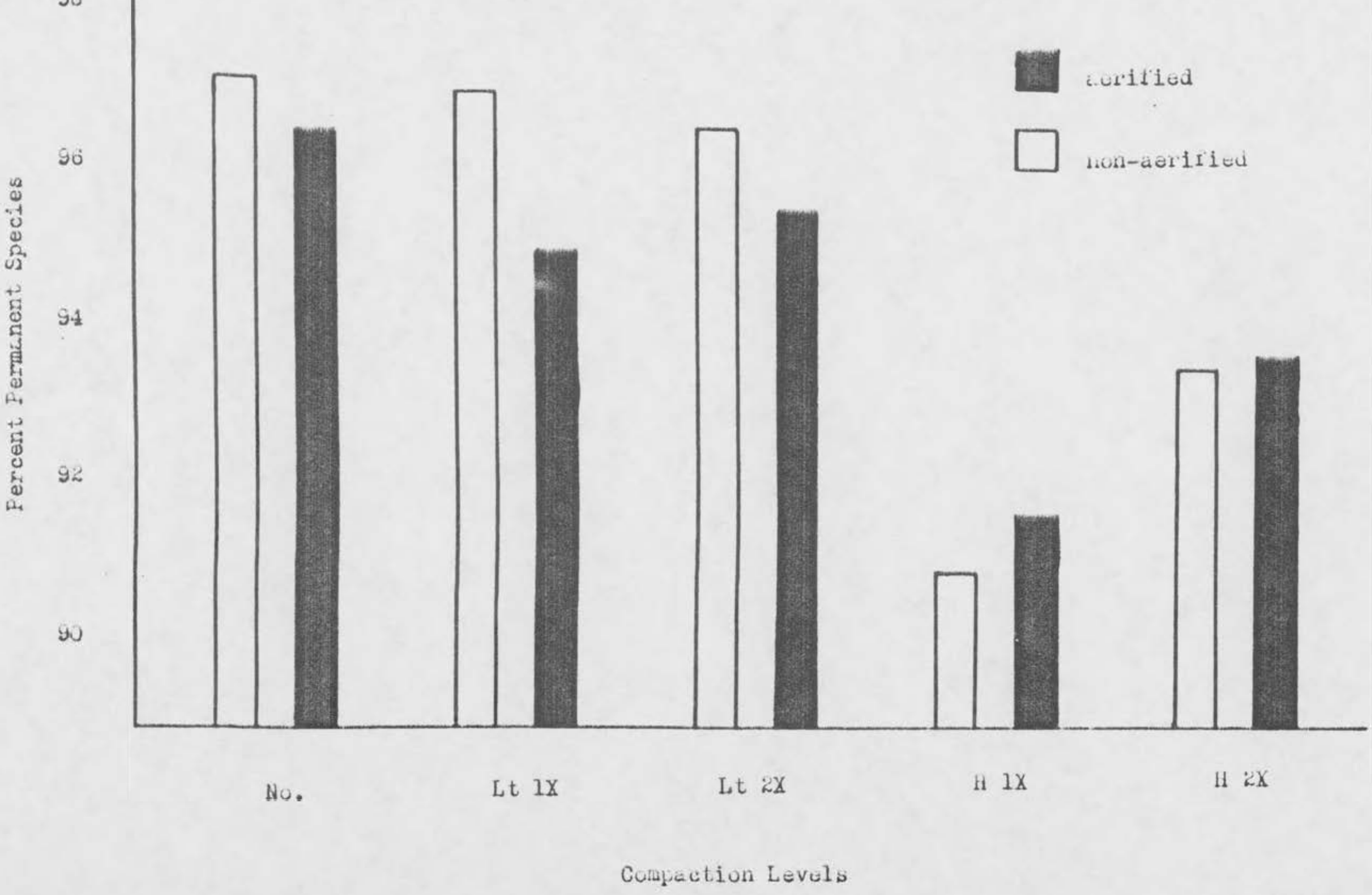
The interactions of aerification x moisture, aerification x compaction, and aerification x moisture x compaction were not significant in 1951.

Table XXVIII of the appendix shows the average percentage difference in percent total species that is permanent species, 1950 to 1951.

Effects of Moisture, Compaction, and Aerification on Individual Species of Permanent Grasses

Bentgrass: Table VII of the appendix shows the average percentage of permanent species that is bentgrass at the various moisture and compaction levels in 1950. The main effects of compaction and moisture were not significant at the five percent level. The average percent bentgrass present under the various compaction levels is quite consistent. The mean average percent bentgrass for all compaction treatments is 91.4 percent. Figure 5 shows a definite trend in the moisture levels. As moisture increases there is also an increase in the percent bentgrass. The effect of moisture x compaction was not significant in 1950.

Fig. 4 Effect of aerification on the percent total species that is permanent species at the various compaction levels, 1951.



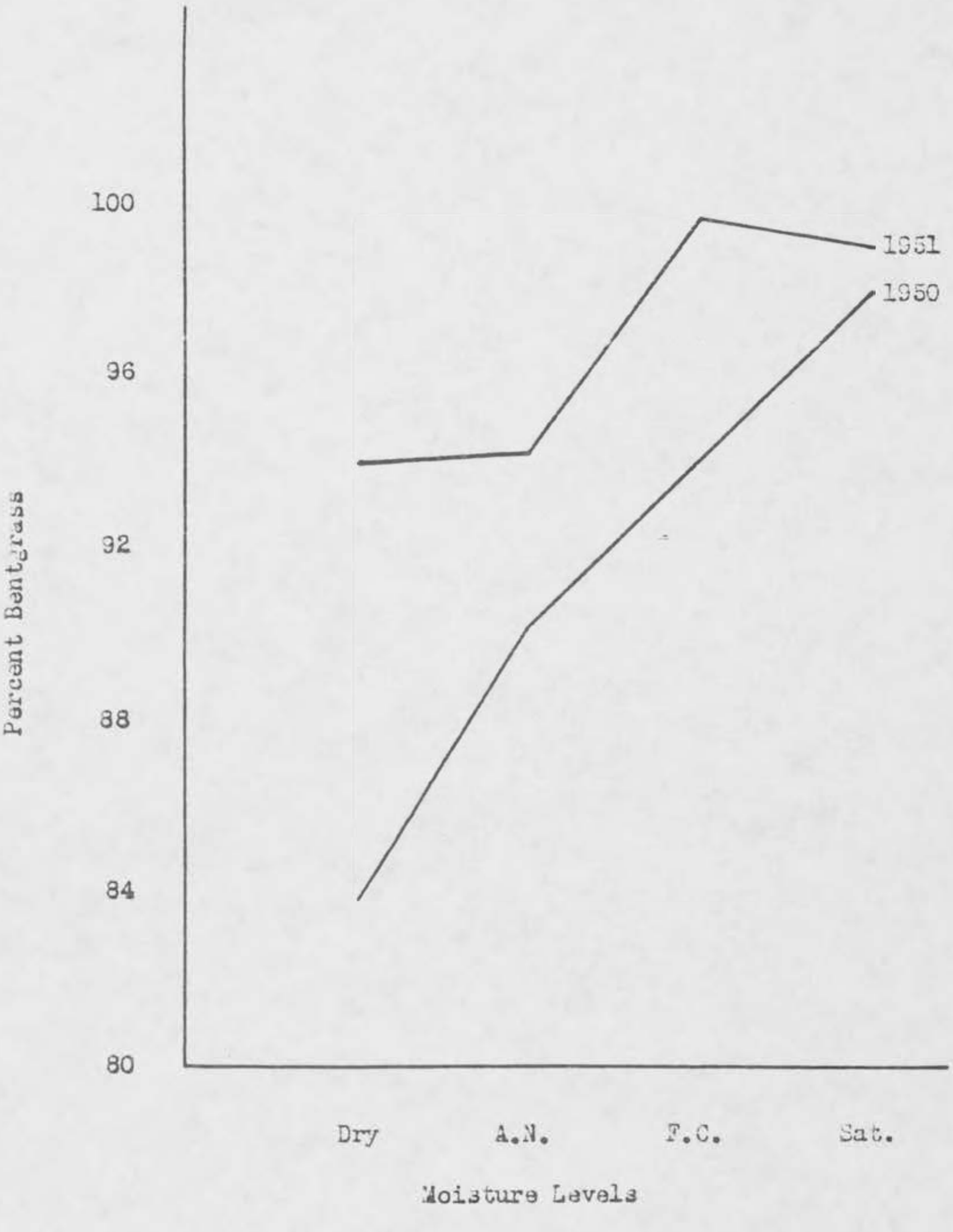


Fig. 5 Effect of moisture on the percent permanent species that is bentgrass, 1950 and 1951.

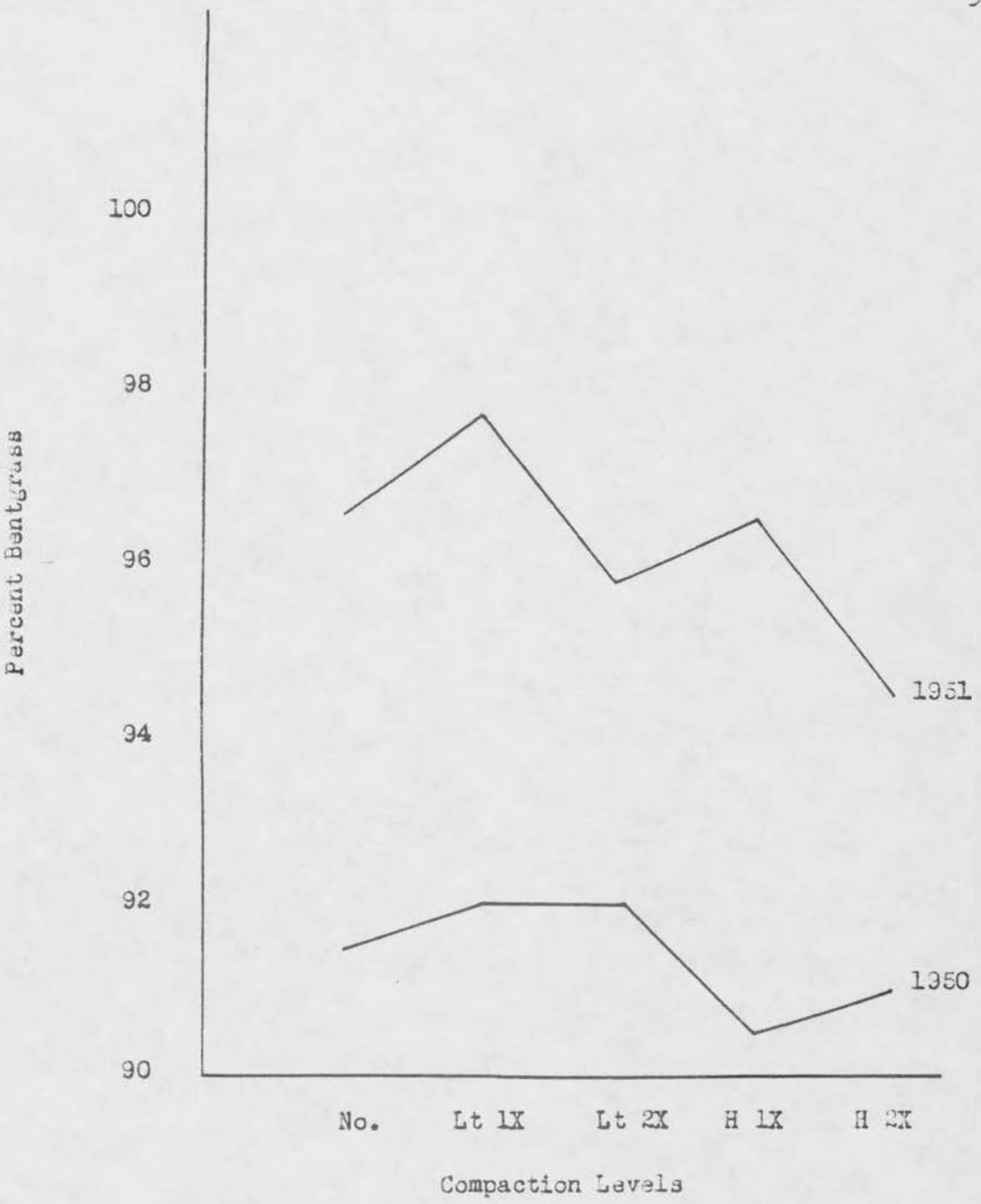


Fig. 6 Effect of compaction on the percent permanent species that is bentgrass, 1950 and 1951.

The average percentage of permanent species that is bentgrass in 1951 is shown in Table VIII of the appendix. The analysis of variance of this data is given in appendix Table IX. Compaction, moisture, and aerification had no significant effect on the bentgrass population at the five percent level. As in 1950 there is an increase in bentgrass as moisture increases (Figure 5).

Figure 6 shows graphically the effect of compaction levels on the percent permanent species that is bentgrass, 1950 and 1951. Table XXV of the appendix shows the average percent differences in the bentgrass population, 1950 to 1951.

Kentucky Bluegrass: Table X of the appendix shows the average percentage of permanent species that is Kentucky bluegrass at the various compaction and moisture levels in 1950. The statistical analysis for this data is also given in the same table. Compaction was found to exert a highly significant effect on the Kentucky bluegrass population. The Kentucky bluegrass population was higher on the heavier compacted plots than it was on the no and light compacted plots. Figure 7 graphically shows the effect of compaction on bluegrass population. Moisture had no significant effect at the five percent level on the percent bluegrass present. The interaction of compaction x moisture was found to be significant at the five percent level in 1950.

Kentucky bluegrass percentages for 1951 under the various moisture, compaction, and aerification levels are given in appendix Table XI. Appendix Table XII gives the analysis of variance for this data. As in 1950, compaction had a significant effect on the bluegrass population.

The H2X plots showed a much higher Kentucky bluegrass population than did any of the other plots. The effect of compaction on the percentage bluegrass present is shown in Figure 7. Moisture had no significant effect on the bluegrass population, but Table XI of the appendix does show a trend towards a decrease in bluegrass population with an increase in moisture. Aerification had a significant effect on the bluegrass population, primarily through its beneficial effects on the weed population. Aerification had more effect on the bluegrass population under the various moisture levels than it did under the different compaction levels. The effect of aerification on the percent bluegrass under the different moisture levels is shown graphically in Figure 8. There were no significant interactions in the 1951 data.

Red Fescue: The average percentage of permanent species that is red fescue under the various moisture and compaction treatments in 1950 is given in Table XIII of the appendix, as is the analysis of variance for this data. Compaction had no significant effect on the fescue population at the five percent level. In like manner, moisture showed no significant effect on the percent fescue present. Moisture did show a decided trend. As the moisture content of the soil increased there was a sharp decrease in the percent fescue present. This is shown graphically in Figure 9.

