INTERRELATIONS OF TEMPERATURE AND SOIL MOISTURE IN THE GROWTH OF YOUNG WHEAT PLANTS

by

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TABLE OF CONTENTS

INTRODUCTION

The growth of any plant is a result of the interaction between the internal factors which embody the plant itself and the external factors which the plant is confronting and reacting with at every moment during its life. The internal factors lead the plant to produce a certain definite form of growth under any given set of conditions, the form being influenced by the external factors. Under a favorable condition, the environment provided by the external factors is such that it allows the internal factors to express themselves in a flourishing growth, while under severe conditions, the same set of internal factors leads to a growth approaching nil.

The "adaptation" of a certain species of plant could therefore be conceived as the manifestation of the internal factors under a set of suitable external conditions. Following this, a successful agriculture would involve the choice of crops with a superior internal complexion and the choice or partial control of the external environment so that it will allow the hidden internals to give the biggest performance.

The need of a basis for such choices points out the desirability of the studies of the influence of various environmental factors on the growth of crop plants. For example, the question of "How much moisture can a wheat crop stand in a region of excessive rainfall at any period during its life?" could be answered satisfactorily only when the effect of moisture on every growth feature of a growing wheat plant is experimentally illustrated. Likewise, the question, "How much growth should a winter wheat plant make before severe winter weather comes so that it will make a good start the next spring?", would find a probable answer from an experiment that analyzes the effect of temperature on the various stages of wheat growth.

Since the enunciation of Blackman's law of limiting factors, it has been well comprehended that the effect of each individual factor on the plant is dependent on the level of the others. As a matter of fact, this law only states the most prominent part of the interrelationships among the multiple environmental factors. From the extreme complexity of the biochemical and biophysical reactions going on in the plant body, one would expect that the effect of these factors on plants is even more complicated than what is brought out by the law of limiting factors. For example, the deficiency of one factor, such as soil aeration, would not only limit the efficiency of the other, such as temperature, at a constant low level, but would even go farther and decrease it because of the increased necessity for good aeration at higher temperatures. While a great amount of work has been done on the influence of each individual factor on plant growth, it would be profitable to add more information on the joint effect of two or more factors that are acting on the plant at once. It is this resultant influence that actually brings out the performance of any plant under any given condition.

Under natural conditions, the most fundamental factors influencing the growth and yield of plants are perhaps heat and moisture. While light follows an unalterable sequence of its own and soil fertility influences plant growth only quantitatively, heat and moisture vary much more irregularly and influence the plant both quantitatively and qualitatively. (By qualitative, is meant here the growth form, and other physiological expressions of the plant.)

The author is especially interested in these two factors because of his acquaintance with the wide climatic variations in the wheat region of China. Even if the weather conditions at seeding time only are considered there will be a great variation in temperature and soil moisture encountered by the tender young plants. These vary from the mild temperature with abundant rainfall and soil moisture in the south and southwestern China to the cold, windy, and more arid regions of the northwest.

It is the aim of this project to work on some of the basic ways by which the temperature and soil moisture act together on the various growth features of wheat during its early stages of growth. It seems, however, that experiments of the same nature, carried through the whole life of this plant are eminently desirable and should go deeper in various particular phases of its growth.

LITERATURE REVIEW

The literature on this subject may be briefly reviewed under separate headings as the effect of temperature and the effect of soil moisture on the growth of the wheat plant.

Effect of Temperature

General effect of temperature on the growth of wheat. Hutcheson and Quantz (27) grew winter wheat and other winter small grains at 75°F., 65°F., 62°F., and 58°F. They found that wheat produced a normal growth in the cool houses but only a mass of leaves in the two warm houses. Hurd-Karrer (25) reported that at all day lengths, the plants grown under 12°C. were taller than the corresponding plants grown under 21°C. She considered this difference as an evidence of the injurious effect of temperature above 20°C. on wheat growth. Dickson (19) and Jones, et. al. (29) both stated that although wheat germinated more rapidly at soil temperature of 24 to 28°C., the germination was more uniform and hardier plants were produced at a temperature range from 8 to 12°C. Wort (54) found that the height, root length, number of tillers, and dry weight of the Marquis wheat plant at an age of 70 days all decreased consistantly when the soil temperature was raised from 22 to 42°C. and that all the plants grown at 44°C. died within 35 days.

While the cardinal temperatures of wheat vary with varieties and other environmental factors, Lundegardh (33) stated in a general way that the maximum temperature for the growth of *Triticum vulgare* could be set at about 30°C. and Hurd-Karrer (25) stated that 8 to 10°C. are quite close to the lower cardinal point of the proper activity of wheat.

Effect of temperature on the relative growth of top and roots of the wheat plant. Wort (54) found that the top/root ratio of Marquis wheat increased from 4.0 at 22°C. to 7.0 at

34°C., then decreased at temperature above 34°C., where the growth of the whole plant was evidently prohibited. McKinney (36) found that the optimum temperature for root development of barley and wheat (Marquis) on a basis of dry weight was approximately 6°C. lower than that of the top development. Brenchley (7) noted that after the wheat plants began to manufacture their own food, there was a steady increase of top/root ratio, and as the temperature increased, root growth received less benefit than the top growth. Dickson (19) observed that when wheat was germinated at 8°C. and 12°C., the plumule did not appear until the root was already several centimeters in length, whereas at 28 to 32°C., the plumule was well out of the soil before the root developed. He stated that stimulating effect of low temperature on root development continued till the heading period. The largest top production, when experimenting with Marquis wheat by this author, was found between 20 and 24°C. during the early seedling stage. As the plant increased in age there was a lowering of the optimum temperature for development of tops, until in the later stages the best top development resulted at 12 to 16°C.

Working with Poa atensis, Darrow (16) verified the ben cial effect of low temperatures on the root development. He was of the opinion that the high temperature favored rapid maturation of roots, with consequently stunted root growth and the production of abundant laterals; while at low temperature, more elongation occurred before maturation of the root took place.

Effect of temperature on the tillering of wheat. Dickson (19) found in Marquis wheat that the plant tillered first at 24 to 28°C., which indicated somewhat similar cardinal temperature with the rapidity of emergence of the plant as found by the same author. Only a limited number of tillers formed at 32°C. and above. Below 24°C., soil temperature was found to have only little effect on tillering until at 8°C., where the tillering was evidently inhibited. Grantham (21) gave evidences that the number of tillers produced per wheat plant was decidedly affected by the quantity of available food in the soil. Fromthis, it seems reasonable to think that the ultimate control of the rate of tillering is the amount of available food in the plant which, when other factors are equal, depends on the available food in the soil. Taylor and McCall (45) observed that 28 percent of the Hard Federation wheats sown 18 mm. deep at 24°C. had failed to develop functional crown roots. This failure was due to the high crowning as a result of both high temperature and the shallow seeding. According to these authors, the formation of adventitious roots was closely related to the moisture condition. When plants grew so that the crown nodes came in contact with the moist soil, roots formed readily. When the crown roots fail to develop, there is undoubtedly a reduction of plant growth and tillering.

Effect of temperature on the food economy of wheat plants. Tottingham (47) observed a decrease in the carbohydrate/protein ratio in wheat grain with increased temperature. This decrease was interpreted as due to the loss of carbohydrate as a result of an accelerated respiration and a relatively less increased photosynthetic rate. Meyer and Anderson (37) stated that in perhaps all species of plants the optimum temperature for respiration is higher than the optimum for photosynthesis. Hence the higher the temperature above the photosynthetic optimum the greater will be the proportion of the photosynthetic products consumed in respiration and the smaller will be the proportion which can be utilized in food accumulation and further growth. Lehenbauer (31) studied the relation between temperature and the growth rate of maize seedlings. He found that although the initial rate of growth increased with increase in temperature, there was a tendency for the rate to drop with time. The higher the temperature, the shorter the period of the time the maximum rate of growth could be maintained, and the more rapid the decline in rate after it was once initiated. A similar idea was given by Blackman (5). Bushnell (10) reported reduced tuber growth of potato at high temperatures. He attributed the result mainly to the reduction of amount of reserve food available for tuber growth as a result of outbalanced relation between respiration and photosynthesis when the temperature was raised. Gregory (21) demonstrated a positive partial correlation between the net assimilation rate of barley and the average day temperature, but a negative partial correlation between the same factor and the average night temperature. By the net assimilation rate, Gregory meant the increase in weight of the dry material of a plant per unit leaf area per unit time. The negative correlation between the assimilation rate and the night temperature was explained as due to the accelerating effect of the high night temperature on the rate of respiration when photosynthesis was absent during that time.

Effect of temperature on the chemical compostion which relate to the sturdiness of the wheat plants. Tottingham (46, 47), Bayles and Martin (5), Dickson (20), and Hurd-Karrer and Dickson (26) all found that wheat seedlings contain higher carbohydrate percentage and lower active metabolic protein percentage at lower temperatures. Dickson stated that the high carbohydrate content of the plant at low temperature causes the young seedlings to have thicker cell walls, especially in the mature sheath tissues, and the high protein content of the tissue at high temperature induces a rapid vegetative growth and less of the carbohydrate is available for the building and thickening the cell walls. Walster (50) analyzed barley plants growing under 15^{o}C. and 20^{o}C. respectively and reached a conclusion similar to that given by Dickson. He found that the plants grown at low temperature are upright while those under high temperature lodged and were prostrate. He concluded that this is due to (a) a greater proportion of culm to leaf, (b) a greater proportion of skeletal material, i.e. the polyssacharide fraction, and (c) a greater degree of lignification of conductive tissue in both leaf and culm in the plants grown under low temperature. Arthur et. al. (3), however, obtained well grown barley with sturdy stems at 25^{o}C. with an artificial light of 620 foot-candles and a day length of 17 - 19 hours a day.