The 1951 data (appendix Tables XIV and XV) for percent fescue present is quite similar to the 1950 data. Compaction had no significant effect at the five percent level. Moisture showed no significant effect, but, as in 1950, a trend towards a decrease in fescue population with an increase in moisture was shown. This is also illustrated

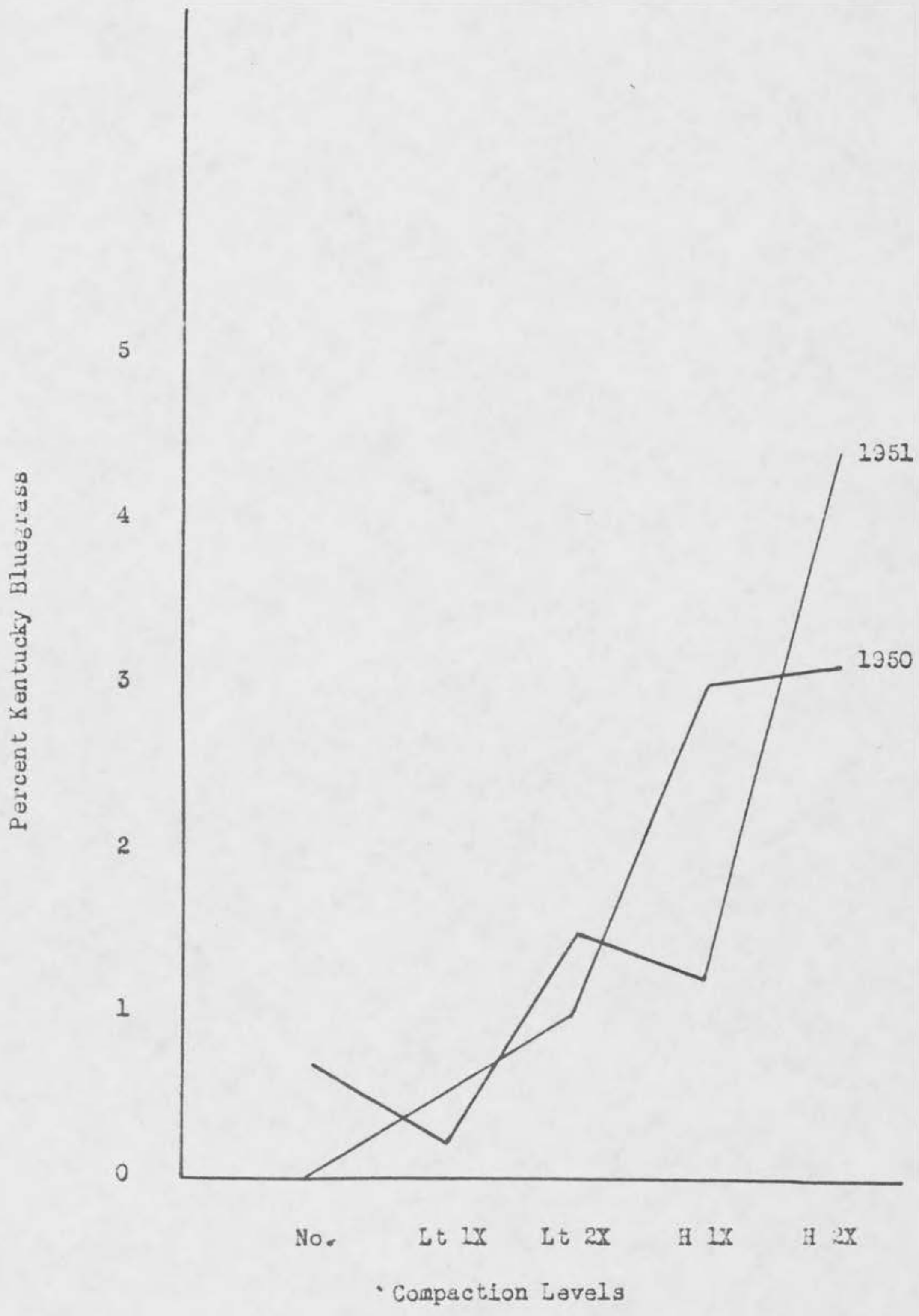


Fig. 7 Effect of compaction on the percent permanent species that is Kentucky bluegrass, 1950 and 1951.

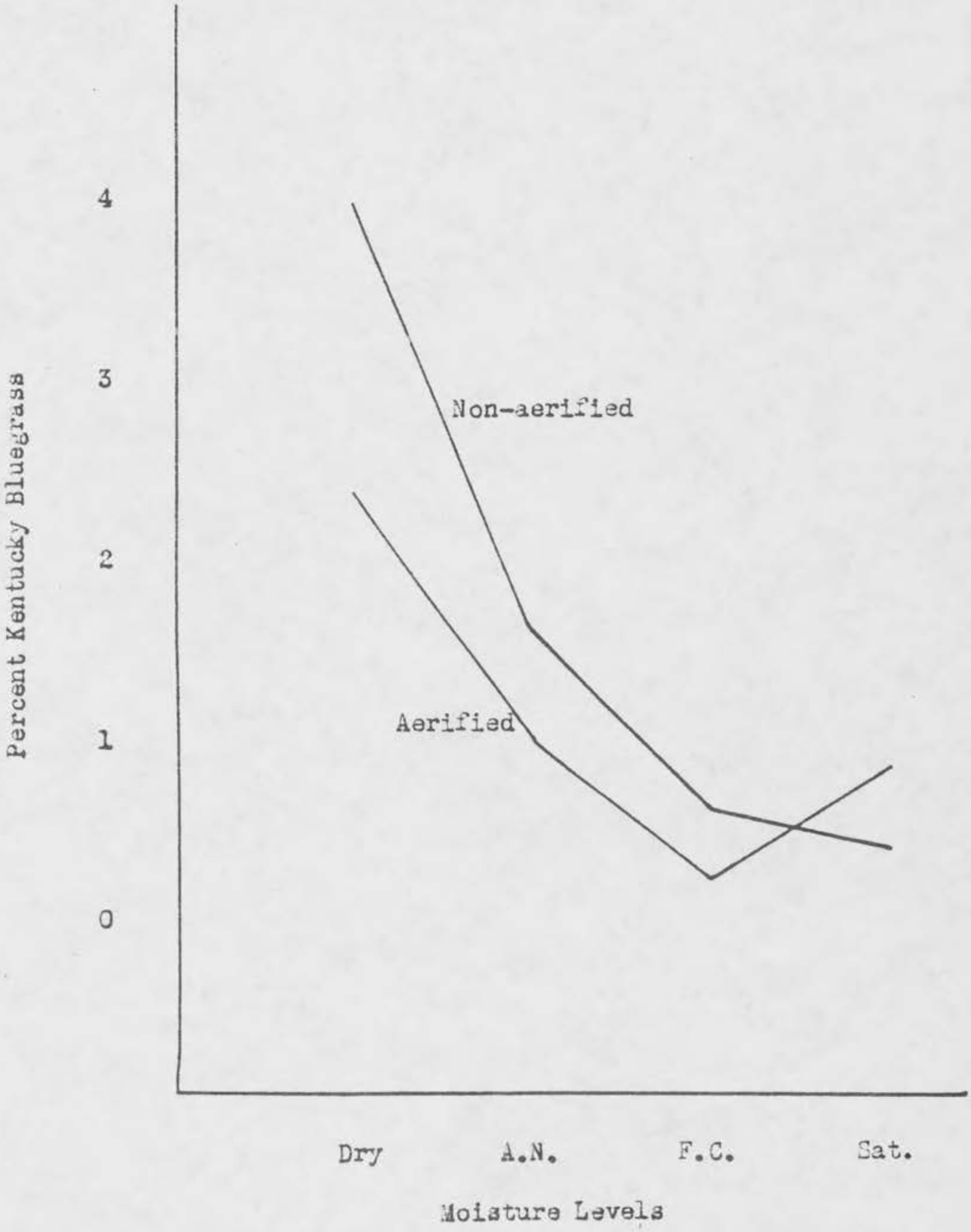


Fig. 8 Effect of aerification on the percent permanent species that is Kentucky bluegrass at the various moisture levels, 1951.

in Figure 9. There was no significant effect on fescue population due to aerification in 1951. None of the interactions involving the three types of treatments were significant.

Effects of Moisture, Compaction, and Aerification on the Percent Clover, Crabgrass, and Total Weeds present in the Turf Population

Clover: Estimates of the percentage total plot area covered by clover at the various compaction and moisture levels in July 1950 are given in appendix Table XVI as is the analysis of variance for this data. At this time compaction and moisture had no significant effect on the ground area covered by clover.

Table XVII of the appendix gives the same information for July 1951. The analysis for this data is found in appendix Table XVIII. Again compaction and moisture had no direct effect on the plot area covered by clover, but the interaction of moisture x compaction was significant at the five percent level.

The average percentage of total species that is clover at the various moisture and compaction levels in September 1950 is given in appendix Table XIX. The statistical analysis is given in the same table. Compaction had no significant effect on clover population at the five percent level, although the calculated F value approaches significance quite closely. Clover appears to be much higher on the heavy compacted plots than on the no compacted and lighter compacted plots. The analysis of variance shows that moisture had no significant effect on the clover population, although there are indications that

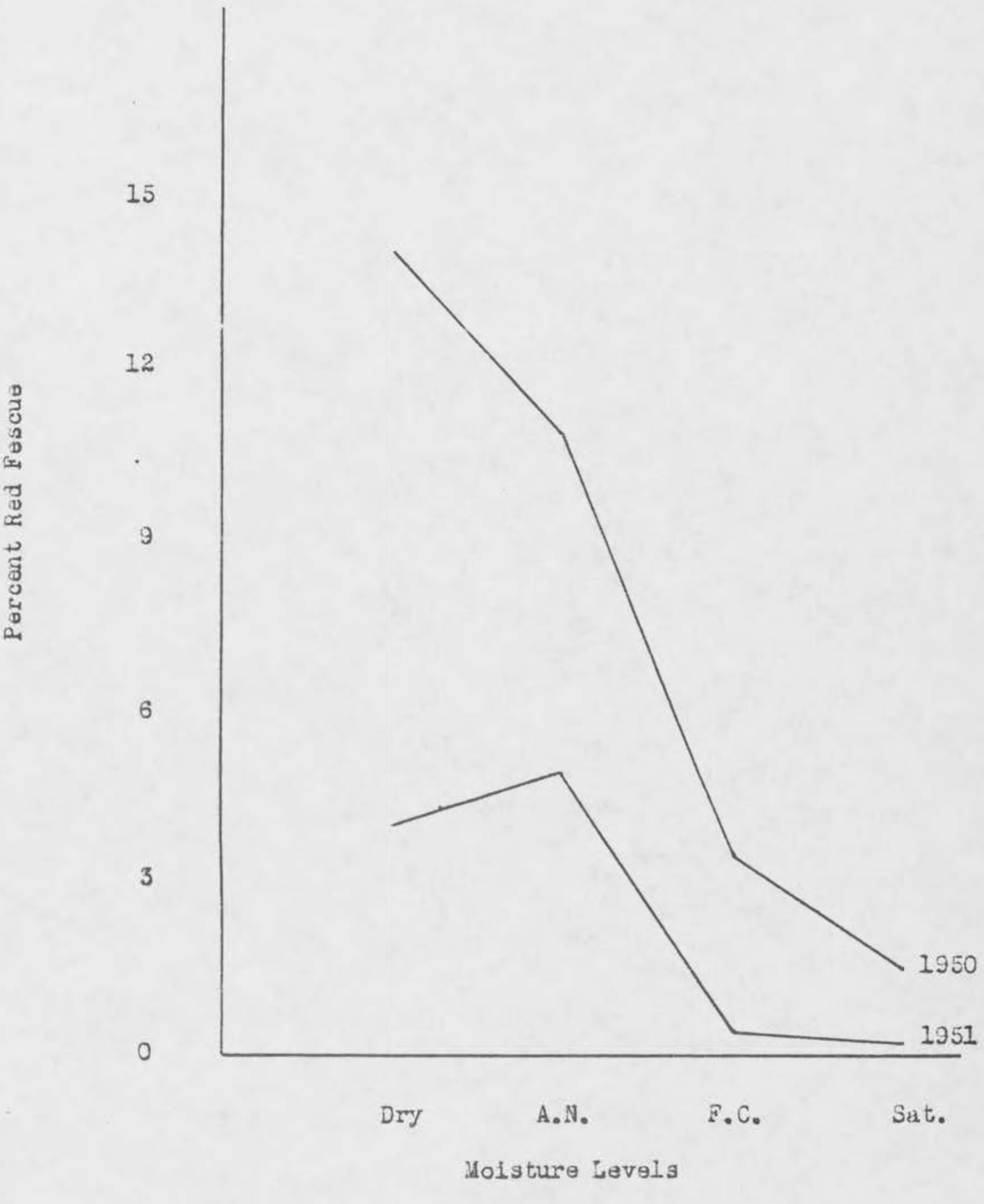


Fig. 9 Effect of moisture on the percent permanent species that is red fescue, 1950 and 1951.

clover increases with an increase in moisture (Figure 10).

Appendix Table XX gives the percent clover present in 1951 and appendix Table XXI gives the statistical analysis for this data. Compaction, moisture, and aerification had no significant effect on the clover population at the five percent level. The trend towards an increase in clover with increasing moisture content was not as evident in 1951 as it was in 1950 (Figure 10). Figure 11 indicates the effect of aerification on the percent clover present at the various moisture levels. As moisture increased from dry to field capacity, there was an increase in clover population. Clover population then decreased, primarily due to the density of the bentgrass and crabgrass which prevented the invasion of the clover.

Crabgrass: The average number of crabgrass plants occurring under double x line diagonals at the various moisture and compaction levels in 1950 is given in appendix Table XXII. The analysis of variance shows that compaction had no significant effect on the crabgrass population. Moisture, however, was found to be highly significant (1% level). Figure 12 indicates that, as moisture increased, there was also an increase in the crabgrass population. Although compaction was not significant, there was, in all cases, a smaller number of crabgrass plants present on the heavy compacted plots, as compared to all other plots. The interaction of compaction x moisture was not significant in 1950.