Effect of Soil Moisture

Under natural conditions, the moisture content of the soil influences the plant in two ways. In the first place, it is essential to the plant's life. In the second place, it influences the soil aeration, causing beneficial or detrimental results. The literature along this line was reviewed under four headings.

General effect of soil moisture content on plant growth. Hopkins (24) reported that most agronomic characters of wheat varieties, including number of shoots, number of heads, number of grain-bearing heads, weight of culms, length of culms, etc. decrease with the lowering of soil moisture content. Martin (34) obtained similar results in his work on Helianthus annus and stated that the lowering of holard resulted in reduced growth in terms of stem diameter, leaf area, dry weight, and usually in stem height. He further stated that growth rate of this plant was affected by even small differences in holard. It was practically the first effect of reduced holard to be detected. Veihmeyer and Hendrickson (49) found in young French prune trees a high correlation coefficient of 0.97 ± 0.11, and 0.95 ± 0.002 between the use of water and (a) the leaf area and (b) the growth in length of the plant respectively. It is universally true that an increase in soil moisture tends to increase the top/root ratio of most of the plants. Evidence of this in various types of plants has been given by Weaver and Clements (51) in corn, Rao (40) in sorghum, Haasis (cited by Rao) in yellow pine seedlings and Crist and Stort (15) in herbaceous plants. Smith (43) found that under the growth condition of North Dakota, the moisture condition during the thirty days following emergence largely determines the number of culms per plant. The number of tillers was materially reduced at dry seasons. Lundegardh (33) is of the opinion that the influence of the water factor alone upon growth of plants, without the interference of other factors, takes the form of a decrement curve. When the water content of the soil increases, the yield of plants increases too, at first rapidly, then more slowly. Bakhuyzen (4) stressed that one of the foremost conditions of growth is a sufficient water supply, because if this is satisfied, the growth and development can take place without a simultaneous increase in dry weight as may be shown by germinating plants in the dark. But it should be pointed out here that this statement merely means that the growth in dimension of a plant is not necessarily keeping pace with the growth in dry weight. After all, growth must be caused by available food material under any growth conditions.

Effect of insufficient amount of soil moisture on plant. Locke and Clark (32) and Webb and Stephens (53) observed that when the surface soil is extremely dry, the development of permanent roots is either entirely prevented or delayed. Under these conditions the seminal roots furnished sufficient moisture to maintain the growth of the wheat plant to maturity. Hayward (23) supporting their results, further stated that under such conditions, the plant does not tiller to any extent; and only the main culm develops, which though reduced in size, is normal. The difficulty in absorbing water encountered by plants at low soil moisture levels was illustrated by Livingston's experiment which was cited by Lundegardh. He found that the soil point removed water from a saturated soil at a rate of 3.64 grams per hour, while from a soil at the wilting point of wheat, it removed only 0.09 grams of water in two hours. Meyer and Anderson (37) stated that there is a sharp inflection of the curve of diffusion pressure deficit of soil at the position corresponding to wilting point of the soil. Around that point the reduction of the water content of the soil by only a very small percentage below that of the wilting percentage results in a very rapid rise in the diffusion pressure deficit of the soil. The limiting effect of the shortage of water on plant growth is further accentuated by the reduction in rate of photosynthesis. Meyer and Anderson (37) considered that the reduction of photosynthesis when the water content of leaves is decreased is due to the reduction in the diffusive capacity of the stomates resulting from the decreased leaf water content, and the reduction in the hydration of the chloroplasts and other parts of the protoplasm. Dastur (17) analyzed Willstatter and Stall's data and showed that decrease in water content of leaves brought about a decrease in assimilation number which designated the ratio between the amount of carbon dioxide assimilation in one hour and the chlorophyll content.

Effect of insufficient aeration brought about by excess soil moisture content. Bryant (9) found in barley that the response of root growth to aeration became evident within a few days after planting, and at the end of sixty days the average length of the roots in aerated solution was 37.4 cm. as against 10.0 cm. for the non-aerated plants. He explained this as due to the fact that the higher respiration rate in aerated roots decreased the sugar concentration to a point where it prevented the rapid cell wall thickening and that there is greater supply of oxygen available to the apical meristem of the aerated roots. Even in hydrophytes, Weaver and Himmel (52) and other authors found that the root depth of the plants increased with decreasing soil moisture content until the soil became too dry for growth. They also observed that the root hairs were progressively more abundant as aeration became better with decreasing water content. Snow (44) found that roots of corn and wheat in well aerated soil produced abundant root hairs after seven days, while the roots of the same plants grown in a saturated soil produced few or no root hairs after the same period. Balls cited by Cannon (13) in Egypt and Albert and Armstrong (1) in the United States observed under field conditions relationship between the cessation of the growth of the cotton plant and the falling off of aeration as a result of high soil temperature and heavy rainfall. An elaborate series of root studies has been made by Cannon (11, 12, 13). Some of his important findings are as follows: (a) The minimum oxygen concentration in all of the species examined is greatest at the highest temperature and least at the lowest temperature. (b) With decreasing aeration, both the optimum and the maximum temperature are greatly reduced. (c) The ratio between root growth rate under limited aeration to that under normal aeration decreases with the increase of soil temperature. The injurious effect of the insufficient aeration brought about by the high soil moisture content is summarized by Miller (39). He stated that

... Interference with the process of respiration is apparently the cause of the injury and eventual death of the roots due to the exclusion or depletion of the oxygen supply of the soil. ... These effects are apparently due to the fact that the protoplasm does not function properly as an absorbing membrane. ... The decreased turgor would thus influence the rates of transpiration, growth, and respiration in the aerial part of the plant.

Water absorption in relation to temperature. There is no doubt that up to a certain limit an increase in temperature will induce an increase in water absorption by plants. But the cause of this increase is still an unsettled question. There are generally two schools in regard to this problem. The first group of people based their explanation on Armstrong's hydrone theory of the structure of water by saying that water at low temperature has several H_2O groups combined into a single group, which breaks down into simpler groups as the temperature rises; and claimed that the increased water absorption at a rising temperature is due to the increased diffusibility of the water molecule after it splits down. This theory was put forth by Brown and Worley (8) from a study on the water absorption of barley seed. They found that the value of Q_{10} for the intake of water followed approximately Van't Hoff's law. Kramer (30) by use of Livingston's soil point, also concluded that physical action played an important role in the root absorption.

On the other hand, Shull (41), Clements and Martin (14), Shull and Shull (42), Denny (18) and others all found that the Q_{10} of water absorption by plant tissue is definitely higher than what can be explained by the physical changes as suggested by Brown and Worley. They considered that both physical and chemical processes are involved in this situation. A summary of the reasons, however, can be found in some of the textbooks. For example, Maximov (35) stated that the decrease of absorption of water at low temperature is due to the increase of the viscosity of water and decrease of permeability of the protoplasm. To these Meyer and Anderson (37) added a third item, that is, the dimunition in the physiological activity of the root cells.

EXPERIMENTAL METHODS

Two varieties of wheat, Tenmarq, a winter variety, and Thatcher, a spring variety, obtained from the Department of Agronomy of Kansas State College and the Division of Agronomy and Plant Genetics of the University of Minnesota, respectively, were used in this experiment. The experiment was first carried through from April to June of 1940 at Kansas State College, Manhattan, Kansas; and was repeated from July to September of the same year at the same place. For each experiment, the plants were grown for a period of two months after their emergence.

The environmental factors under consideration were mainly temperature and soil moisture. But in the second run of the experiment, it was found to be necessary to modify the light intensity and the day length in order to get better results, so the light factor was incidentally introduced and received a part of the attention.

Controlled Methods

The methods of growing plants. The soil used in this study was a composite soil prepared by mixing two parts of heavy silt loam obtained from the surface layer of a cultivated field soil and one part of coarse sand. This composite soil had a loose texture which greatly facilitated the desired rapid water distribution and at the same time it had a field capacity considerably higher than the ordinary sandy loam. The soil and sand were thoroughly mixed by repeatedly working through a one-fourth inch mesh screen. The resulting soil was then laid out indoors until air dried. Before filling the jars, it was screened once more to assure uniform moisture distribution. Moisture samples were taken when filling the jars. The plants were grown in one gallon glazed jars. An equal weight of soil was added to each jar and moderately tamped. In order to prevent excess evaporation, the surface of the soil was sealed with a thin layer of wax. To accommodate the seedlings, five circular openings, one inch in diameter, were cut through the wax covering by using a heated cork borer. Each opening was seeded with two grains. After germination, the seedlings were thinned so that only one was left in each opening or altogether, five seedlings in each jar.