Crabgrass data for 1951 is found in Table XXIII of the appendix and the analysis of variance for the data in appendix Table XXIV. As in 1950, compaction had no significant effect on crabgrass population

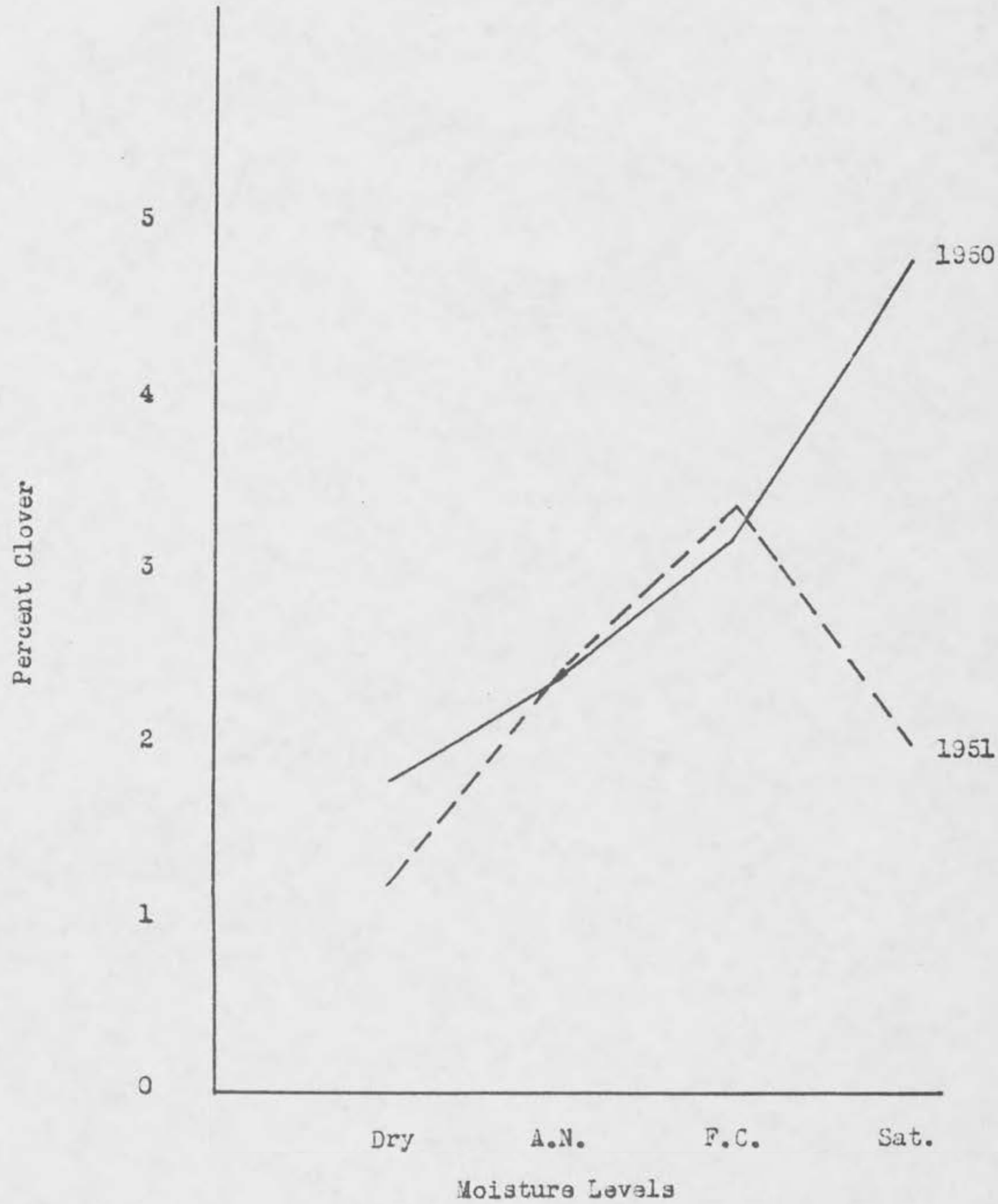


Fig. 10 Effect of moisture on the percent-total species that is clover, 1950 and 1951.

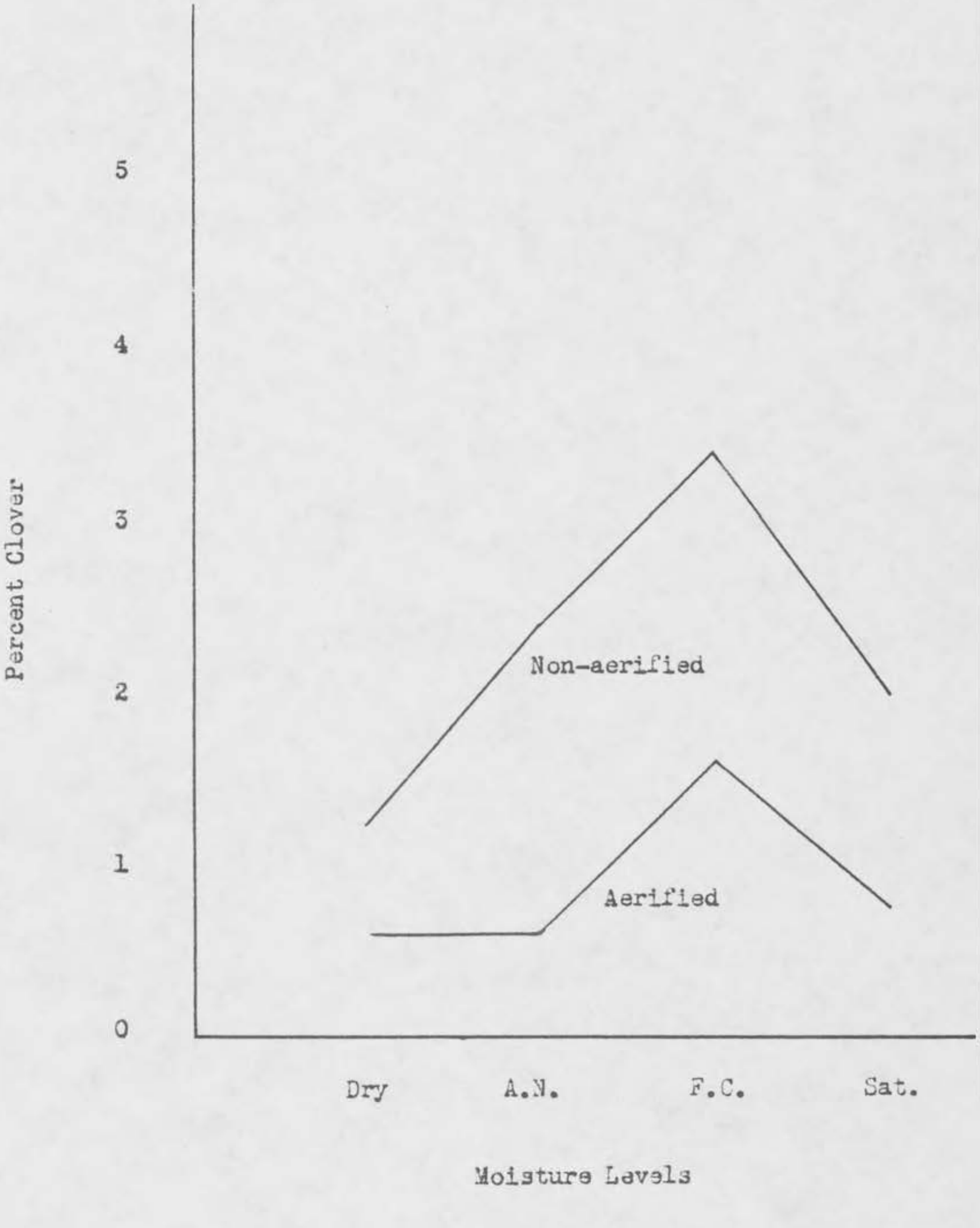


Fig. 11 Effect of aerification on percent clover present at the various moisture levels, 1951.

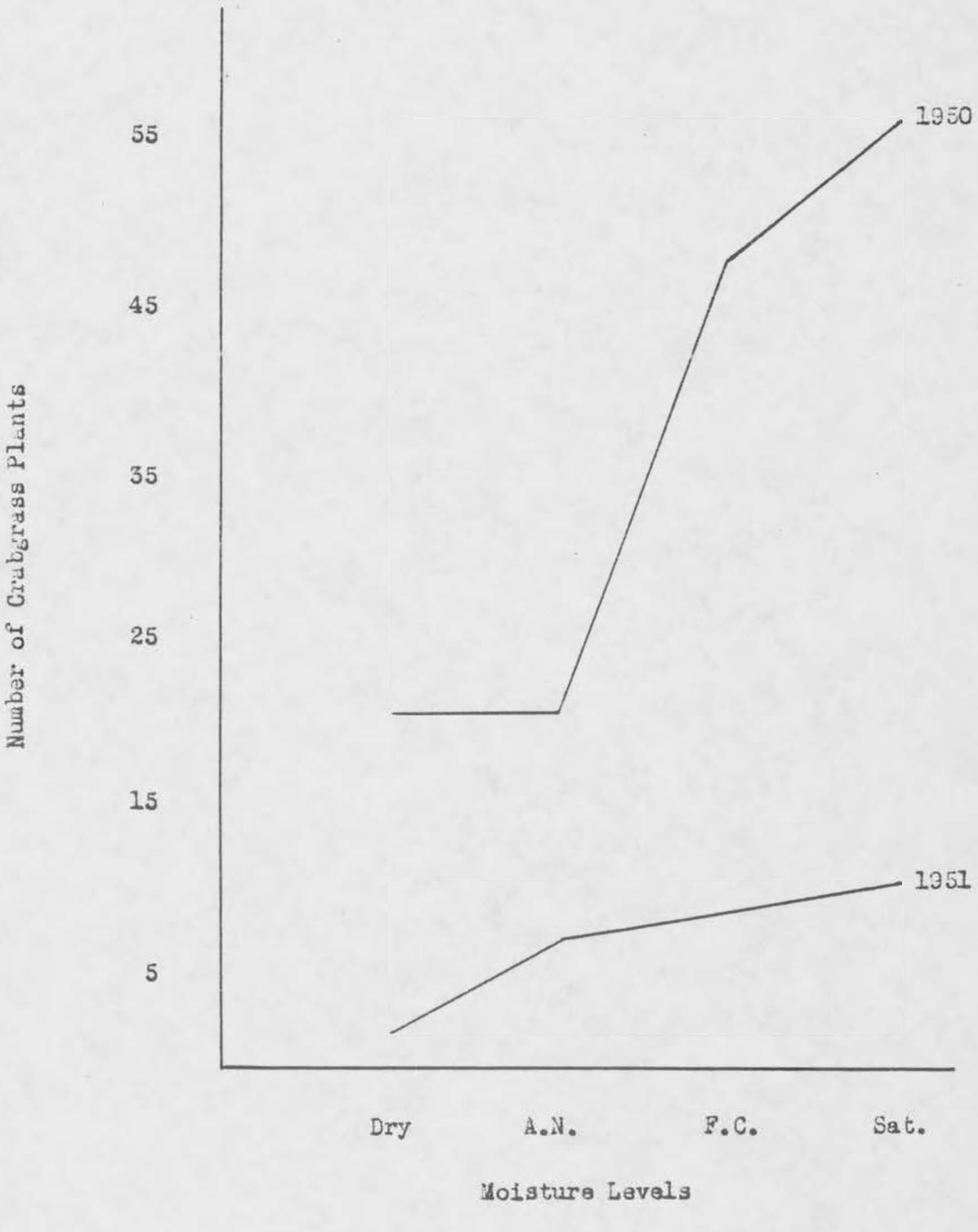


Fig. 12 Effect of moisture on the number of crab-grass plants occurring under line diagonals, 1950 and 1951.

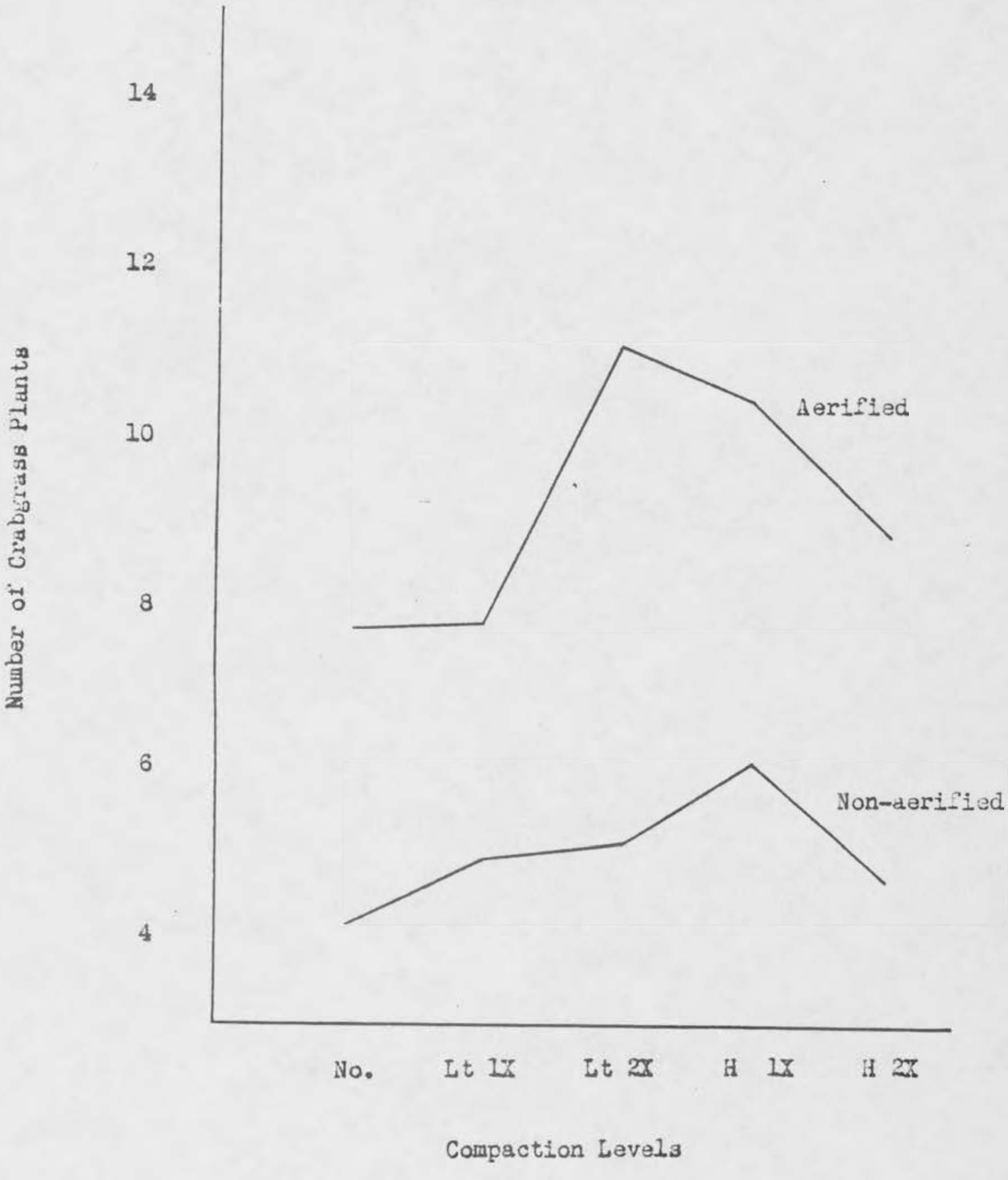


Fig. 13 Effect of aerification on the number of crabgrass plants occurring under line diagonals at various compaction levels, 1951.