Soil moisture control. It was decided to keep the soil moisture at four levels. These were (a) slightly above the wilting coefficient of the soil, (b) intermediate between wilting coefficient and field capacity, (c) field capacity, and (d) 7 percent (on basis of soil dry weight) above the field capacity. The field capacity of the soil was assumed to be approximately equal to the moisture equivalent (49) which was determined by centrifugal method. The highest level was arbitrarily determined by first bringing the soil moisture to field capacity and then adding excess water till the soil was evidently supersaturated with water and poor aeration was insured. These levels as determined on the basis of dry weight of soil were as follows:

	Moisture levels%			
	A (Wilt. coef.)	B	C (Field cap.)	D
1st expt.	12.0	17.0	22.0	29.0
2nd expt.	11.2	15.9	20.6	27.6

Two methods of moisture control were employed. For the two high moisture levels, the sand-core-watering system described by Miller (38) and Johnston and Miller (28) was used. Briefly, when filling the jars, a core of coarse sand, two inches in diameter was set up in the center of the soil mass, extending from the surface to three-fourths the depth of the jar. A sixth opening was cut into the wax surface so as to permit the insertion of a glass funnel into the sand core through which the right amount of water could be added by a graduated cylinder. The water then diffused rapidly throughout the sand core and finally to the soil mass in all directions. For the two lower moisture levels, there were evidences that the above described method could not be used satisfactorily. The water, when added in small amounts, tends to wet only the soil immediately surrounding the sand core and leaves the peripheral layer dry.

Therefore, the copper-coil-irrigating device of Grandfield[1] was used. In this method, the irrigating scheme consists chiefly of a perforated coil made of copper tubing about 3.5 mm. in diameter, the upper end of the coil being sealed while the lower end is straight and extends out of a hole in the bottom of the jar through a single-holed rubber stopper. This coil was set in the jar in such a way that it occupied the center part of the soil mass and its top was about an inch below the soil surface. Through its open, extended, lower end, water was forced into the coil and it spread out uniformly in all directions into the soil mass through many tiny perforations in the wall of the coil. When watering, the jar was set on a wooden frame which had a hole in the top board to let through the extended end of the copper coil. The frame, with the jar on it, was then set on a solution balance. As the weight of soil in each jar was constant and the original moisture content of the soil was previously determined, the extra amount of water needed to make up the required moisture could be readily calculated. The balance was set for the total weight of the jar, including the wax covering, the copper coil, the rubber stopper, the wooden frame, the soil and the water to be added. A hose with a valve control was then connected to the extended end of the copper coil, and water let in until the scale was balanced. This total weight was recorded on each jar and brought back at every three day interval by adding water in the same manner to replace the water that was lost through evaporation and

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1. Grandfield, C. O., Assistant Agronomist, U.S.D.A., Kansas Agricultural Experiment Station. Method unpublished.

transpiration. The whole set up is shown digramatically in Fig. 1. When the roots were examined after harvest, the presence of the copper coils in soil apparently made no hinderance or disturbance to the root development or distribution.

In the first experiment, the moisture content of each jar was brought to its required level before seeding. In the second experiment, in order to get a more uniform rate of germination, a small amount of water was added to each hole over the surface until the plants germinated, then more water was added and the whole soil mass adjusted to its required moisture level.

Temperature control. The control of temperature was satisfactorily attained by using a suite of four refrigerating rooms of the Chemistry Department of Kansas State College. The temperature of these four rooms was automatically kept constant at 6, 20, 25, and 34°C. respectively during the first experiment. For the second experiment, the 20°C. room was changed and maintained at 12°C. The relative humidity of these rooms was not controlled. On an average, it was 87, 85, 80, 74, and 62 percent for the 6, 12, 20, 25, and 34°C. rooms respectively according to sling psychrometer measurements.

Treatments. As mentioned above, four temperatures, four soil moisture levels and two wheat varieties were used, there were altogether thirty-two treatments in this experiment. These are tabulated in Table 1. Three replicated jars, containing five plants in each, were given to each treatment. So the whole experiment consisted of 96 jars with 480 plants, whose measurements were made individually. These 96 jars were divided into four sets. Each set of 24 jars was placed in one refrigerat-

Table 1. The 32 combinations of temperature, soil moisture, and variety treatments used in this experiment.

Moisture levels	Wheat varieties	Temperature °C.			
		6	20, 12	25	34
A	Thatcher(s)	6-A-s	20 12-A-s	25-A-s	34-A-s
	Tenmarq (w)	6-A-w	20 12-A-w	25-A-w	34-A-w
B	Thatcher(s)	6-B-s	20 12-B-s	25-B-s	34-B-s
	Tenmarq (w)	6-B-w	20 12-B-w	25-B-w	34-B-w
C	Thatcher(s)	6-C-s	20 12-C-s	25-C-s	34-C-s
	Tenmarq (w)	6-C-w	20 12-C-w	25-C-w	34-C-w
D	Thatcher(s)	6-D-s	20 12-D-s	25-D-s	34-D-s
	Tenmarq (s)	6-D-w	20 12-D-w	25-D-w	34-D-w

ing room for temperature treatment. The arrangement of these 24 jars was made according to the moisture levels and the light control, as will be explained in the next paragraph.

Light control. In each room, the 24 jars were arranged as shown in Fig. 2. The whole thing had a shape of a square with its four corners cut off. Each diagonally divided quarter of the square consisted of 6 jars, which were maintained at one of the four moisture levels. In the first experiment, four Madza reflector lamp bulbs of 150 watts each were hung 3 feet above the surface of the jars at the positions indicated by cross signs in Fig. 2. The day length then used was 16 hours. In the second experiment, the bulbs were lowered to two feet above the surface of the jars and the day length was reduced to 10 hours. A measurement with a Weston illumination-meter revealed that the light intensity was lower at the outer rim of the whole illuminated area than in the inner areas. The range of the intensity was from 180 to 230 footcandles during the first experiment and from 250-350 footcandles during the second. This particular defect, however, was considerably overcome by moving the position of the jars within each moisture level systematically every two days. The direction of the movement of the jars was shown in Fig. 2 by the arrows.

Measurements Taken

Height of plant. The plants were measured twice a week with a meterstick. The measurement was made from the surface of the wax covering to the tip of the plant. In this experiment, the tip of plant was always the tip of the leaf which reached the greatest height.

The total length of leaf sheaths. The length was measured at the time of harvest from the surface of the soil to the ligule of the highest leaf.

The date of emergence of the successive leaves. This was recorded as the time when the tip of the new leaf just emerged from the coleoptile or the sheath of the next older leaf.

Tillering. The number of tillered plants and the number of tillers per plant were counted at the end of the experiment.

Top dry weight. At the end of two months, the top of each plant was cut off at the soil surface, and brought to the laboratory, where it was immediately oven dried at a temperature of 95°C. for about one hour, then at 85°C. for 23 hours, After being dried, it was weighed to an accuracy of one-tenth of a milligram.

<u>Root dry weight.</u> After the top was harvested, the jar was emptied and the roots carefully removed. The roots grown at the two lower moisture levels could be picked out without much difficulty. At the higher moisture levels, more breaking of the roots occurred and the picking was supplimented by washing over a fine screen whereupon the broken roots were caught and collected. The roots after removal from the soil were carefully rinsed in tap water to remove the adhereing soil particles. Since it was impossible to avoid the breaking of the finner roots, the dry weight of the roots was obtained on the basis of an individual jar, instead of an individual plant. The roots of the five plants in each jar were collected together and weighed as a total after being oven dried.

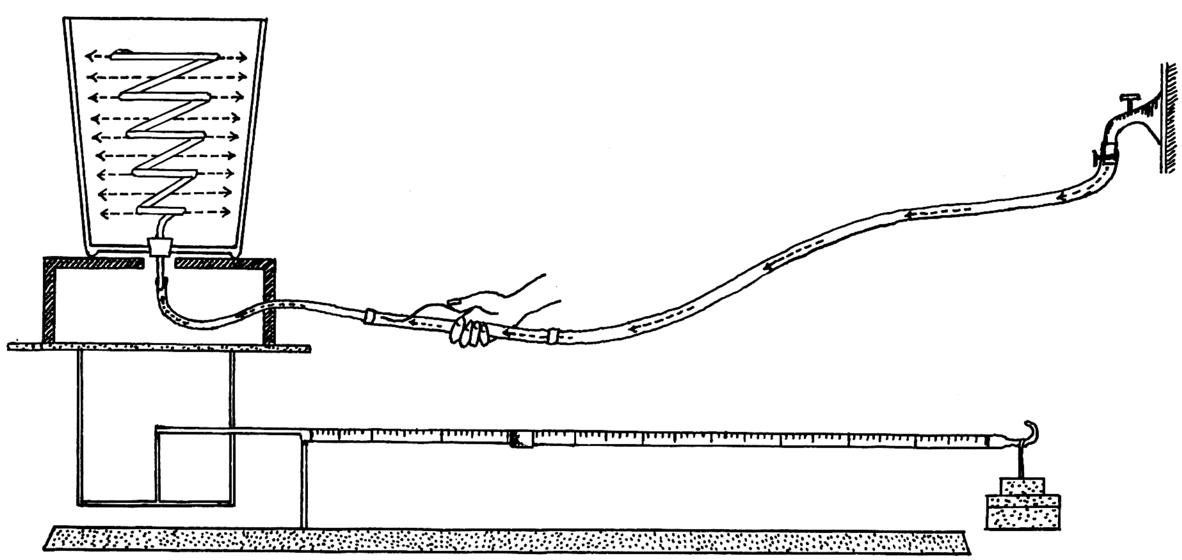

Fig. 1. A diagram showing the working scheme of Grandfield's copper coil irrigating method.

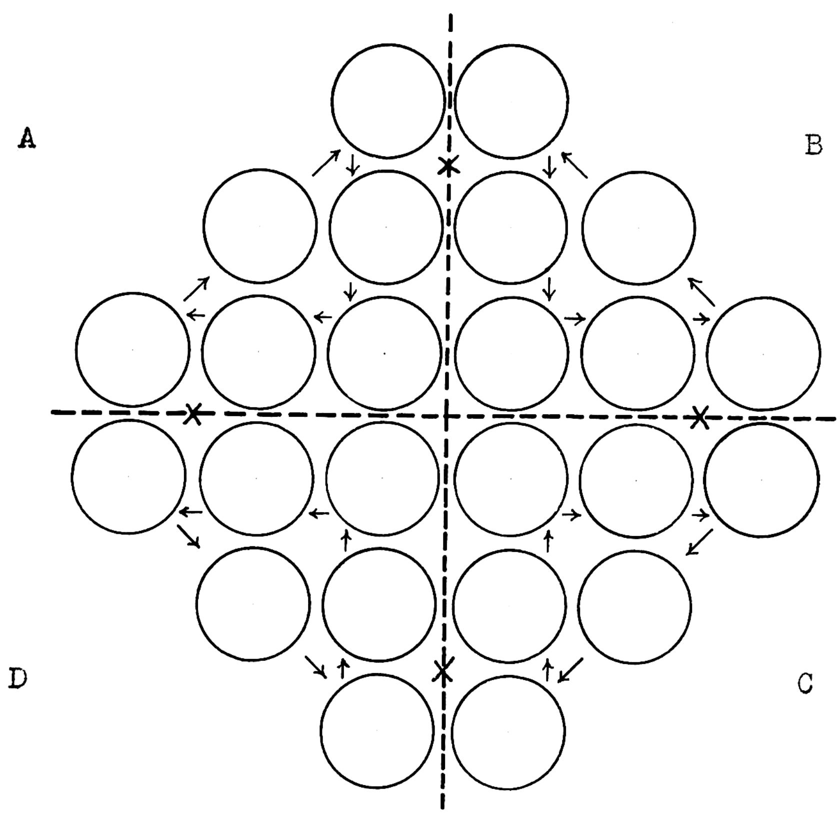

Fig. 2. A diagram showing the arrangement of the jars in the refrigerating rooms. The 'A, B, C, D' designate the soil moisture levels. The crosses designate the position of the light bulbs. The arrows designate the direction in which the jars were moved at two day intervals.

EXPERIMENTAL RESULTS

It has already been mentioned that this experiment was repeated, and modifications of some of the controlled methods were made when it was performed the second time. For the convenience of discussion, it is necessary to state once more those modifications. These are shown as follows:

Treatment	1st experiment	2nd experiment
Temperature(^{o}C.)...........	6, 20, 25, 34	6, 12, 25, 34
Soil moisture..............	not changed	not changed
Light intensity............	180-230 ft. cd.	250-350 ft. cd.
Day length.................	16 hours	10 hours

A few statements should be made before discussing the results. First, in the following discussion, more weight will be given to the results of the second experiment than to those of the first, because as will be seen later, better and more measurements were taken in the second than in the first experiment, and it is believed that the control measures used in the second experiment were nearer to normal than those used in the first, although the first experiment also gave information that is valuable for supplementing and contrasting with the second. Next, it should be mentioned that the data of various items presented in the following discussion were mostly the final average figures of the fifteen plants that received the same treatment. It is true that there were some variations within treatment, but the levels of the treatments used were so wide that the contrast between treatments was distinct and it seemed that the average figures could be used as a fairly sound basis for the present type of discussion. Third, a high death rate occurred among the plants grown at 34°C. for both experiments. The data for this set of plants were therefore the average of the figures of these plants which lived till the end of the experiment. The actual death rate will be given and discussed later.

The results of the experiment will be discussed under separate headings as follows:

Dry Weight of the Tops

Since the dry weight of the plant is the summary expression of the plant growth, it is dealt with first. Considerably different results were obtained in the first and second experiment. So the results of the two will be discussed separately.

Result of second experiment. Table 2 gives the average dry weight of the plants under different treatments obtained in the second experiment. These figures were graphically expressed in Fig. 3.

A glimpse at Fig. 3 reveals three general facts. First, under the 10 hour day length which is about normal for the time during the wheat seedling stage, the response of the spring and winter varieties toward temperature and soil moisture was essentially the same in regard to their dry weight performance. Second, the plants increased in dry weight with the increase of temperature up to 25°C. The plants in the 34°C. room always gave a much lower weight than those grown under 25° and 12°C. Third, the plants also increased in dry weight with the increase in soil moisture until the latter reached the field capacity, beyond which, plants under different temperatures reacted differ-

Table 2. The average dry weight (mg.) of the tops under different treatments at the end of two months (result of the 2nd experiment).

Moisture & variety		Temperature ^{o}C.		
	6	12	25	34
A - Thatcher	17.0	94.0	73.3	20.9
- Tenmarq	19.9	88.6	72.8	36.0
B - Thatcher	17.5	131.3	137.1	27.6
- Tenmarq	21.4	148.6	177.9	41.3
C - Thatcher	31.5	142.5	248.9	51.3
- Tenmarq	41.7	152.3	249.7	67.6
D - Thatcher	51.7	160.5	177.6	33.9
- Tenmarq	52.4	133.4	165.9	----

ently.

More detailed examination of Table 2 and Fig. 3 will bring out more complex interrelations between the temperature and soil moisture. For both Thatcher and Tenmarq wheat grown at 6°C., the dry weight curves show an uninterrupted rise with increase in soil moisture. At 12°C., Thatcher wheat at the highest soil moisture level still led in dry weight. But at the same temperature, the dry weight of Tenmarq showed a slight decrease at the highest moisture level. At 25° and 34°C., both Thatcher and Tenmarq wheat produced less dry weight at the highest moisture level than at field capacity level. At 34°C., the extremity of the case was shown by the high death rate of the plants grown at and above the field capacity level.

The above findings illustrate the effect of the soil aeration on the plant growth in relation to temperature. Under the conditions of the present experiment, it seems that at a low temperature of 6°C., the amount of oxygen present in soil and soil

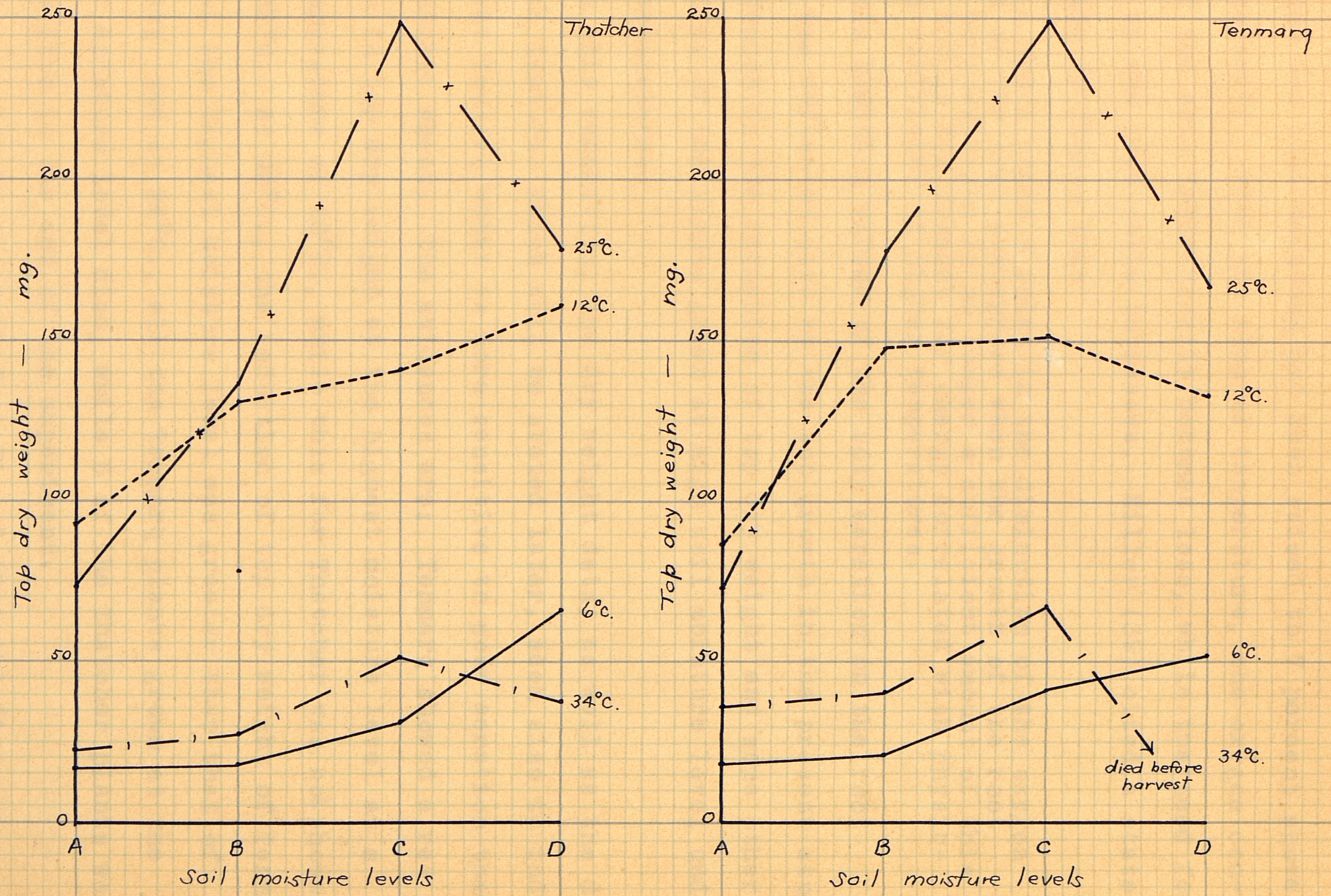

Fig. 3. A graph showing the variation of the top dry weight of the plants under different treatments at the end of two months under a day length of 10 hours. (results of 2nd experiment)

water was still sufficient to meet the need of the root cells even when the soil moisture had been raised to 7 percent above field capacity. With the rise of temperature, the oxygen content of the soil theoretically becomes less, while the need for oxygen by the root cells increases. Miller (39) cited a statement made by Cannon that

> ... there comes a point in the diminution of the oxygen content of the soil atmosphere when the growth of the root ceases because there is no longer a sufficient amount of this gas to supply the demands for energy correlated with physiological activities of higher temperatures.