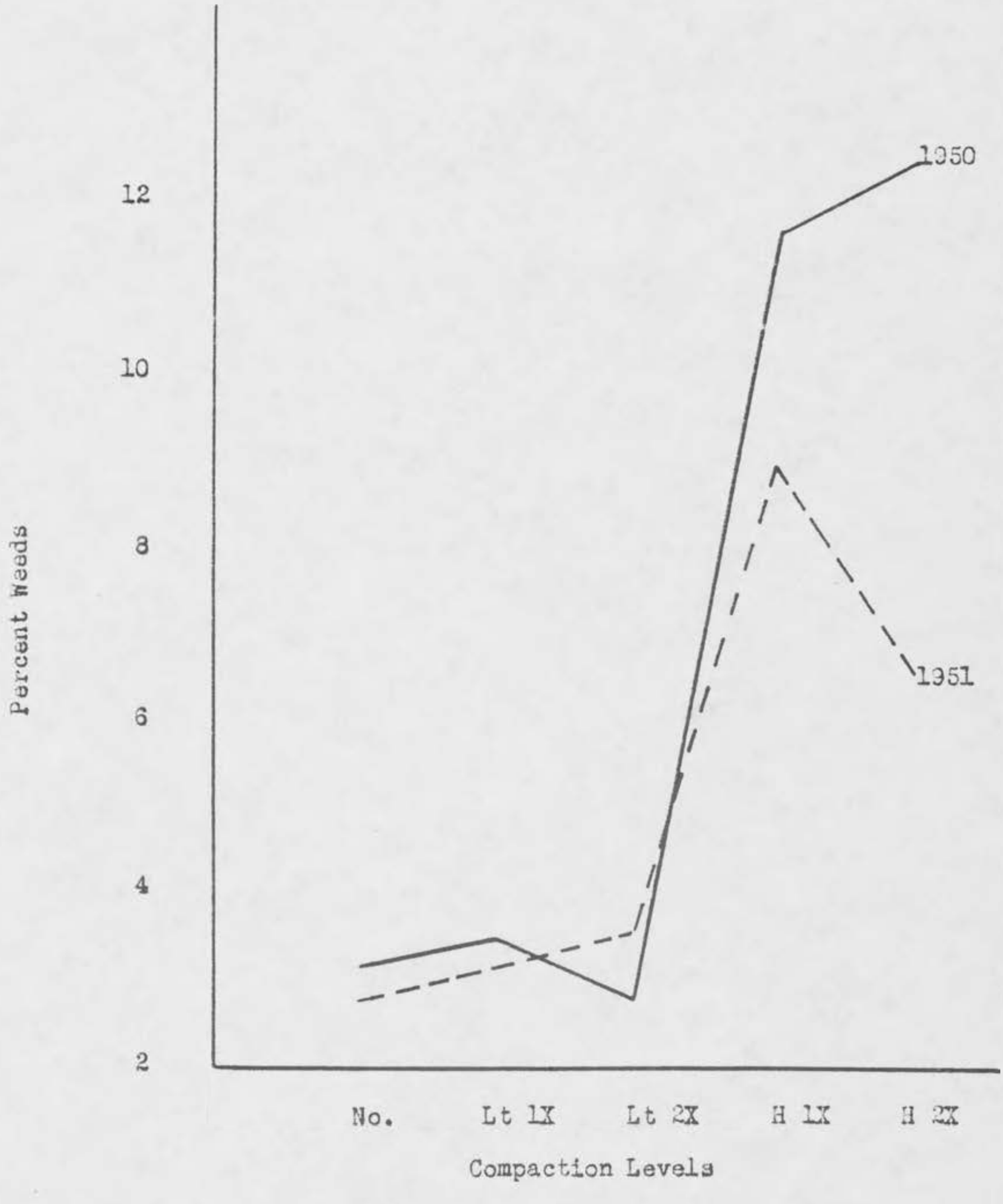


Fig. 14 Effect of compaction on the percent total species that is weeds, 1950 and 1951.

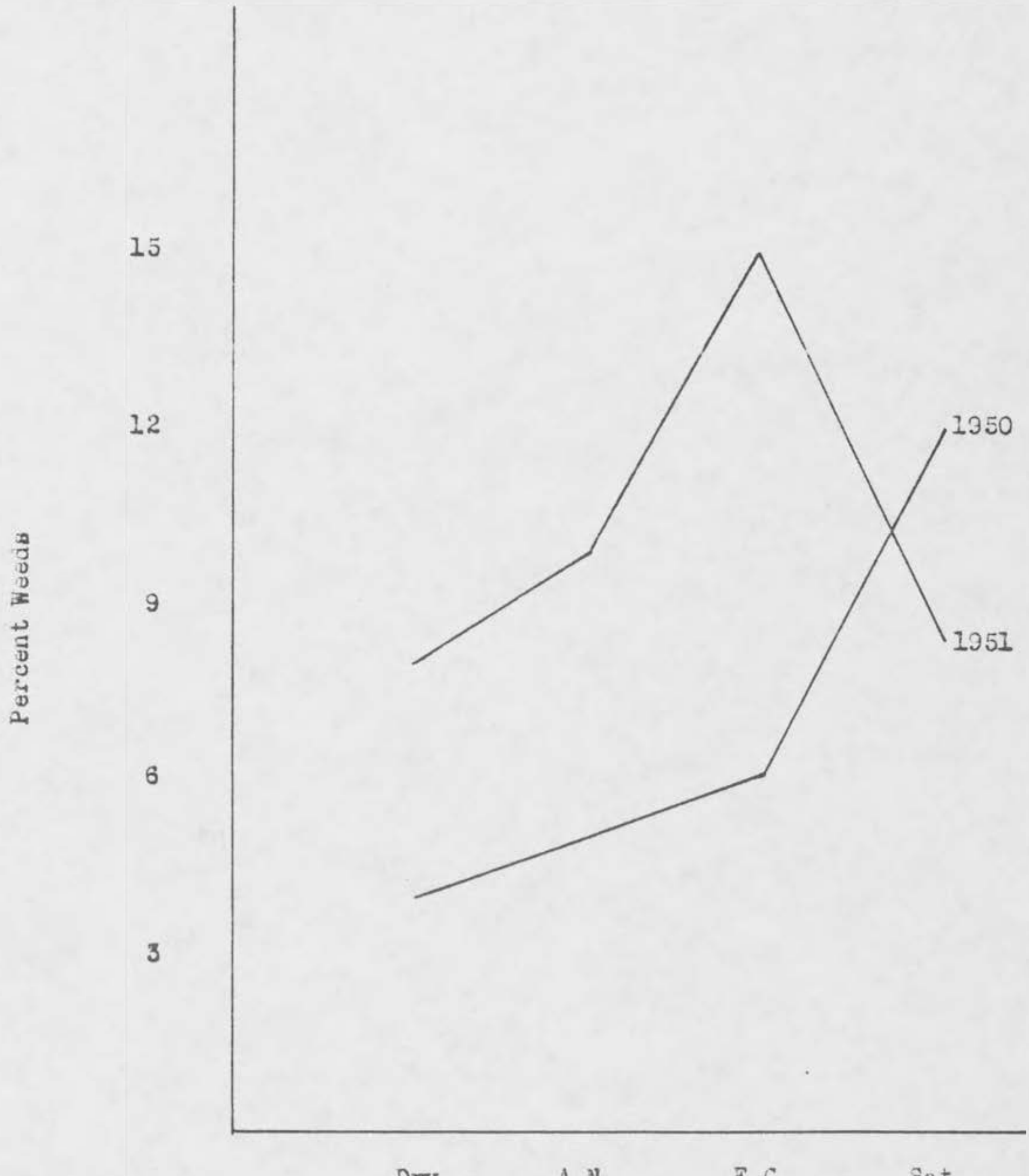


Fig. 15 Effect of moisture on the percent total species that is weeds, 1950 and 1951.

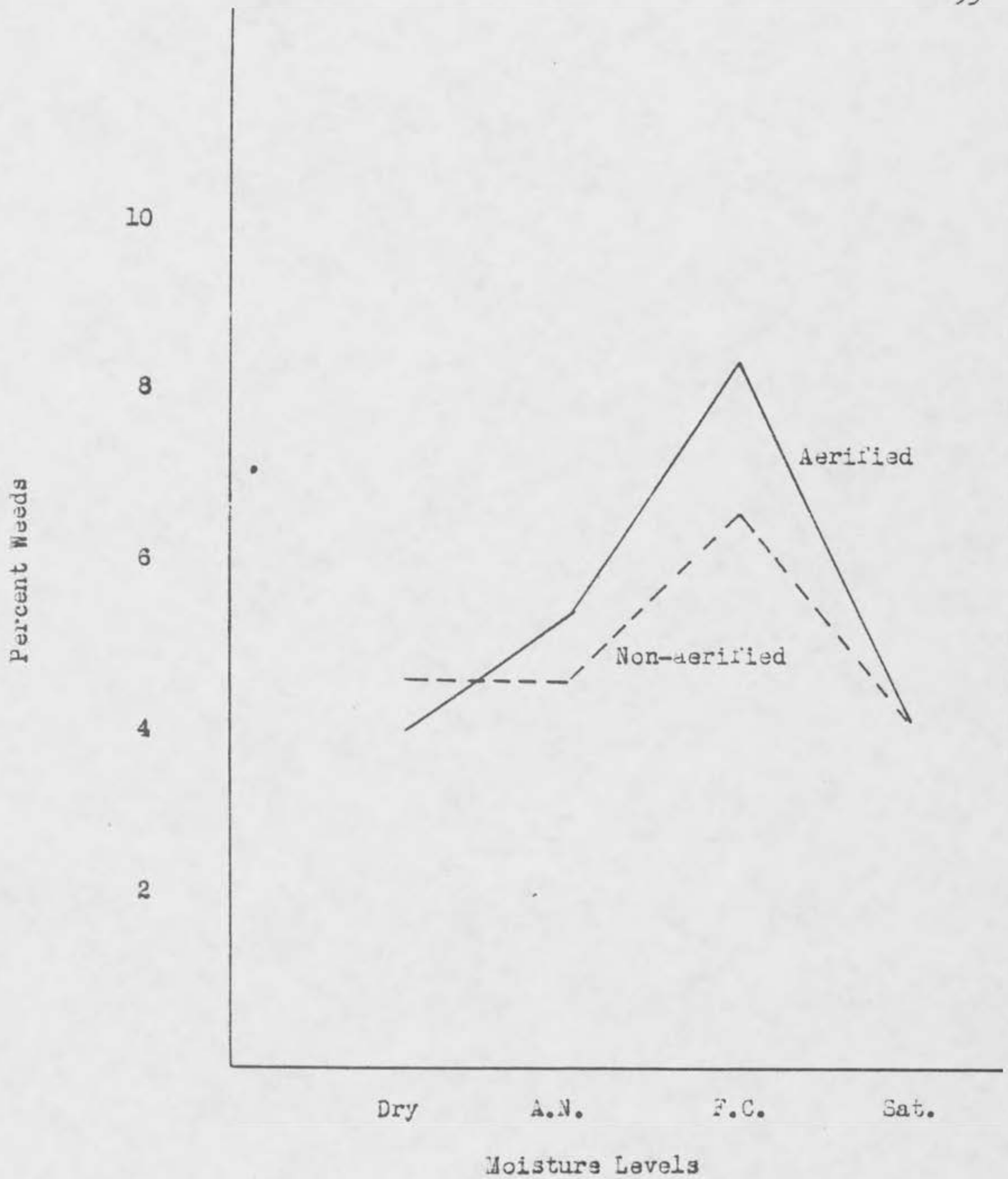


Fig. 16 Effect of aerification on weed population at various moisture levels, 1951.

at the five percent level. Contrary to the 1950 results, moisture was not significant in 1951. However, as Figure 12 indicates, there was still a tendency for the crabgrass population to increase with an increase in moisture. In 1951 aerification had a highly significant effect on the crabgrass population. Under any given compaction level there was a highly significant increase in the amount of crabgrass on the aerified half of the individual plots. This is shown graphically in Figure 13. No interactions were significant.

<u>Weeds</u>: Table IV gives the average percentage of total species that is weeds at the various compaction and moisture levels in 1950. Compaction had no significant effect on the weed population, although the data indicates that there is a heavier weed infestation on the heaviest compacted plots as compared to the no compacted and light compacted plots. This is shown graphically in Figure 14. Moisture showed a definite trend, but was not significant at the five percent level. As the moisture content increased, there was an increase in the weed population. Figure 15 illustrates this trend. The interaction of moisture x compaction was not significant at the five percent level.

Appendix Tables V and VI give the weed population data for 1951. As in 1950, compaction and moisture had no significant effect on the percent weeds present. Moisture and compaction trends (Figures 14 and 15) were not as pronounced in 1951 as they were in 1950. This may be due to the lower severity of crabgrass infestation in 1951. Although aerification was not significant at the five percent level, there was a very marked increase in weed population on the aerified plots as compared to the non-aerified plots. Figure 16 shows the effect of aerification under the various moisture levels in 1951.

The interactions of moisture x compaction, moisture x aerification, aerification x compaction, and aerification x moisture x compaction had no significant effect on weed population.

Effects of Moisture, Compaction, and Aerification on Root Quantities and Distribution

Moisture and compaction had very little effect on the total quantity of roots produced in 1950 and 1951. The average grams of oven dry roots present in soil cores one and five eighths inches in diameter to a depth of six inches in September 1950, may be found in appendix Table XXXI. The same data for September 1951 may be found in appendix Tables XXXII and XXXIII. The 1951 data shows a much higher total quantity of roots on the dry plots as compared to the irrigated plots.

Appendix Table XXXIV shows the average percentage of total roots in the upper two inch layer of a total six inch layer under the various moisture and compaction levels in 1950. Compaction and moisture were not significant in 1950 at the five percent level and exerted very little influence on root distribution. In 1951 moisture had a very significant effect on the distribution of roots (Appendix Table XXXVI). As moisture increased, there was an increase in the percentage of the total roots found in the upper two inches. This is shown graphically in Figure 17. The L.S.D. for moisture may be found in appendix Table XXXVI and applied to the root values found in appendix Table XXXV. Compaction and aerification had no significant effect on root

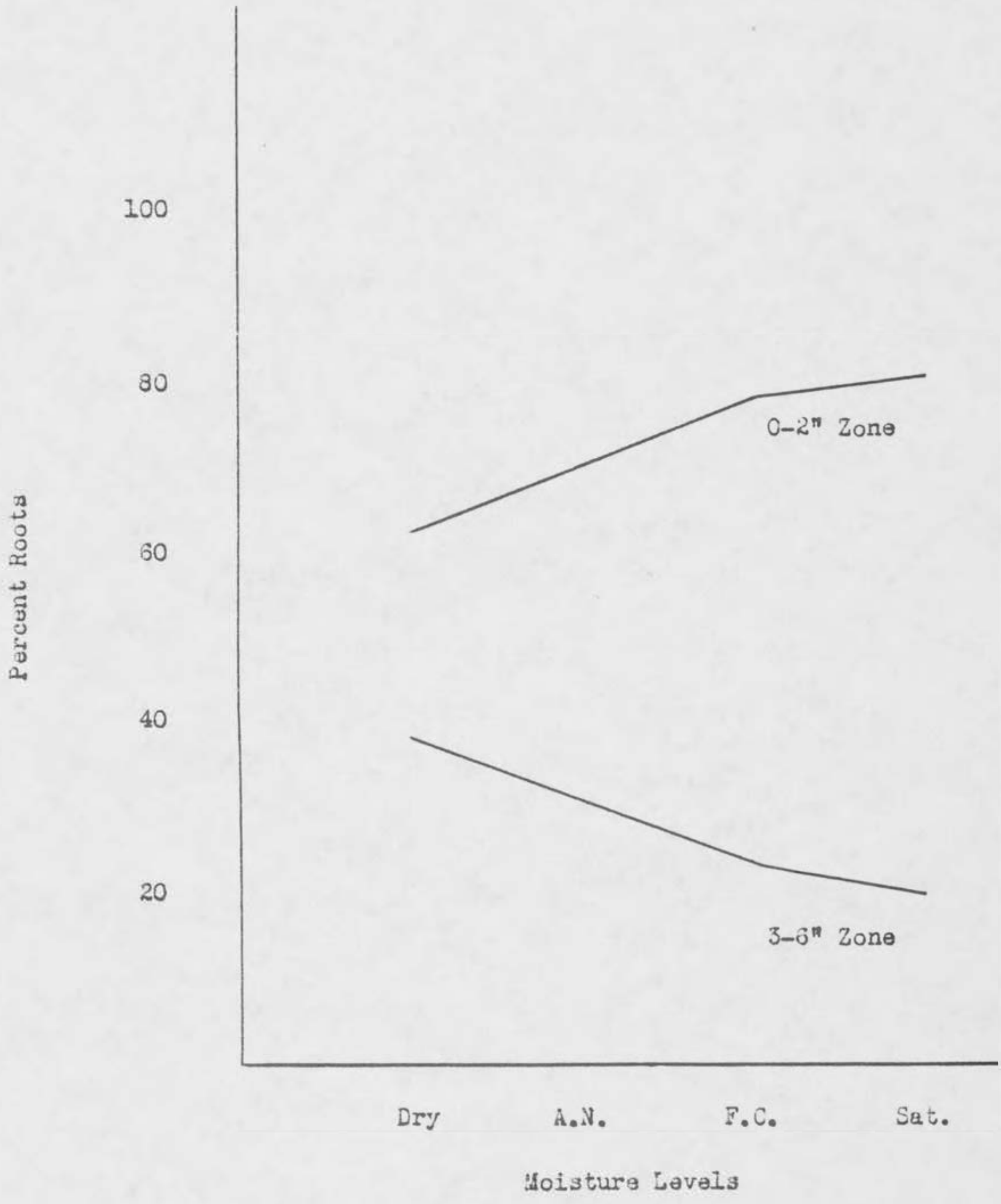


Fig. 17 Effect of moisture on the percent of total roots found in various soil zones, 1951.

distribution in 1951.

The percentage roots found in the lower four inches of the total six inch layer and the statistical analysis of this data is found in Tables XXXVII, XXXVIII, and XXXIX of the appendix. As expected from the results indicated in the upper two inches, compaction and moisture had no significant effect on the root distribution in 1950. Compaction had no significant effect in 1951. As in the upper two inches, moisture had a significant effect on the distribution of the roots in the lower four inches in 1951. In the lower four inch layer there was a decrease in roots with an increase in moisture. This was due to an increase in roots with an increase in moisture in the upper two inch layer. (The percentage roots in the lower four inches having been determined by 100 minus the percentage roots in the upper two inches.)

Aerification showed no significant effect on root quantity or distribution in 1951. This statement may, in some instances, be quite misleading. Under extreme conditions, e.g., heavy compaction and little or no irrigation, there were positive indications that aerification did have some beneficial effects. Although these differences were quite small, they assume much greater importance when converted to a pounds per acre or lineal feet of roots per acre basis. Further discussion of this subject will be taken up later in the text.

Effects of Moisture, Compaction, and Aerification on Phosphorus Penetration

Appendix Table XL shows the average pounds per acre of phosphorus found in the lower four inch layer of a total six inch layer at the various compaction, moisture, and aerification levels in June 1951. The statistical analysis for this data is given in Table XLI of the appendix. Compaction had no significant effect on the penetration of phosphorus. Moisture had a significant effect on phosphorus penetration at the five percent level. High irrigation resulted in the downward movement of phosphorus, irrespective of the presence of aerifier holes.

Aerification had a very significant effect on phosphorus penetration, primarily due to mechanical movement of the superphosphate down the aerifier holes. This may have occurred at the time of fertilization by the direct fall of the fertilizer from the spreader into the aerifier holes; it may have occurred during the matting operation, or it may have occurred through the action of rainwater or irrigation water. Aerification was found to increase the amount of phosphorus found in the 3-6 inch soil zone approximately 26.0 percent. The average increase, due to aerification under the various compaction levels, was approximately 27.4 percent. This is shown graphically in Figure 18. Figure 19 shows the average percentage increase under the various moisture levels to be about 23.6 percent.

Compaction x moisture, aerification x compaction, and aerification x moisture x compaction were all found to be significant at the five percent level.

Fig. 18 Effect of aerification on the pounds phosphorus per acre present in the 3-6" soil zone at the various compaction levels, 1951.

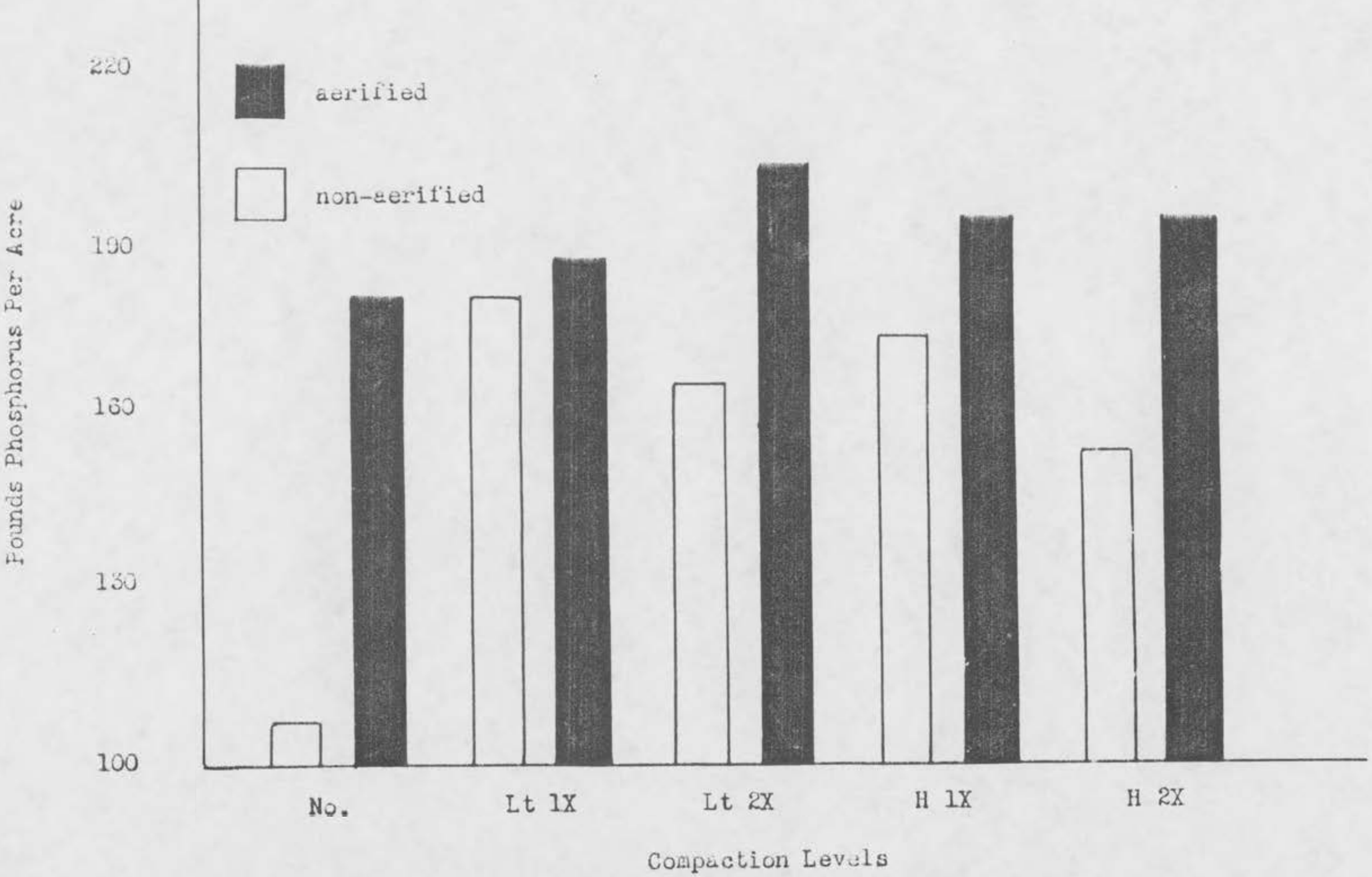
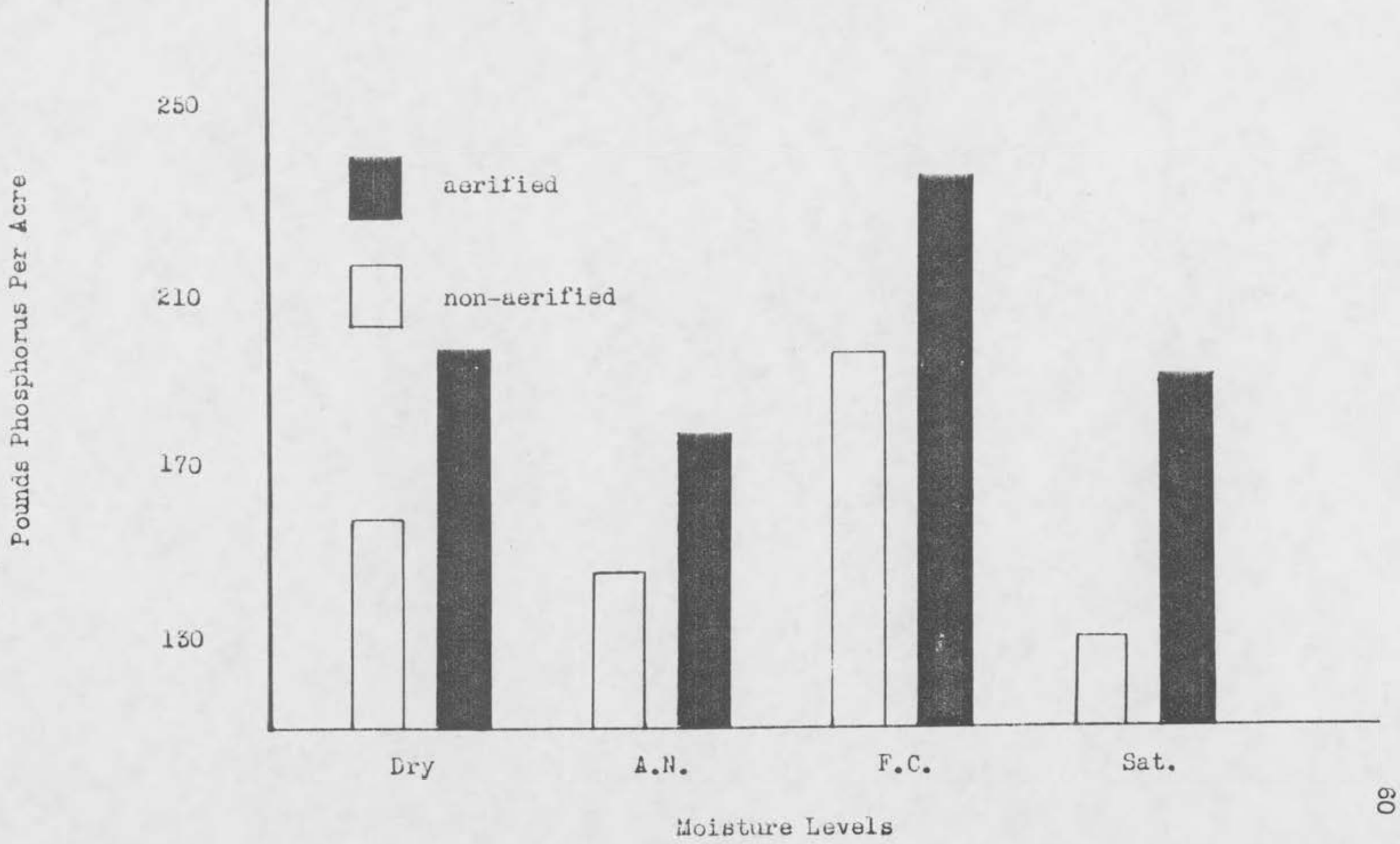
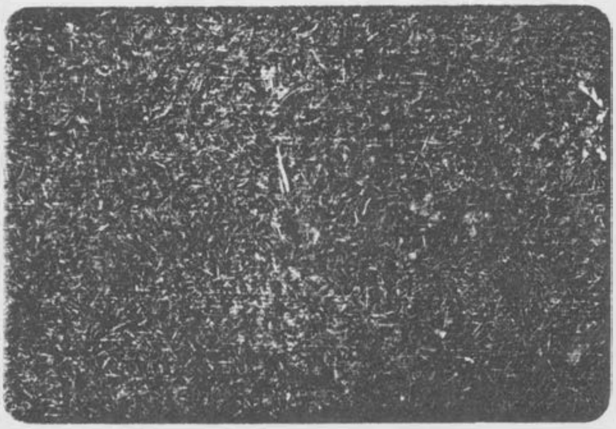


Fig. 19 Effect of aerification on the pounds phosphorus per acre present in the 3-6" soil zone at the various moisture levels, 1951.

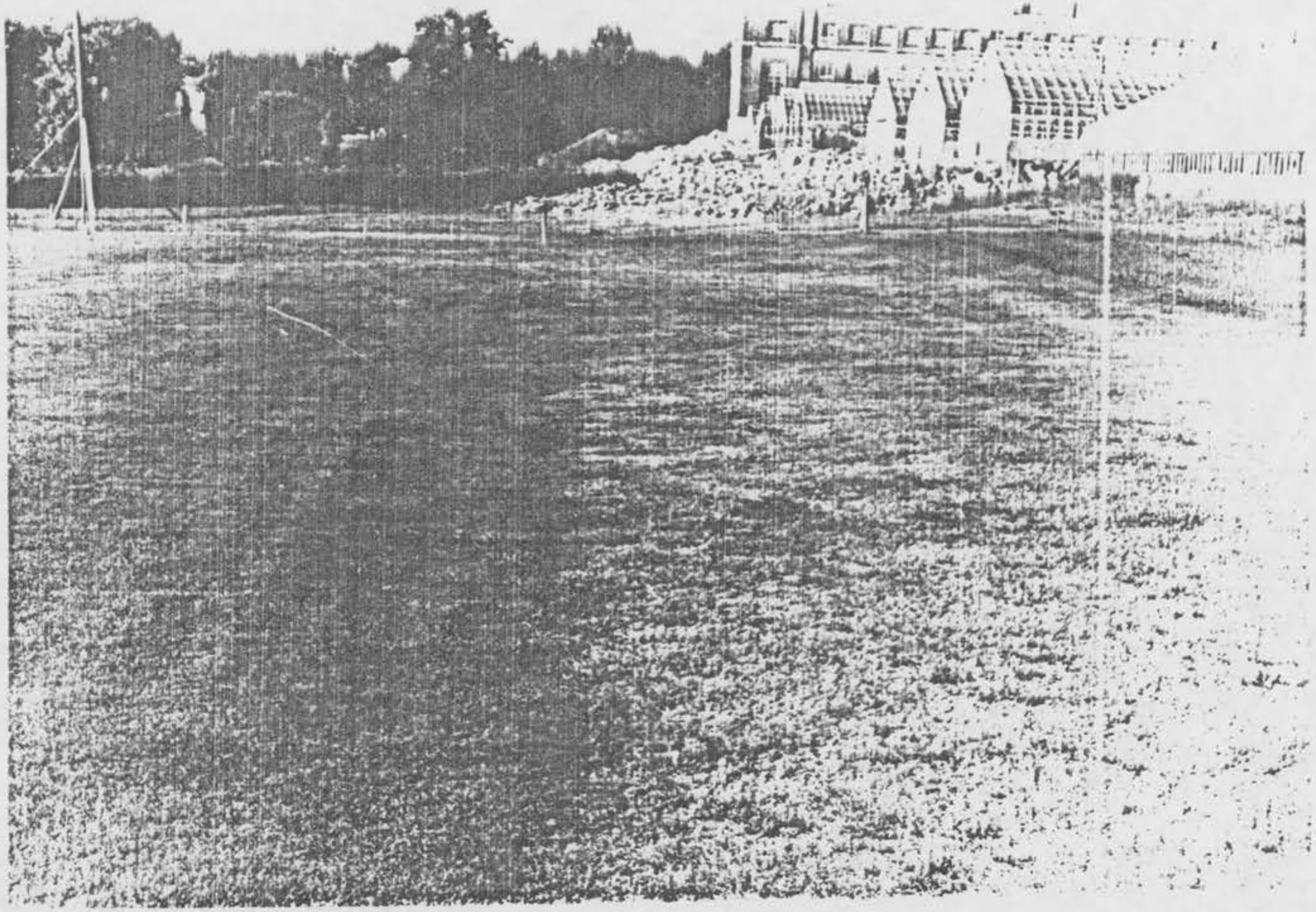


Effects of Moisture, Compaction, and Aerification on Disease Incidence

Very little disease was observed on any of the plots during the summers of 1950 and 1951. There were no serious infestations of large brownpatch or dollar spot on the plots at any time. During the winter of 1950, some snow mold was observed on localized spots where the plots had been trampled on while frozen or where the snow had drifted and persisted for a considerable length of time.