This limiting effect of the soil aeration on the root growth was reflected also by the top growth in the present study as evidenced by the reduction of top dry weight and some other characters of the plants grown at high soil moisture level under high temperatures.

In this connection, the dry weight data, as well as the data of other features which will be stated later, seem also to indicate that Tenmarq wheat is more sensitive to poor aeration than the Thatcher wheat. The evidences are: Tenmarq showed a reduction in top dry weight at the highest moisture level at a low temperature of 12°C., while this for Thatcher was not shown until 25°C. At 25°C., the reduction of top dry weight of Tenmarq grown at the highest moisture level was greater than that of Thatcher; and at 34°C., all the Tenmarq plants grown at the highest moisture level died, while 6 of the Thatcher plants were able to live to the end of the experiment.

It can also be observed from Fig. 3 that the divergence of the four curves increases from moisture A, the lowest moisture level, toward moisture C, the field capacity level, and then decreases again at moisture D, the highest moisture level; which indicates that the effect of temperature is more prominent when the soil moisture condition is such as to allow greater growth and can be regarded as an illustration of Blackman's law of limiting factor.

Another point observed from the same figure is the consistency between Thatcher and Tenmarq wheat in that at the lowest moisture level, the 25°C. plants made less growth in dry weight than the 12°C. plants. This fact probably could be attributed to the lower photosynthetic / respiration ratio and the lower water economy of the plants grown at 25°C. This assumption was virtually true and could be confirmed by the flabbiness of the 25°C. plants at this moisture level.

Finally, Table 2 shows that within a temperature range from 6° to 25°C., and a soil moisture range from wilting coefficient to field capacity, the growth of dry weight of the above ground part of a single wheat plant within a period of two months after its emergence could vary from less than 20 mg. at the lowest temperature and soil moisture level to about 250 mg. at the highest temperature and soil moisture level. Under natural conditions where the light intensity and the weight of the plant are higher the differences wouldbe expected to be still greater than this.

Result of first experiment. The average top dry weight of the plants obtained in the first experiment is given in Table 3 and graphed in Fig. 4.

Table 3. The average dry weight (mg.) of the tops under different treatments at the end of two months (result of the 1st experiment).

Moisture & variety		Temperature °C.		
	6	20	25	34
A - Thatcher	31.7	79.8	42.3	13.3
- Tenmarq	32.1	124.3	64.0	24.7
B - Thatcher	27.1	99.9	46.1	11.3
- Tenmarq	31.3	150.4	89.9	19.8
C - Thatcher	33.7	81.4	79.8	19.0
- Tenmarq	37.1	107.0	180.4	25.8
D - Thatcher	45.5	62.4	61.7	----
- Tenmarq	37.4	85.5	151.3	22.9

The plants grown at 6°C. apparently showed no great difference from the same set of plants in the second experiment, except that the limiting effect of the low soil moisture was not so well shown. This was due to a variation in the experiment that was introduced because the plants in the low moisture jars at all temperatures germinated slowly as a result of the unfavorable moisture condition. A small amount of water was added periodically over the surface until the plants germinated. In the three higher temperature rooms, this additional water did not influence the final moisture content of the soil because of the fairly rapid evaporation. In the 6°C. room, however, the loss of water from the jar was so slow that the additional water used to stimulate germination, although small in amount, might have percolated to a greater depth and thereby accumulated before it was evaporated. These jars for a period varying from three weeks to a month maintained a weight greater than the original weight

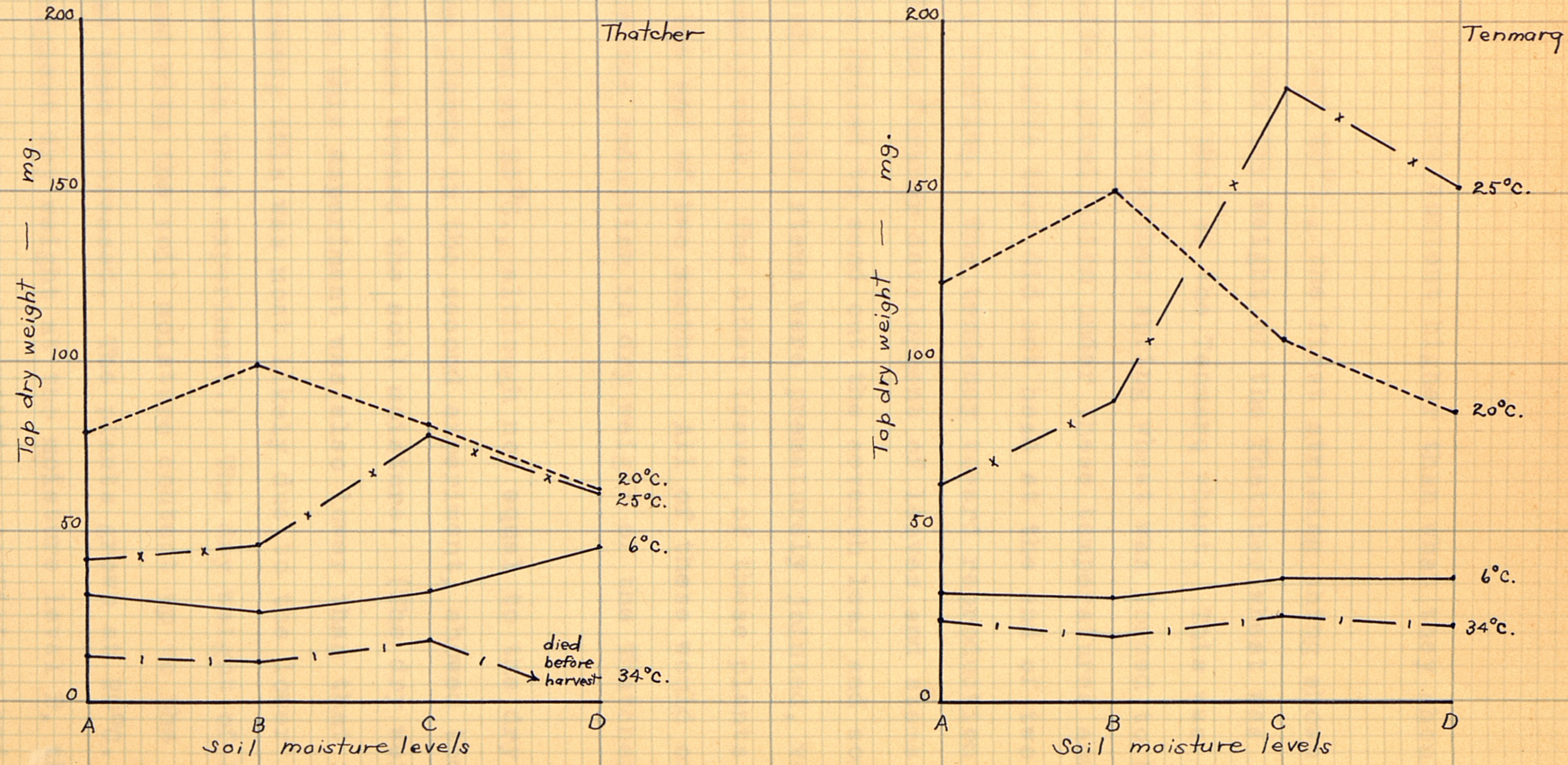

Fig. 4. A graph showing the variation of the top dry weight of the plants under different treatments at the end of two months under a day length of 16 hours. (result of 1st experiment)

indicating a soil moisture content higher than what they should have been.

Under both 20° and 25°C., the first striking thing shown by the data is that the dry weight of the Thatcher wheat was considerably lower than that of the Tenmarq wheat. This was due to the fact that the Thatcher spring wheat was forced to head at 6 to 8 weeks after germination under these temperatures and day length. Those plants that did not head at the end of two months were mostly booting. The tendency toward reproduction evidently checked the further development of leaves and stems. Most of the plants failed to send out the seventh leaf and some even the sixth leaf. Their stems were prematurely jointed, very slender and extremely weak. The older leaves of these plants died long before the end of two months. All of these would of course account for the reduction in dry weight of the Thatcher wheat.