Photograph 1 Photograph showing section of plot following aerification. The right hand side has been aerified three times over. The left hand side has received no aerification. Photograph was taken immediately following aerification and before fertilization and matting has taken place. Photograph taken May 1, 1951.



Photograph 4   General view of plots showing As Needed tier on left and Dry tier on right

DISCUSSION

Effects of Moisture, Compaction, and Aerification on the Total Percent of Permanent Species in the Turf Population

The data presented shows that moisture and compaction had very little influence on the percent permanent species present in 1950 and 1951 as compared to the original population of permanent species in 1947 before any treatments had been inaugurated. According to Watson[25], the original population on these plots consisted of 96 percent permanent species. The present experimental work showed 94 percent permanent species present in 1950 and 95 percent permanent species present in 1951. From a statistical standpoint this is not a significant change.

The percent permanent species present in the original turf was not influenced by the dry and as needed moisture treatments. The field capacity and saturated moisture treatments decreased slightly the percent permanent species present. This was undoubtedly due to an increase in weed population, especially crabgrass, under the higher moisture levels. Contrary to that found by Watson[25], the greatest reduction in permanent species present under the various compaction levels came about on the H1X and H2X (heavy compaction) plots. This was due primarily to the larger increase in total weed population on the heavy compacted plots as compared to the increase in weed population on the lighter compacted plots. There was no change in percent permanent species present on the no compacted and light compacted plots.

Although aerification showed no significant effect on the percent permanent species present, there were indications that aerification did slightly reduce the percent permanent species present. Results show this was due, at least in part, to the increase in weed population under Spring aerification. It may well be that this situation would not exist under Fall aerification.

The relatively small changes which occurred in the percent permanent species present does not indicate the actual changes in the turf population. The individual species were greatly influenced by the different moisture, compaction, and aerification levels.

Effects of Moisture, Compaction, and Aerification on Individual Species of Permanent Grasses

The unbalanced condition that existed among the permanent species (bentgrass, Kentucky bluegrass, red fescue) in 1949 was little changed during the summers of 1950 and 1951. Among the permanent species, bentgrass continued its complete dominance as shown by Watson[(25)]. Under high levels of irrigation there was an increase in bentgrass at the expense of the red fescue and Kentucky bluegrass. These increases in bentgrass were very minute as compared to the increases shown by Watson[(25)], but it must be pointed out that during the 1949, 1950 and 1951 growing seasons the percent bentgrass present closely approached 100 percent. Although increases in density were still possible (and probably occurring) there was little possibility for increases in the percent bentgrass present. The rapid growth rate coupled with its ability to withstand high temperatures when given sufficient moisture allowed the bentgrass to continue growth during the hot summer months while Kentucky bluegrass and red fescue remained dormant. This characteristic of bentgrass makes it quite desirable for use on the irrigated fairways of our modern golf courses. Indeed the results of this investigation clearly show that under summer irrigation rates high enough to maintain desirable playing conditions bentgrass will naturally become the dominant species present in the turf population.

Compaction had no effect on the percent bentgrass and red fescue present during 1950 and 1951. Under all compaction levels there was approximately the same percent bentgrass present. The same was true for red fescue. Kentucky bluegrass was significantly affected by compaction. Kentucky bluegrass persisted much better on the heaviest compacted plots than it did on the no compacted and light compacted plots. The original population of Kentucky bluegrass on the no compacted plots in 1947 was 11% of the total population. In 1950 and 1951, the Kentucky bluegrass population dropped to less than 1% of the total population. In contrast, on the heavy compacted plots, the Kentucky bluegrass population dropped from an original population of 9% to 3.5% in 1950 and 4.5% in 1951. A possible explanation lies in the fact that the bentgrass was not as vigorous on the heavy compacted plots as it was on the lighter compacted plots, and, therefore, did not offer as much competition to the bluegrass under compacted conditions.

Aerification had very little effect on the bentgrass and red fescue population. Statistical analysis showed aerification to have a significant effect in reducing the Kentucky bluegrass population. This statement must be interpreted with caution. It is reasonable to expect that aerification itself did not directly reduce the Kentucky bluegrass population. It was previously pointed out that aerification, by stimulating the development of root systems, increased the vigor of the bentgrass. Spring aerification also brought soil plugs to the surface which were infested with weed seed and caused an increase in crabgrass population. The reduction in Kentucky bluegrass population, therefore, was due primarily to increased competition from the bentgrass and crabgrass.

Effects of Moisture, Compaction, and Aerification on the Percent Clover, Crabgrass, and Total Weeds Present in the Turf Population

Clover infestation of the experimental area during this investigation was quite low. The low clover population undoubtedly can be attributed to (1) the high fertility level maintained throughout the investigation and (2) the vigorous growth of the bentgrass, particularly on the irrigated plots. A high percentage of clover in a turf area usually is associated with low fertility, especially low nitrogen. The use of organic nitrogen in this experiment provided available nitrogen over a long enough period of the growing season to maintain vigorous grass growth. The greatest population of clover was found on the heavy compacted plots. Moisture apparently had no effect on the clover population in 1951, although the 1950 data shows a definite increase in clover population with increasing moisture applications. Watson[25] has shown that, in 1948 and 1949, there was a significant increase in clover population with increasing moisture content.

The field capacity and saturated plots had an extremely high crabgrass infestation as compared to the dry and as needed plots in 1950 and 1951. In 1950 there was over two and one quarter times as much crabgrass on the high moisture plots as there was on the low moisture plots. The high moisture levels undoubtedly were ideal for the germination of crabgrass seed. Watson[25] has reported that crabgrass germination is strongly inhibited by compaction. The 1950 and 1951 data showed no significant reductions in crabgrass population due to compaction. The H2X plots did show considerable reduction of crabgrass in 1950, but in 1951 there was only a slight decrease. It is quite likely that this slight reduction of crabgrass on the H2X plots can be attributed to the injurious effects of the roller used in making the compaction treatments rather than to compaction itself. Watson[25] has reported that the use of the heavy roller crushed or severely injured the young crabgrass seedlings so that they did not develop. The heavy roller used in this investigation delivered considerably higher pounds pressure per square inch than did the roller used by Watson[25].

Results, as indicated in Figure 13, show that the crabgrass population was significantly influenced by Spring aerification. Under any given compaction level, the aerified plots showed a much higher number of crabgrass plants than did the non-aerified plots. The plugs pulled by the Aerifier undoubtedly contained crabgrass seed that was buried too deeply to germinate. The matting operation broke up these plugs and distributed the weed infested soil over the surface of the area, providing ideal germination conditions. This is not only true for crabgrass, but also for all other weeds. It is highly probable that Spring aerification would not increase the weed population if aerification was done early in the Spring when conditions were not ideal for weed seed germination but were favorable for grass growth.

Total weeds, as considered in this investigation, included plaintain, dandelion, chickweed, knotweed, clover, crabgrass, *Poa annua*, *Poa trivialis*, and any other species of vegetation present in the turf other than the three permanent species already discussed. Although compaction had no significant effect on weed population for the overall analysis there was a significant difference between the heaviest compacted plots and the no compacted plots. The heavy compacted plots had a much higher weed population than did the no compacted plots. Clover, plaintain, knotweed, and chickweed populations were higher on the heavy compacted than on the light compacted plots. Crabgrass populations were higher on the no compacted and light compacted plots than on the heavy compacted plots. The 1950 data shows a definite increase in weed population with increasing moisture. The 1951 data shows the same trend for the dry, as needed, and field capacity plots, but there is an unexplainable drop on the saturated plots. Aerification had a tendency to increase the weed population on the no compacted and light compacted plots but reduced the total weed population on the heavy compacted plots.

Effects of Moisture, Compaction, and Aerification on Root Quantities and Distribution

Under the higher moisture levels (field capacity and saturation) the root system developed was very shallow. On these plots over 80 percent of the total roots found in a six inch layer were in the upper two inches of this layer. This is in agreement with the findings of Daubenmire[8] and Weaver and Clements[28]. Under low moisture conditions roots tend to elongate in their search for moisture, whereas there is no necessity for this when abundant or excessive moisture is available. In addition to the increased percentage of total roots found below the two inch layer on the dry plots, it was also shown in 1951 that there was a greater total quantity of roots under these plots. It may be speculated that under saturated conditions there was some loss of roots due to poor aeration. Weaver and Clements[28] have shown that under conditions comparable to saturation, roots will not elongate and some roots already present may die from lack of oxygen. High quality turf requires good root systems. Needless to say, the amount and particularly the distribution of irrigation water is one of the prime essentials in any program of fine turf management where high quality turf is desired.

The low total quantities of roots found on all the plots may be attributed in part to the clipping treatment used throughout the investigation. Graber[9] and Harrison[10] have reported that close clipping of turf reduces the root system of the turf.

The total quantity of roots produced in 1950 and 1951 were quite consistent under the various compaction levels. Compaction did not appear to have any effect on the root distribution. The degree of compaction developed in this investigation was probably not sufficient to cause serious soil deterioration and subsequent root disturbances.

The total quantity of roots found under the aerified plots was only slightly higher than the total quantity of roots found under the non-aerified plots. Under 5,000 square feet of turf there was an increase of approximately 2.25 pounds of roots (dry matter) on the aerified plots, as compared to the non-aerified plots. This may appear as a rather insignificant amount of roots, but when converted into number of lineal feet or miles of roots available for plant feeding it presents a quite different picture. By actual measurement it was found that one pound of bentgrass roots (dry matter) contain approximately 540,476 lineal feet or 102 miles, exclusive of root hairs. The inclusion of root hairs would increase this figure many times. By applying these measurements to the data from the aerified and non-aerified plots, it was found that there was approximately 230 more miles of roots under 5,000 square feet of aerified turf as contrasted with 5,000 square feet of non-aerified turf. On an acre basis there would be approximately 2,040 more miles of roots due to aerification. The above figures have been calculated on the basis of the total quantity of roots per given area under all levels of moisture and compaction. Under extreme conditions, such as heavy compaction and low moisture, these differences are even greater. This phase of the investigation warrants further investigation to obtain a clearer view of the exact relationships existing between aerification and root growth. If a more adequate number of samples could be obtained, aerification would probably show very significant effects on the root quantities and distribution.

Effects of Moisture, Compaction, and Aerification on Phosphorus Penetration

In conducting the phase of the investigation dealing with phosphorus penetration, the 3-6" soil zone was of primary concern because it is the most desirable root feeding zone. Phosphorus is almost universally considered to be immovable in the soil. This has already been pointed out in the review of literature. It is essential, therefore, that we have some mechanical means of moving surface applications of phosphorus on established turf into the soil zone where it can best be utilized by the feeding roots.

Water was found to have a significant effect on phosphorus penetration under conditions of high phosphorus application and excessive water applications (field capacity and saturation). The results indicate that there was considerable movement of phosphorus downward when high amounts of water were applied. Excessive water will move phosphorus downward to the root feeding zone, but the deteriorating effects of excessive water on turf quality and soil structure preclude using it as a method of moving phosphorus. It is necessary, therefore, to resort to some mechanical means of moving phosphorus applications into the root feeding zone.

Considerable question has arisen as to the relative merits of the various aerating devices. Basically, these devices may be divided into three general classes; those having solid tines (Greens spiker), those having hollow tines (Soil-Aire), and those having spoons (West Point Aerifier). In this phase of the investigation there was little concern regarding the type of hole produced, inasmuch as the primary interest was in determining how much phosphorus moves mechanically down the holes. It should be pointed out that there is reason to believe that the type hole produced by the aerating device may be of extreme importance when considering water movement, gaseous exchange and other related topics.

Aerification had a very definite effect on phosphorus penetration in this investigation. The exact means by which the phosphorus mechanically moved down the Aerifier holes is not known, but it may be speculated that it may have occurred in three ways. The fertilizer may have fallen directly from the spreader into the Aerifier hole, it may have been knocked down the Aerifier holes during the matting operation, or it may have been washed down the Aerifier holes by rain or irrigation water. In every instance it was found that there was more phosphorus in the 3-6" soil zone of the aerified half of the main plots than there was in the non-aerified half of the main plots. Under all compaction levels there was an average increase of 27.4 percent more phosphorus present where aerification had been used. Under all moisture levels there was an average increase of 23.6 percent more phosphorus where aerification had been used. Figures 18 and 19 show the effect of aerification on phosphorus penetration under each moisture and compaction treatment. Under all compaction and moisture treatments combined, there was an increase of 25.5 percent more phosphorus on the aerified plots.

It has been shown that aerification plays a very important part in the movement of phosphorus into the root feeding zone. On this basis alone, the use of the Aerifier in any program of good turf management is justifiable.

SUMMARY

Objective

The objective of this experiment was to determine the direct and interacting effects of moisture, compaction, and aerification on phosphorous penetration, root development, and population changes in a mixed turf of permanent grasses.

Location, Duration, and Design of Experiment

The investigation was carried out on an established turf area on the campus of the Pennsylvania State College. Treatments originally begun by Watson(25) in 1948 were continued, with some modifications, from the Fall of 1949 to the Spring of 1952. The design of the experiment was a modified split plot involving five levels of compaction, four levels of moisture, and two levels of aerification in all possible combinations. Maintenance practices used on the area conformed as nearly as possible to those used on most modern golf courses.

Evaluation

Compaction: [Soil compaction was determined by penetrometer readings and volume weight determinations. A highly significant correlation between the two methods was established. These determinations showed that measurable differences in compaction were produced under the various compaction treatments.] #1 The Geiger Counter X-ray spectrometer was found to be unreliable for soil compaction determination.

Moisture: In the field, Lark soil tensiometers were used to check approximate day to day moisture levels on the field capacity and saturated plots. Periodically, absolute soil moisture content was determined by laboratory tests.

Turf quality: Several factors were considered in determining turf quality.