The plants grown at 25°C., although not equal to the dry weight of the same plants in the second experiment, showed the same trend of response toward the soil moisture. (The dry weight of Tenmarq wheat in this experiment was also lower than that in the second experiment; this was most likely due to the lower light intensity used in this experiment.) The dry weight of both varieties increased with the soil moisture content up to the field capacity and then decreased. The plants grown at 20°C. however had the highest dry weight at the moisture level B, that is the level intermediate between the wilting coefficient and the field capacity. The plants grown in soil wet to field capacity showed a lower dry weight, while those in the highest moisture level still lower. This is one of the results for which no satisfactory interpretation could be given, for there is no explanation for the fact that the field capacity moisture level shown to be too high at 20°C. did not cause a reduction in dry weight of the plant at higher temperatures of 25° and 34°C. More about this will be discussed under the topic concerning the number of leaves.

The 34°C. plants were severely injured as indicated by the high death rate and the low dry weight. Evidently, when the light intensity and hence the photosynthetic rate were low, the plants were more susceptible to the high temperature which induced the high respiration rate. The prematuration of Thatcher wheat also occurred under this temperature, as shown by the jointing of all the plants of this variety and the heading of three of them. In regard to soil moisture, the highest dry weight was still attained at the field capacity level. Contradictory to the result of the second experiment, under this temperature and at the highest soil moisture level, the Thatcher plants all died while six of the Tenmarq plants were able to last to the end of the experiment. The Thatcher plants were obviously handicaped by a poor initial growth and also by the forcing effect of the long day length.

Dry Weight of Roots

In the first experiment, there was a considerable variation in the rate of germination of the plants, especially at the two low soil moisture levels. The difference in date of germination of the plants in the same jar might be sometimes as great as ten days, although the usual difference was from one to seven days. The top part was harvested when each plant had reached the age of two months. The roots were taken out at once after the latest plant in the jar was harvested. During the period between the harvest of the top of the earliest plant and the harvest of the roots, some of the roots, whose tops had already been cut off, must have made some new growth or undergone some disintegration. Considerable error was then introduced and the data were not used in the present discussion.

In the second experiment, a very uniform germination was obtained because of the use of an improved method of seeding; as for most of the jars, the five plants emerged the same day. Only in a few cases did some plants emerge one to two days later than the others in the same jar. At the end of the experiment, the tops were harvested at the same time and the roots were taken out immediately after the tops were harvested. The data were considered then to be fairly accurate so far as the age of the plants was concerned. Still other sources of error, however, should be admitted before discussing the result. The soil that had the higher moisture content was more compact than the drier soil at the end of the experiment. In working out the roots, more difficulty was encountered at the higher moisture levels. At the two low moisture levels, the whole root system could be picked out at once with few breaks. While at the two higher moisture levels, considerable breaking occurred and some finer parts were probably lost, in spite of the utmost care that was taken in picking up the broken fragments. As was mentioned before, each jar was seeded with ten grains at first and then thinned to five seedlings. The root parts of those removed plants remained in the soil until the time of harvest. They were all short, dry, and shriveled and were picked out from the roots of the experimental plants. But in case of breaking, the broken parts were difficult to be separated from those of the living plants. Again, in the 34°C. room, a considerable number of plants died before harvest. The roots of those plants were very fragmental or even completely disintegrated at the time of harvest. Even the roots of the plants that lived to the end of the experiment, were so small and broken down so much that an accurate collection was practically impossible. In the following discussions, therefore, only the dry weight of the roots of the plants grown at the three lower temperatures will be dealt with. For the plants grown at 34°C., it needs only to be remembered that the roots were very shallow and small and a very light dry weight was expected.

Table 4 and Fig. 5 give the average dry weight of the root and the average top/root ratio of the plants under different treatments.

For both Thatcher and Tenmarq, the greatest root growth was obtained at 12°C. at all moisture levels, the second greatest weight was obtained at 25°C., and the lowest weight was obtained

Table 4. The average root dry weight (mg.) and the top/root ratio (in parenthesis) obtained under different treatments at the end of two months. (results of the 2nd experiment.)

Moisture & variety		Temperature °C. 6	12	25
A	- Thatcher	7.9 (2.2)	23.6 (4.0)	15.6 (4.7)
	- Tenmarq	9.2 (2.2)	25.1 (3.5)	14.2 (5.1)
B	- Thatcher	8.6 (2.0)	20.0 (6.6)	18.1 (7.5)
	- Tenmarq	8.6 (2.5)	32.9 (4.5)	24.8 (7.1)
C	- Thatcher	12.4 (2.5)	25.0 (5.7)	16.0(15.6)
	- Tenmarq	15.0 (2.8)	23.2 (6.6)	22.4(11.1)
D	- Thatcher	12.0 (4.3)	24.3 (6.6)	14.8(10.7)
	- Tenmarq	10.7 (4.9)	25.0 (5.3)	10.3(16.1)

at 6°C., with only one exception. The beneficial effect of the low temperature on the root growth is shown by the greater root dry weight of the plants grown at 12°C. over that at 25°C. and 34°C. But the low root dry weight of the plants grown at 6°C. seems also to indicate that although the low temperature generally favors the root development, the absolute amount of the root growth is associated in some way with the amount of growth made by the top. For example, at 12° and 25°C., the root system at the end of two months consists of both primary and secondary roots, while at 6°C. only primary root was developed. In a general statement, perhaps it could be said that when the temperature is so low that the growth of the tops is greatly checked, the weight of roots is accordingly reduced.

The limiting effect of the high soil moisture on the root growth was evidently much more prominent than on the top. In no case did the plants grown at the highest soil moisture make

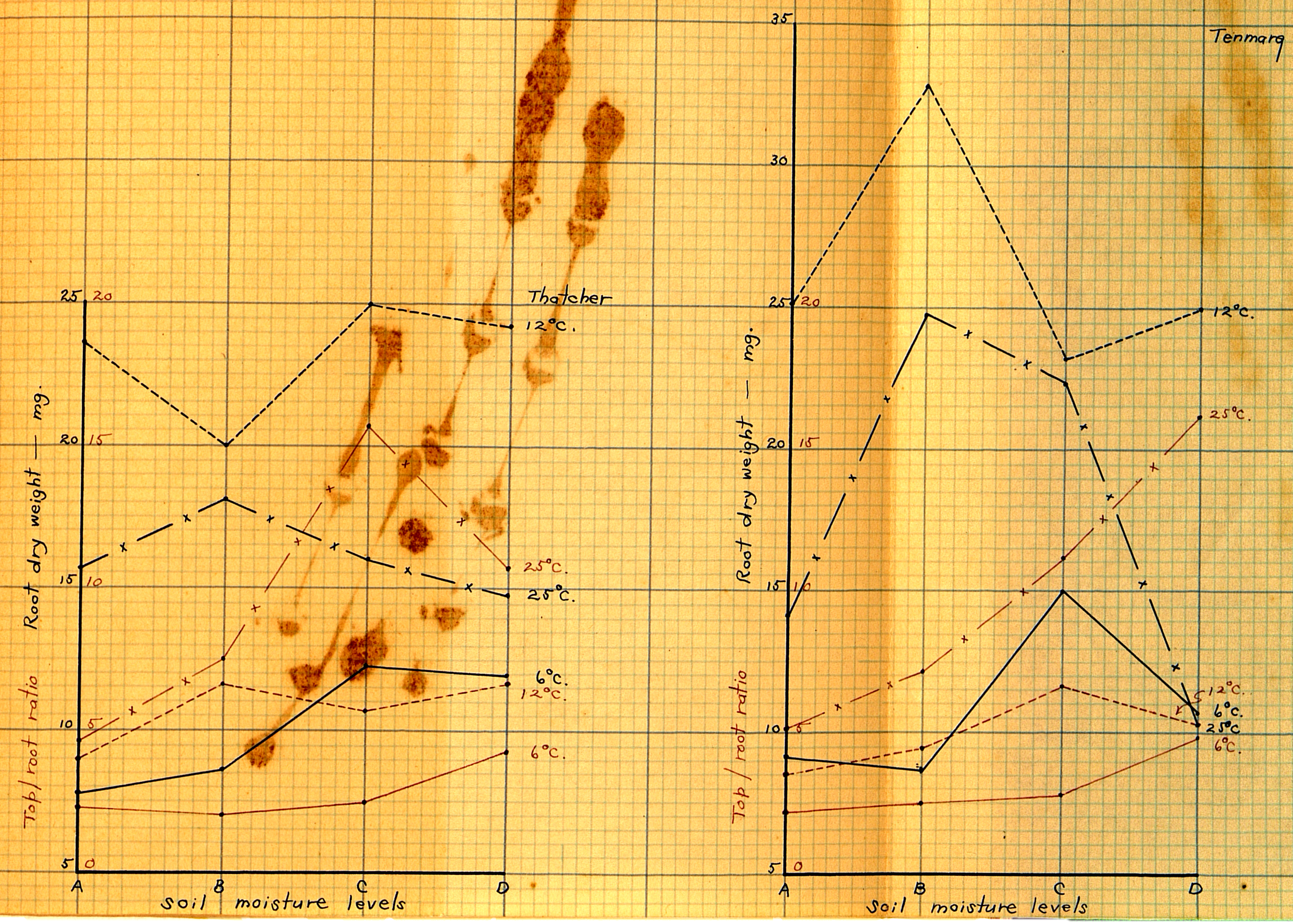

Fig. 5. A graph showing the **average root dry weight** and top/root ratio of the plants under different treatments at the end of two months. (the result of the 2nd expt.)

the greatest root growth. For the plants grown at 6°C. and the Thatcher wheat grown at 12°C., the greatest root weight was obtained at the field capacity, while that of the rest was obtained at the moisture level B. It is interesting to note that at 12°C., the greatest weight of root of Thatcher wheat was obtained at a higher moisture level than that of Tenmarq; and at 25°C. the reduction of the root weight at the two high soil moisture levels in case of Tenmarq was much greater than Thatcher. This tends to add evidence to the statement that Tenmarq is more susceptible to the poor soil aeration, and perhaps the greater reduction of the top part of this variety was a direct result of the greater reduction in the growth of roots.

In observing the data and the graph for the top/root ratio, the results show definitely an increase in the ratio with the increase in temperature, and less regularly with soil moisture, until the point was reached where the top part as well as the roots was injured.

The statement that increase of temperature and moisture are unfavorable for root development, therefore, is only correct in the sense of the top/root ratio. The absolute amount of growth of roots still followed the usual parabola curve in a course of increasing temperature or soil moisture, although its climax in both cases was attained at a lower level than the tops. It seems that the top/root ratio cannot be used as a good criterion for indicating the actual condition of the growth of tops and roots. An increase in the ratio, for instance, can occur when both the tops and the roots increase in amount of growth, when tops increase while the roots decrease, or when both decrease.

Rate of Emergence of Leaves

The rate of emergence of leaves was studied because this possibly indicates in some way the activity of the apical meristem of the plants.

In the first experiment, the date of leaf emergence was recorded after the whole leaf was completely extended out of the sheath of the preceding leaf. But it was later discovered that it was rather difficult to decide exactly when the leaf should be considered as completely emerged, especially in the 6°C. room where the growth was extremely slow and the daily extention of the leaves was minute. These data were therefore again considered as lacking accuracy and were not used.

In the second experiment, the date of emergence was recorded as the day when the leaf was just emerging from the sheath of the older leaf. This method apparently introduced no error, except sometimes where the young leaf tip was in the more or less rolled base of the next older leaf, and would not be observed till it grew longer. Careful observation reduced this error to a minimum. The data given in Table 5 include the average rate of leaf emergence in terms of days after the emergence of the coleoptile. The response of the rate of leaf emergence toward the temperature and soil moisture followed rather closely that of the top dry weight. It generally increased from 6° to 25°C. and then decreased again at 34°C.

At 6°C., the result was invariably in favor of the higher

Table 5. The days required for the emergence of successive leaves after the emergence of the coleoptile under different treatments. (results of the second experiment).

Temperature	Moisture	Variety	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
6°C.	A	Tha.	19.6	40.0							
		Ten.	21.4	40.5							
	B	Tha.	18.9	36.9							
		Ten.	19.1	36.2							
	C	Tha.	16.1	33.5	57.5						
		Ten.	15.5	34.4	61.1						
	D	Tha.	15.3	31.9	54.3						
		Ten.	13.4	32.1	51.6						
12°C.	A	Tha.	8.3	21.7	36.2	50.7	63.7*				
		Ten.	8.5	23.6	38.1	49.1	60.1				
	B	Tha.	7.8	19.5	33.0	45.4	59.1				
		Ten.	7.9	20.2	32.1	42.2	52.2	63.2*			
	C	Tha.	6.8	18.2	30.6	43.5	57.4				
		Ten.	6.9	18.7	30.4	40.1	49.3	61.4			
	D	Tha.	6.8	17.4	30.6	42.3	56.3				
		Ten.	6.9	18.0	30.0	41.2	51.6	62.9			
25°C.	A	Tha.	5.9	16.1	25.7	34.6	43.9	52.7	62.2		
		Ten.	5.9	22.6	33.2	42.2	51.6	60.5			
	B	Tha.	5.2	13.6	22.1	30.8	37.8	45.5	53.2	60.2	
		Ten.	4.8	15.9	26.2	32.8	39.4	46.0	53.3	59.3	
	C	Tha.	4.2	11.6	19.5	26.5	34.1	40.5	47.8	54.8	
		Ten.	3.6	12.6	22.0	30.1	35.9	41.4	48.1	53.5	60.5
	D	Tha.	4.1	11.9	21.1	28.0	35.3	42.4	49.1	55.4	
		Ten.	3.7	13.4	22.9	30.9	36.8	43.2	50.2	58.0	

Table 5. (Cont.)

$34^{o}C.$ - A - Tha.	11.0	25.7	38.0	47.3	56.7		
- Ten.	6.9	24.6	38.7	49.0	59.0		
- B - Tha.	6.8	18.4	28.1	38.0	45.5	55.3	65.8*
- Ten.	4.0	19.8	34.8	47.6	56.3		
- C - Tha.	7.0	19.7	26.3	37.2	46.2	56.4	63.9*
- Ten.	4.6	15.6	26.0	36.0	47.0	57.5	
- D - Tha.	6.9	17.6	24.7	33.7	43.1	51.7	60.7
- Ten.	4.3	20.0	31.7	----	----		

Note 1. The data for the first leaf is not used because the plants were germinated with a uniform small amount of water poured over the surface. The soil moisture was adjusted to the specific levels after the plants had germinated. The rate of emergence of the first leaf, therefore, showed no variation with moistures.

Note 2. All the figures which have a sign of * are greater than 62, the number of days of the experimental period, and therefore seem to be illogical. A little explanation is needed. All the figures for the last leaf of the plants (not only those that have the * sign.) are subjected to an error introduced by the fact that not all the plants of the group had produced that leaf at the end of the experiment. For example, the average number of days required for the emergence of the fifth leaf of the Thatcher wheat grown at $12^{o}C.$ and the lowest moisture level (in Table 5, it is designated as $12^{o}C.$ - A - Tha.) is 50.7. After that, only two of the plants of the group had produced the sixth leaf. Plant No. 1 in jar. No. 1 of that set produced the sixth leaf 12 days after the emergence of the fifth leaf, while plant No. 4 of jar No. 2 of the same set produced this leaf 14 days after the fifth leaf. Since these were the only figures available, they were averaged and gave a value of 13 days. Adding this to 50.7, we obtained the figure 63.7 for the sixth leaf, which is given in the table.

soil moisture content. That is, the time taken for the emergence of the different leaves constantly became shorter as the soil moisture increased. At this temperature, no sharp contrast between Thatcher and Tenmarq wheat in regard to the rate of leaf emergence was observed. At 12°C., the rate of leaf emergence was considerably shortened as compared with the plants grown at 6°C. The response toward moisture was the same, though two points need to be mentioned. First, the Tenmarq wheat at the highest moisture level was shown to be able to send out the first four leaves within a slightly shorter period than the same plants grown at the field capacity moisture level; but from the fifth leaf on, it lagged behind the latter, indicating that the injurious effect of the high moisture content did not occur until the plants had grown older and larger. Second, at this temperature (12°C.), the Tenmarq wheat at early stages was able to send leaves faster than the Thatcher wheat at all moisture levels as indicated by shorter period of leaf emergence. At the two low moisture levels, the Thatcher wheat sent out leaves faster than Tenmarq wheat until the fourth leaf stage; from there on, they were again surpassed by the Tenmarq wheat. This fact seems to indicate that while winter wheat tends to become dormant and remain shorter than the spring wheat under low temperature, it does not necessarily mean that its apical meristem is rendered less active than the spring wheat which makes an apparently greater and taller growth under this temperature. Unfortunately, this assumption was not strongly supported by the plants grown in the 6°C. room because of their delay in the fourth leaf stage at the end of the experiment, except that no evidence was found in this room that the winter wheat had a slower rate of leaf emergence than the spring wheat.

In the 25°C. room, the leaves of the plants emerged fastest at field capacity, and then slowed down toward the highest soil moisture. This was true for both varieties and for every leaf of the plants. The contrast between Thatcher and Tenmarq again was remarkable. At the highest and the lowest moisture levels, the rate of leaf emergence of Tenmarq was constantly lower than that of the Thatcher. For the two intermediate moisture levels, the rate was also in favor of Thatcher until the eight leaf stage. Tenmarq wheat however was able to send out the ninth leaf about a day earlier than the corresponding Thatcher wheat. The Tenmarq plants grown at the field capacity moisture level under this temperature had the greatest rate of leaf emergence among all the treatments of the experiment, and three of its plants were the only three that had developed the tenth leaf. As a whole, however, it appeared that under this temperature, Thatcher wheat was able to send out leaves faster than the Tenmarq wheat, at least in the earlier part of the young plant's life. This is exactly the reverse of the condition found at 12°C. Should the rate of leaf emergence be used as an indication of the activity of the apical meristem, the result of the present study would indicate that the temperature affects the activity of the meristem of the spring and winter variety of wheat in a different manner. Contrary to the general belief that cold temperature tends to retard the activity of winter wheat more than that of the spring wheat, the present results show that spring wheat has actually been retarded to a greater extent than the winter wheat.

In the 34°C. room, the greatest rate of leaf emergence for Tenmarq wheat was again reached at the field capacity moisture level. But, it was rather unexpected that the rate for Thatcher wheat increased from the lowest moisture level clear to the highest moisture level. Why the unfavorable effect of the high moisture level that has been demonstrated at the two intermediate temperature could be avoided by the Thatcher wheat at this highest temperature is again not to be answered, except that we should be reminded of the special nature of the data for this temperature as mentioned before. Under this temperature, the rate of leaf emergence of Thatcher was again greater than that of Tenmarq.