(1) Ecological changes in the population of the permanent species (Kentucky bluegrass, red fescue, bentgrass) were studied by use of the inclined point quadrat method.

(2) Invasions of crabgrass, clover, and other weeds, including Poa annua were recorded. Clover and other weed determinations were made by use of the inclined point quadrat method. The percent area of the total plots covered by clover was also made by visual estimates. Crabgrass determinations were made by use of the double x line quadrat.

(3) Root quantities and root distribution were considered. Samples were taken at one inch intervals to a depth of six inches, washed, oven dried, and weighed. The total quantity of roots and the distribution of the roots in the 0-2" soil zone and the 3-6" soil zone was determined.

(4) Severity of natural disease infection was considered. Disease injury was so slight during the course of the investigation that no records were taken.

Phosphorus Penetration: Penetration of surface applications of phosphorus into the 3-6" root feeding zone was studied. Samples were taken at one inch intervals to a depth of six inches and tested for available phosphorus content in the laboratory] by use of the Deniges Stannous-Reduced Phosphomolybdic blue color method as adapted to photoelectric measurements.

#2

Results

Compaction: Compaction had no significant effect on the total percent permanent species present in the turf population, although there were changes in the proportions of individual species making up the total population. This change was significant in the case of the Kentucky bluegrass population. On the heavy compacted plots there was a greater population of bluegrass than on the light and no compacted plots. Clover population was slightly higher on the heavy compacted plots than it was on the other compaction levels. Increases in compaction tended to decrease the crabgrass population. Compaction tended to increase other weeds. Compaction had no significant effect on root quantity and root distribution. Phosphorus penetration was not influenced by compaction.

Moisture: Under the high moisture levels (field capacity and saturation) there was a definite increase in the bentgrass population. Increasing moisture tended to decrease the percent permanent species present. This was primarily due to an increase in weed population with increasing soil moisture content. There was a highly significant increase of crabgrass under the field capacity and saturation moisture treatments. High moisture tended to decrease red fescue and Kentucky bluegrass population while increasing bentgrass population. Clover also showed an increase under the high moisture levels. Increasing amounts of water above field capacity had a detrimental effect on the total quantity of roots produced. The highest total quantity of roots was found under the dry and As Needed moisture levels. Root distribution was significantly affected by moisture. At the low moisture rates a greater percentage of the total roots were found in the 3-6" soil zone than on the field capacity and saturated plots. Moisture was also found to have a significant effect on the downward movement of phosphorous, but only under the field capacity and saturated conditions.

Aerification: Spring aerification significantly decreased the Kentucky bluegrass population on the heavy compacted plots. Aerification had no significant effect on the bentgrass and red fescue population. There was a trend towards a decrease in percent permanent species on the aerified plots. This may be attributed to the high increase in weeds following Spring aerification. Aerification increased the clover population under the lower moisture levels, but not under the higher moisture levels. Although aerification showed no significant effect on roots, there was a trend towards increased root systems due to aerification. It is felt that with more adequate sampling, definite differences could be obtained on the aerified and non-aerified plots. Phosphorous penetration was significantly influenced by aerification. It was shown that aerification resulted in considerable downward mechanical movement of phosphorous.

Interactions: The interaction of moisture x compaction was found to have a significant effect on the Kentucky bluegrass population in 1950. This interaction had no effect on Kentucky bluegrass population in 1951. The interactions of compaction x moisture, aerification x compaction, and aerification x moisture x compaction had a significant effect on the pounds per acre of phosphorus found in the lower four inches of a total six inch layer. No other interactions were found to be significant.

Conclusions

The following conclusions may be drawn from the results obtained in this investigation.

1. Moisture and aerification treatments exerted greater influence on turf quality during the investigation than did compaction treatments.
2. The use of supplemental irrigation on a turf containing bentgrass will favor the development of the bentgrass at the expense of the red fescue and Kentucky bluegrass.
3. Spring aerification will significantly aid in the downward movement of superphosphate applications applied on the surface at the time of aerification.
4. Excessive use of supplemental irrigation will result in shallow rooted turf.
5. Turf containing a high percentage of bentgrass requires some supplemental irrigation over the growing season in order to maintain desirable playing conditions.

6. Spring aerification, if done at a time when conditions are ideal for weed seed germination, will increase the weed population, especially crabgrass, in an established turf.
7. Excessive use of supplemental irrigation will increase the crabgrass population in an established turf.
8. Surface applications of superphosphate may move downward under excessive watering.
9. The dry plots were unsuitable for play over most of the growing season.]#3

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APPENDIX

Table I Average percent of total species that is permanent species at the various moisture and compaction levels, 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	99	100	98	87	96	96.0
A.N.	97	96	97	88	97	95.0
F.C.	98	97	98	92	83	93.6
Sat.	93	93	96	86	83	90.2
$\bar{x}$	96.7	96.5	97.2	88.2	89.7	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D .05	L.S.D .01
Compaction	4	230.25	2.08		
Replications	2	314.50			
Error A	8	110.87			
Moisture	3	103.00	1.97		
Error B	6	52.16			
Compaction x Moisture	12	38.42	1.27		
Error B_1	24	30.21			

Table II Average percentage of total species that is permanent species at the various compaction, moisture, and aerification levels, 1951

Moisture Levels	Compaction and Aerification Levels										
	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	$\bar{x}$
Dry	99	95	99	96	99	97	84	96	96	96	95.7
A.M.	94	97	99	94	95	98	92	87	97	97	95.0
F.C.	97	95	94	93	95	94	92	87	89	89	92.5
Sat.	99	99	95	97	97	93	96	97	92	93	95.8
$\bar{x}$	97.2	96.5	96.7	95.0	96.5	95.5	91.0	91.7	93.5	93.7	

Table III Percentage of total species that is permanent species at the various compaction, moisture, and aerification levels, 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	126.00	1.63		
Replications	2	343.50			
Error A	8	77.12			
Moisture	3	69.33	0.50		
Error B	6	137.66			
Compaction x Moisture	12	30.50			
Error B_1	24	48.29			
Aerification	1	6.00	0.10		
Error C	2	58.00			
Aerification x Compaction	4	5.75			
Aerification x Moisture	3	7.33			
Aerification x Moisture x Compaction	12	42.75			
Error C_1	38	36.18			

Table IV Average percent of total species that is weeds at the various compaction and moisture levels, 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	1	0	2	13	4	4.0
A.M.	3	4	3	12	3	5.0
F.C.	2	3	2	8	17	6.4
Sat.	7	7	4	14	17	12.2
$\bar{x}$	3.2	3.5	2.7	11.7	12.5	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	230.25	2.08		
Replications	2	314.50			
Error A	8	110.87			
Moisture	3	103.00	1.97		
Error B	6	52.17			
Compaction x Moisture	12	38.42	1.27		
Error B_1	24	30.21			

Table V Average percentage of total species that is weeds at the various compaction, moisture, and aerifications levels, 1951

Moisture Levels	Compaction and Aerification Levels										
	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	$\bar{x}$
Dry	1	5	1	4	1	3	16	4	4	4	8.6
A.M.	6	3	1	6	5	2	8	13	3	3	10.0
F.C.	3	5	6	7	5	6	8	13	11	11	15.0
Sat.	1	1	5	3	3	7	4	3	8	7	8.4
$\bar{x}$	2.7	3.5	3.2	5.0	3.5	4.5	9.0	8.2	6.5	6.2	

Table VI Percentage of permanent species that is weeds at the various compaction, moisture, and aerification levels, 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	125.26	1.64		
Replications	2	346.80			
Error A	8	76.44			
Moisture	3	65.17	0.47		
Error B	6	139.05			
Compaction x Moisture	12	31.50			
Error B_1	24	48.16			
Aerification	1	7.01	0.12		
Error C	2	56.43			
Aerification x Compaction	4	6.01			
Aerification x Moisture	3	10.34			
Aerification x Moisture x Compaction	12	31.70			
Error C_1	38	35.40			

Table VII Average percentage of permanent species that is bentgrass at the various compaction and moisture levels, 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	89	84	83	78	85	83.8
A.M.	85	95	89	91	89	89.8
F.C.	94	94	97	94	91	94.0
Sat.	98	95	99	99	99	98.0
$\bar{x}$	91.5	92.0	92.0	90.5	91.0	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	5.50	0.13		
Replications	2	178.00			
Error A	8	43.37			
Moisture	3	562.33	2.52		
Error B	6	223.00			
Compaction x Moisture	12	35.08	1.34		
Error B_1	24	26.08			

Table VIII Average percentage of permanent species that is bentgrass at the various compaction, moisture, and aerification levels, 1951.

Moisture Levels	Compaction and Aerification Levels										
	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer H1X	H2X	Aer. H2X	$\bar{x}$
Dry	97	92	96	94	92	96	93	93	89	89	93.1
A.M.	90	89	95	95	91	98	93	91	95	97	93.4
F.C.	100	100	100	100	100	100	100	100	97	100	99.7
Sat.	99	98	100	98	100	99	100	99	97	97	98.7
$\bar{x}$	96.5	94.7	97.7	96.7	95.7	98.2	96.5	95.7	94.5	95.7	

Table IX Percentage of permanent species that is bentgrass at the various compaction, moisture, and aerification levels, 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	19.50	0.74		
Replications	2	367.00			
Error A	8	26.50			
Moisture	3	354.00	1.08		
Error B	6	326.67			
Compaction x Moisture	12	23.92			
Error B_1	24	24.00			
Aerification	1	1.00	0.07		
Error C	2	15.00			
Aerification x Compaction	4	18.00			
Aerification x Moisture	3	9.00			
Aerification x Moisture x Compaction	12	7.00			
Error C_1	38	9.00			

Table X Average percentage of permanent species that is Kentucky bluegrass at the various compaction and moisture levels, 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	0	0	2	4	4	2.0
A.M.	0	1	0	3	4	1.6
F.C.	0	1	1	5	5	2.4
Sat.	0	0	1	0	0	0.2
$\bar{x}$	0.0	0.5	1.0	3.0	3.2	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	23.81	9.72 **	1.18	2.13
Replications	2	5.85			
Error A	8	2.45			
Moisture	3	13.17	1.13		
Error B	6	11.67			
Compaction x Moisture	12	4.56	3.28 **	2.31	3.30
Error B_1	24	1.39			

Table XI Average percentage of permanent species that is Kentucky bluegrass at the various compaction, moisture, and aerification levels, 1951.

Moisture Levels	Compaction and Aerification Levels										$\bar{x}$
	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	
Dry	1	4	0	0	5	1	5	0	9	7	3.2
A.M.	2	1	1	1	0	1	0	0	5	2	1.3
F.C.	0	0	0	1	1	0	0	0	2	0	0.4
Sat.	0	0	0	1	0	1	0	0	2	2	0.6
$\bar{x}$	0.7	1.2	0.2	0.7	1.5	0.7	1.2	0	4.5	2.7	

Table XII Percentage of permanent species that is Kentucky bluegrass at the various compaction, moisture, and aerification levels, 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	43.66	4.46 *	1.67	
Replications	2	33.23			
Error A	8	9.78			
Moisture	3	52.60	3.92		
Error B	6	13.34			
Compaction x Moisture	12	9.98			
Error B_1	24	10.09			
Aerification	1	13.34	58.00 *	0.19	
Error C	2	0.23			
Aerification x Compaction	4	6.02			
Aerification x Moisture	3	4.82			
Aerification x Moisture x Compaction	12	5.05			
Error C_1	38	3.87			

Table XIII Average percentage of permanent species that is red fescue at the various moisture and compaction levels, 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	11	16	15	18	12	14.4
A.M.	15	4	11	6	8	11.0
F.C.	5	5	2	1	4	3.4
Sat.	1	5	0	1	1	1.6
$\bar{x}$	8.0	7.5	7.0	6.5	6.2	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	10.50	0.32		
Replications	2	226.50			
Error A	8	32.25			
Moisture	3	481.66	2.79		
Error B	6	172.50			
Compaction x Moisture	12	31.83	1.46		
Error B_1	24	21.83			

Table XIV Average percentage of permanent species that is red fescue at the various compaction, moisture, and aerification levels, 1951.

Moisture Levels	Compaction and Aerification Levels										
	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	$\bar{x}$
Dry	3	4	4	6	3	3	6	6	2	4	4.1
A.M.	8	10	4	4	9	1	9	9	0	0	5.4
F.C.	0	0	0	0	0	0	0	0	3	0	0.3
Sat.	0	0	0	1	0	0	0	0	0	1	0.2
$\bar{x}$	2.7	3.5	2.0	2.7	3.0	1.0	3.7	3.7	1.2	1.2	

Table XV Percentage permanent species that is red fescue at the various compaction, moisture, and aerification levels, 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	16.72	0.58		
Replications	2	183.66			
Error A	8	29.02			
Moisture	3	193.34	0.84		
Error B	6	229.97			
Compaction x Moisture	12	19.95			
Error B_1	24	18.00			
Aerification	1	4.80	0.86		
Error C	2	5.57			
Aerification x Compaction	4	10.11			
Aerification x Moisture	3	13.62			
Aerification x Moisture x Compaction	12	6.07			
Error C_1	38	7.13			

Table XVI Average percentage of total plot area covered by clover at the various compaction and moisture levels, 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	0.5	0.3	0.6	12.3	3.3	3.40
A.M.	0.3	0.5	1.3	10.3	2.0	2.88
F.C.	1.3	1.1	2.3	4.6	10.1	3.88
Sat.	0.8	1.1	3.6	4.1	4.0	2.72
$\bar{x}$	0.72	0.75	1.95	7.82	4.85	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	115.57	1.35		
Replications	2	231.35			
Error A	8	85.60			
Moisture	3	4.09	0.57		
Error B	6	7.12			
Compaction x Moisture	12	22.94	1.01		
Error B_1	24	22.63			

Table XVII Average percentage of total plot area covered by clover at the various compaction, moisture, and aerification levels, July 1951.

Moisture Levels	Compaction and Aerification Levels										
	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	$\bar{x}$
Dry	0 *	0	1	0	1	0	6	0	1	0	0.9
A.M.	0	1	1	1	1	1	2	2	1	0	1.0
F.C.	0	0	1	0	1	0	2	0	7	1	1.2
Sat.	1	1	0	0	0	1	1	0	1	1	0.6
$\bar{x}$	0.2	0.5	0.7	0.2	0.7	0.5	2.7	0.5	2.5	0.5	

* "0" does not necessarily denote no clover present. "0" denotes less than 1% of total plot area is covered by clover.

Table XVIII Percentage of total plot area covered by clover at the various compaction, moisture, and aerification levels, July 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	6.98	3.02		
Replications	2	14.17			
Error A	8	2.31			
Moisture	3	1.97	1.45		
Error B	6	1.36			
Compaction x Moisture	12	6.54	2.37 *	3.96	
Error B_1	24	2.76			
Aerification	1	23.41	6.06		
Error C	2	3.86			
Aerification x Compaction	4	7.43			
Aerification x Moisture	3	6.16			
Aerification x Moisture x Compaction	12	4.32			
Error C_1	38	2.74			

Table XIX Average percentage of total species that is clover at the various compaction and moisture levels, 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	1	0	0	6	2	1.8
A.M.	1	0	1	7	3	2.4
F.C.	1	1	1	3	10	3.2
Sat.	1	2	0	9	12	4.8
$\bar{x}$	1.0	0.7	0.5	6.2	6.7	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	117.61	3.17		
Replications	2	74.31			
Error A	8	37.05			
Moisture	3	28.42	1.28		
Error B	6	22.25			
Compaction x Moisture	12	18.43	0.99		
Error B_1	24	18.53			

Table XI Average percentage of total species that is clover at the various compaction, moisture, and aerification levels, 1951.

Compaction and Aerification Levels

Moisture Levels	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	$\bar{x}$
Dry	0	1	0	0	0	0	6	2	0	0	0.9
A.N.	6	1	1	2	3	0	2	0	0	0	1.5
F.C.	1	0	1	2	2	1	4	0	9	5	2.5
Sat.	0	0	1	1	3	1	2	1	3	1	1.3
$\bar{x}$	1.7	0.5	0.7	1.2	2.0	0.5	3.5	0.7	3.0	2.0	

Table XXI Percentage of total species that is clover at the various compaction, moisture, and aerification levels, 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	7.43	0.96		
Replications	2	98.86			
Error A	8	7.72			
Moisture	3	12.01	2.40		
Error B	6	5.00			
Compaction x Moisture	12	21.13			
Error B_1	24	10.13			
Aerification	1	48.14	1.78		
Error C	2	27.10			
Aerification x Compaction	4	8.86			
Aerification x Moisture	3	2.82			
Aerification x Moisture x Compaction	12	4.72			
Error C_1	38	6.66			

Table XXII Average number of crabgrass plants occurring under line diagonals at the various compaction and moisture levels, 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	22	13	19	48	6	21.6
A.M.	27	13	28	29	8	21.0
F.C.	48	43	49	68	33	48.2
Sat.	66	58	57	49	50	56.0
$\bar{x}$	40.7	31.7	38.2	48.5	24.2	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	1059	0.73		
Replications	2	7512			
Error A	8	1444			
Moisture	3	4579	44.89 **	9.00	9.96
Error B	6	102			
Compaction x Moisture	12	231	0.85		
Error B_1	24	271			

Table XXIII Average number of crabgrass plants occurring under line diagonals at the various compaction, moisture, and aerification levels, 1951.

Moisture Levels	Compaction and Aerification Levels										$\bar{x}$
	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	
Dry	0	1	2	7	1	1	5	1	0	1	1.9
A.M.	4	11	3	5	6	8	8	18	2	8	7.3
F.C.	6	9	6	12	10	15	5	12	6	11	9.2
Sat.	7	10	9	7	4	21	7	11	11	16	10.3
$\bar{x}$	4.2	7.7	5.0	7.7	5.2	11.2	6.2	10.5	4.7	9.0	

Table XXIV Average number of crabgrass plants occuring under line diagonals at the various compaction, moisture, and aerification levels, 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	27.50	0.32		
Replications	2	53.00			
Error A	8	64.62			
Moisture	3	402.66	1.45		
Error B	6	277.66			
Compaction x Moisture	12	44.25			
Error B_1	24	50.67			
Aerification	1	542.00	216.80 **	1.24	2.86
Error C	2	2.50			
Aerification x Compaction	4	13.00			
Aerification x Moisture	3	44.67			
Aerification x Moisture x Compaction	12	34.50			
Error C_1	38	21.20			

Table XXV Average percentage difference in bentgrass population at the various compaction and moisture levels, 1950 to 1951.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	+8*	+12	+9	+15	+4	+9.6
A.M.	+5	0	+2	+ 2	+6	+3.0
F.C.	+6	+6	+3	+ 6	+6	+5.4
Sat.	+1	+5	+1	+ 1	-2**	+1.2
$\bar{x}$	+5.0	+5.7	+3.7	+ 6.0	+3.5	

Table XXVI Average percentage difference in Kentucky bluegrass population at the various compaction and moisture levels, 1950 to 1951.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	+1	0	+3	+1	+5	+2.0
A.M.	+2	0	0	-3	+1	0
F.C.	0	-1	0	-5	-3	-1.8
Sat.	0	0	-1	0	+2	+0.2
$\bar{x}$	+0.7	-0.2	+0.5	-1.7	+1.2	

* + sign denotes increase in 1951 over 1950.

** - sign denotes decrease in 1951 over 1950.

Table XXVII Average percentage difference in red fescue population at the various compaction and moisture levels, 1950 to 1951.

Compaction Levels

Moisture Level	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	-8	-12	-12	-12	-10	-10.8
A.N.	-7	0	- 2	+3	- 8	- 2.8
F.C.	-5	- 5	- 2	-1	- 1	- 2.8
Sat.	-1	- 5	0	-1	- 1	- 1.6
$\bar{x}$	-5.2	- 5.5	- 4.0	-2.7	- 5.0	

Table XXVIII Average percentage difference in percent total species that is permanent species at the various moisture and compaction levels, 1950 to 1951.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	0	-1	+1	-3	0	-0.6
A.N.	-3	+3	-2	+4	0	+0.4
F.C.	-1	-3	-3	0	+6	-0.2
Sat.	+6	+2	+1	+10	+9	+5.6
$\bar{x}$	+0.5	+0.2	-0.7	+2.7	+3.7	

Table XXIX Average percentage difference in weed population at the various compaction and moisture levels, 1950 to 1951.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	0	+1	-1	+3	0	+0.6
A.M.	+3	-3	+2	-4	0	-0.4
F.C.	+1	+3	+3	0	-6	+0.2
Sat.	-6	-2	-1	-10	-9	-5.6
$\bar{x}$	-0.5	-0.2	+0.7	-2.7	-3.7	

Table XXX Average percentage difference in clover population at the various compaction and moisture levels, 1950 to 1951.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	-1	0	0	0	-2	-0.6
A.M.	+5	+1	+2	-5	-3	0
F.C.	0	0	+1	+1	-1	+0.2
Sat.	-1	-1	+3	-7	-9	-3.0
$\bar{x}$	+0.7	0	+1.5	-2.7	-3.7	

Table XXXI Average grams of oven dry roots present in soil cores one and five-eighths inches in diameter to a depth of six inches at the various compaction and moisture levels, September 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	0.549	0.634	0.850	0.507	0.590	0.626
A.M.	0.731	0.369	0.395	0.478	0.454	0.485
F.C.	0.363	0.556	0.395	0.295	0.405	0.403
Sat.	0.569	0.455	0.560	0.769	0.753	0.621
$\bar{x}$	0.553	0.503	0.550	0.512	0.550	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	0.025	0.44		
Replications	2	0.250			
Error A	8	0.057			
Moisture	3	0.163	3.62		
Error B	6	0.045			
Compaction x Moisture	12	0.060	1.07		
Error B_1	24	0.056			

Table XXXII Average grams of oven dry roots present in soil cores one and five-eighths inches in diameter to a depth of six inches at the various compaction, moisture, and aerification levels, 1951.

Compaction and Aerification Levels

Moisture Levels	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	$\bar{x}$
Dry	0.445	0.432	0.598	0.542	0.308	0.512	0.492	0.535	0.613	0.623	0.510
A.M.	0.402	0.328	0.460	0.422	0.347	0.397	0.350	0.337	0.435	0.487	0.396
F.C.	0.333	0.290	0.445	0.422	0.347	0.307	0.177	0.195	0.405	0.373	0.329
Sat.	0.333	0.250	0.262	0.498	0.322	0.343	0.441	0.227	0.263	0.312	0.325
$\bar{x}$	0.378	0.325	0.441	0.471	0.331	0.390	0.365	0.323	0.429	0.449	

Table XXXIII Grams of oven dry roots present in soil cores one and five-eighths inches in diameter to a depth of six inches at the various compaction, moisture, and aerification levels, September 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	0.067	1.86		
Replications	2	0.695			
Error A	8	0.036			
Moisture	3	0.223	3.60		
Error	6	0.062			
Compaction x Moisture	12	0.019			
Error B_1	24	0.027			
Aerification	1	0	0		
Error C	2	0.015			
Aerification x Compaction	4	0.012			
Aerification x Moisture	3	0.003			
Aerification x Moisture x Compaction	12	0.017			
Error C_1	38	0.013			

Table XXXIV Average percentage roots in upper two inch layer of a total six inch layer at the various compaction and moisture levels, September 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	78	77	80	83	80	79.6
A.M.	74	74	91	88	76	80.6
F.C.	80	76	73	76	62	73.4
Sat.	75	89	86	83	86	83.8
$\bar{x}$	76.7	79.0	82.5	82.5	76.0	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	72.75	1.12		
Replications	2	450.00			
Error A	8	65.12			
Moisture	3	262.33	2.49		
Error B	6	105.33			
Compaction x Moisture	12	106.08	1.45		
Error B_1	24	73.29			

Table XXXV Average percentage roots in upper two inch layer of a total six inch layer at the various compaction, moisture, and aerification levels, 1951.

Moisture Levels	Compaction and Aerification Levels										
	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	$\bar{x}$
Dry	62	58	66	64	60	70	62	63	64	56	62.5
A.M.	69	72	73	61	71	69	68	70	67	70	69.0
F.C.	70	86	78	74	76	73	71	80	78	83	76.9
Sat.	76	82	72	79	84	88	81	82	81	73	79.8
$\bar{x}$	69.2	74.5	72.2	69.5	72.7	75.0	70.5	73.7	72.5	70.5	

Table XXXVI Percentage roots in upper two inch layer of a total six inch layer at the various compaction, moisture, and aerification levels, September 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	26.75	0.45		
Replications	2	641.50			
Error A	8	60.00			
Moisture	3	1859.67	17.46 **	6.51	9.86
Error B	6	106.50			
Compaction x Moisture	12	52.42			
Error B_1	24	70.62			
Aerification	1	38.00	0.41		
Error C	2	91.50			
Aerification x Compaction	4	67.25			
Aerification x Moisture	3	50.33			
Aerification x Moisture x Compaction	12	70.17			
Error C_1	38	58.60			

Table XXXVII Average percentage roots in lower four inch layer of a total six inch layer at the various compaction and moisture levels, September 1950.

Compaction Levels

Moisture Levels	No	Lt1X	Lt2X	H1X	H2X	$\bar{x}$
Dry	22	23	20	17	20	20.4
A.M.	26	26	9	12	24	19.4
F.C.	20	24	27	24	38	26.6
Sat.	25	11	14	17	14	16.2
$\bar{x}$	23.2	21.0	17.5	17.5	24.0	

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	72.75	1.12		
Replications	2	450.00			
Error A	8	65.12			
Moisture	3	262.33	2.49		
Error B	6	105.33			
Compaction x Moisture	12	106.08	1.45		
Error B_1	24	73.29			

Table XXXVIII Average percentage roots in lower four inch layer of a total six inch layer at the various compaction, moisture, and aerification levels, 1951.

Moisture Levels	Compaction and Aerification Levels										
	No	Aer. No.	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	$\bar{x}$
Dry	38	42	34	36	40	30	38	37	36	44	37.5
A.M.	31	28	27	39	29	31	32	30	33	30	31.0
F.C.	30	14	22	26	24	27	29	20	22	17	23.1
Sat.	24	18	28	21	16	12	19	18	19	27	20.2
$\bar{x}$	30.7	25.5	27.7	27.2	27.2	25.0	29.5	26.2	27.5	29.5	

Table XXXIX Percentage roots in lower four inch layer of total six inch layer at the various compaction, moisture, and aerification levels, September 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	26.75	0.45		
Replications	2	641.50			
Error A	8	60.00			
Moisture	3	1859.67	17.46 **	6.51	9.86
Error B	6	106.50			
Compaction x Moisture	12	52.42			
Error B_1	24	70.62			
Aerification	1	38.00	0.41		
Error C	2	91.50			
Aerification x Compaction	4	67.25			
Aerification x Moisture	3	50.33			
Aerification x Moisture x Compaction	12	70.17			
Error C_1	38	58.60			

Table 1L   Average pounds per acre of phosphorus found in the lower four inch layer of a total six inch layer at the various compaction, moisture, and aerification levels, June 1951.

	Compaction and Aerification Levels										
Moisture Levels	No.	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	$\bar{x}$
Dry	59	94	283	230	144	228	198	172	106	264	178
A.M.	90	192	165	179	214	153	118	222	116	142	159
F.C.	108	123	210	276	171	323	205	193	293	279	218
Sat.	168	320	72	60	133	119	183	192	101	97	144
$\bar{x}$	106	182	182	187	165	206	176	195	154	195	

Table XLI Pounds per acre of phosphorus in the lower four inch layer of a total six inch layer at the various compaction, moisture, and aerification levels, June 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	7549	3.21		
Replications	2	14558			
Error A	8	2352			
Moisture	3	30401	5.90 *	45.34	
Error B	6	5152			
Compaction x Moisture	12	25471	4.82 ***		
Error B_1	24	5280			
Aerification	1	39060	25.76 *	31.97	
Error C	2	1516			
Aerification x Compaction	4	4473	3.01 *		
Aerification x Moisture	3	359			
Aerification x Moisture x Compaction	12	9446	6.36 ***		
Error C_1	38	1486			

Table XLII Analysis of variance for penetrometer and volume weight data, aerification omitted, 1951.

		Penetrometer		Volume Weights	
Source	D.F.	M.S.	F.	M.S.	F.
Compaction	1	3.470	231.33 **	1.440	144.00 **
Replications	2	0.060		0.270	
Error A	2	0.015		0.010	
Moisture	3	0.037	2.18	0.010	0.07
Error B	6	0.017		0.140	
Compaction x Moisture	3	0.046	5.11 *	0.030	0.75
Error B_1	6	0.090		0.040	

	L.S.D.		L.S.D.	
	.05	.01	.05	.01
Compaction	0.21	0.50	0.18	0.41
Compaction x Moisture	0.60			

Table XLIII Average penetrometer penetration (inches) at the various compaction, moisture, and aerification levels, 1951.

Compaction and Aerification Levels

Moisture Levels	No	Aer. No	Lt1X	Aer. Lt1X	Lt2X	Aer. Lt2X	H1X	Aer. H1X	H2X	Aer. H2X	$\bar{x}$
Dry	2.69	2.81	2.49	2.56	2.36	2.77	2.13	2.79	1.82	2.53	2.49
A.M.	2.37	2.62	2.32	2.56	2.25	2.47	2.45	2.63	1.88	2.26	2.38
F.C.	2.73	2.83	2.49	2.61	2.26	2.43	2.00	2.57	1.88	2.56	2.44
Sat.	2.71	2.92	2.49	2.61	2.34	2.39	2.12	2.47	1.86	2.31	2.42
$\bar{x}$	2.62	2.79	2.45	2.59	2.30	2.51	2.18	2.61	1.86	2.41	

Table XLIV Penetrometer penetration (inches) at the various compaction, moisture, and aerification levels, 1951.

Statistical Data

Source	D.F.	M.S.	F.	L.S.D. .05	L.S.D. .01
Compaction	4	1.04	34.66 **	0.09	0.16
Replications	2	1.04			
Error A	8	0.03			
Moisture	3	0.07	0.35		
Error B	6	0.20			
Compaction x Moisture	12	0.07			
Error B_1	24	0.10			
Aerification	1	2.75	22.9 *	0.27	
Error C	2	0.12			
Aerification x Compaction	4	0.20			
Aerification x Moisture	3	0.04			
Aerification x Moisture x Compaction	12	0.03			
Error C_1	38	0.03			