A close examination of the data of the rate of leaf emergence disclosed another interesting point. Table 6 gives the number of days required for the emergence of each leaf after the emergence of the preceding leaf. The result showed that except in the 6°C. room, the period required for the second leaf to appear after the emergence of the preceding leaf was always significantly shorter than the period required by the other leaves. At 25° and 34°C., the period required by the third and fourth leaves were shown in most cases to be longer than the rest of the leaves. In addition, this difference was greater when the soil moisture became lower. For example, at 25°C. the periods between the emergence of the second and the third leaves of the Tenmarq wheat were 16.7,

Table 6. The days required for the emergence of successive leaves after the emergence of their preceding leaves. (result of the second experiment.)

Temperature Moisture Variety	Leaves								
	2nd	3rd	4th	5th	6th	7th	8th	9th	10th
6^{o}C. -A - Tha.	19.6	20.4							
- Ten.	21.4	19.1							
-B - Tha.	18.9	18.0							
- Ten.	19.1	17.1							
-C - Tha.	16.1	17.4	24.0						
- Ten.	15.5	18.9	26.7						
-D - Tha.	15.3	16.6	22.4						
- Ten.	13.4	18.7	19.5						
12^{o}C.-A - Tha.	8.3	13.4	14.5	14.5	13.0				
- Ten.	8.5	15.1	14.5	11.0	11.0				
-B - Tha.	7.8	11.7	13.5	12.4	13.7				
- Ten.	7.9	12.3	11.9	10.1	10.0	11.0			
-C - Tha.	6.8	11.4	12.4	12.9	13.9				
- Ten.	6.9	11.8	11.7	9.7	9.2	12.1			
-D - Tha.	6.8	10.6	13.2	11.7	14.0				
- Ten.	6.9	11.1	12.0	11.2	10.4	11.3			

Table 6. (cont.)

25°C.-A	- Tha.	5.9	10.2	9.6	8.9	9.3	8.8	9.5		
	- Ten.	5.9	16.7	10.6	9.0	9.4	8.9			
-B	- Tha.	5.2	8.4	8.5	8.7	7.0	7.7	7.6	7.1	
	- Ten.	4.8	11.1	10.3	6.6	6.6	6.6	7.3	6.0	
-C	- Tha.	4.2	7.4	7.9	7.0	7.6	6.4	7.3	7.0	
	- Ten.	3.6	9.0	9.4	8.1	5.8	5.5	6.7	5.4	7.0
-D	- Tha.	4.1	7.8	9.2	6.9	7.3	7.1	6.7	6.3	
	- Ten.	3.8	9.6	9.5	8.0	5.9	6.4	7.0	7.8	
34°C.-A	- Tha.	11.0	14.7	12.3	9.3	9.4				
	- Ten.	6.9	17.7	14.1	10.3	10.3				
-B	- Tha.	6.8	11.6	9.7	9.9	7.5	9.8	10.5		
	- Ten.	4.0	15.8	15.0	12.8	8.7				
-C	- Tha.	7.0	12.7	6.6	10.9	9.0	10.2	7.5		
	- Ten.	4.6	11.0	10.4	10.0	11.0	10.5			
-D	- Tha.	6.9	10.7	7.1	9.0	9.4	8.6	9.0		
	- Ten.	4.3	15.7	11.7	----	----				

11.1, 9.1, and 9.6 days for the moisture A, B, C, and D, respectively, while the periods between the emergence of the fifth and the sixth leaves (which is taken as a representative of all the leaves after the fourth leaf) were 9.4, 6.6, 5.8, and 5.9 days for the respective moisture levels. The differences between the figures of these two sets were therefore 7.3, 4.5, 3.2, and 3.7 days for the soil moisture levels A, B, C, and D respectively. Furthermore, if these figures within the sets are compared, the difference between the period of emergence for the same leaf at different moisture levels was also greater at the third and fourth leaves than the later leaves. Take the same sets of figures as an illustration. For the third leaf, the difference between the moisture A and B was (16.7 - 11.1) 5.6 days, A and C 7.7 days, and A and D, 7.1 days. While at the sixth leaf, the difference between moisture A and B was only (9.4 - 6.6) 2.8 days, A and C, 3.6 days, and A and D, 3.5 days. The data for the 34°C. plants showed the same fact. The 12°C. plants showed a slight tendency, while no such evidence was found in the 6°C. room.

This fact points out two important practical aspects. In the first place, the effect of soil moisture is more pronounced on a wheat plant at its third and fourth leaf stage than when it grows older. A drought occurring at this critical period therefore would give greater retardation in growth than if it occurs later. It also showed that at lower temperature, the variation in soil moisture is less significant than when the temperature is high, at least as far as the rate of leaf development is concerned.

For an explanation of this fact, previous work can be cited. Brenchley (7) makes the following statement:

> ... Growth may be divided conveniently into two well-marked periods. (a) First period ... from the seedling stage till the time that the plant regains its initial weight after the loss by respiration. ... (b) Second period ... (succeeding the first stage) during which the plant is obviously making growth, and which continues till the latter ceases and desiccation sets in. .... The length of the first period varies inversely with the mean maximum temperature. ...

Bakhuyzen (4) and Alsberg, and Griffing (2) have the idea that the first leaf of wheat plant is formed very largely from the stored food in the kernel, and that the photosynthates formed by the first leaf are the principal structural material out of which the second leaf is formed, and so on. From the uniformly short period of the emergence of the second leaf shown in the present study, it seems that the second leaf may also receive a part of its structural material from the kernel. Brenchley's 'first period' seems to be passively ended by the exhaustion of the reserve food in the kernel, and the second period is actively initiated by the ability of the first and the second leaves to perform photosynthesis. Two factors are important in this connection. One is the rate at which the kernel is exhausted, the other is the effectiveness of the photosynthetic power of the first and the second leaves after the reserve food is exhausted. Besides the transferring of food into the developing young leaf, a part of the food is apparently lost due to respiration of the activated kernel. The higher the temperature, it is likely the higher will be the fraction wasted in respiration. This, together with the heavier drawing of reserves by the young leaf at a higher temperature, will cause a sooner exhaustion of the kernel. After the kernel is exhausted, if the environment is favorable for photosynthesis and other physiological processes, the food will be built up in the first and second leaves faster than if the environment is not favorable. For instance, when the young seedling, being already deprived of the supply from the endosperm, meets a low soil moisture, and water and salt absorption are both retarded, food is manufactured in these young leaves slowly, then the time required for the formation and emergence of the third leaf is bound to be long. If, on the other hand, moisture conditions or other factors at that time are favorable, the third leaf will, of course, appear earlier. When the plant grows older, more and more leaves can contribute the food for the building of new leaves, consequently the effect of the moisture and other factors becomes less critical. Alsberg and Griffing (2) called attention to two critical periods in the life of the wheat plant, viz. the germination and formation of the first leaf, and the flowering period. They stated that during these two periods, the plant is much more sensitive to weather than at any other time. According to the result discussed here, it seems that the first critical period mentioned by Alsberg and Griffing may not be limited only to the formation of the first leaf, but coincides with the end of the 'first period' mentioned by Brenchley, that is the time when the endosperm is just exhausted and the plant becomes independent. It may end before the complete information of the first leaf or after the second leaf is partly extended, depending on the environmental condition at that time. The top and roots then are still unstable for photosynthesis and root absorption and are vitally sensitive to the environmental conditions.

Tillering

Because of the low light intensity used, the tillering of the experimental plants was below normal in both the first and second experiments. The results, however, did show influences of temperature, moisture, and light on the tillering of the spring and winter wheat varieties.

Under either day length, none of the plants grown at 6° and 34°C. had tillered, indicating the limiting effect of the unfavorable temperatures. The plants grown at 6°C. were yet too young at the end of two months to initiate any tillering, but the plants grown at 34°C. were really devoid of the ability to tiller. The low photosynthesis/respiration ratio and the consequent exhaustion of the food accumulation would appear to be the main cause of the failure for these plants to tiller. Table 7 gives the percentage of the plants that were able to tiller at 12°, 20° and 25°C., disregarding the number of the tillers per plant.

Table 7. The percentage of the plants which tillered under different temperature and soil moisture treatments at the end of two months.

Variety	Moisture	Temperature °C. 12	20	25
		(16 hour day length)		
Thatcher	A		(11/15) 73.3	(3/13)23.1
	B		(12/15) 80.0	(7/12)58.3
	C		(12/15) 80.0	(7/ 8)87.5
	D		(8/11) 72.7	(6/ 7)85.8
	Average		(43/56) 76.8	(23/40)57.5
Tenmarq	A		(0/13) 0.0	(0/10) 0.0
	B		(0/11) 0.0	(0/14) 0.0
	C		(0/14) 0.0	(0/ 9) 0.0
	D		(0/13) 0.0	(0/11) 0.0
	Average		(0/51) 0.0	(0/54) 0.0
		(10 hour day length)		
Thatcher	A	(0/11) 0.0		(1/15) 6.7
	B	(2/13)14.6		(0/13) 0.0
	C	(0/13) 0.0		(10/13)76.9
	D	(3/15)20.0		(2/11)18.2
	Average	(5/52) 9.6		(13/52)25.0
Tenmarq	A	(6/ 9) 66.7		(0/14) 0.0
	B	(14/14)100.0		(1/14) 7.1
	C	(15/15)100.0		(7/11)63.6
	D	(14/14)100.0		(4/14)28.6
	Average	(49/52) 94.2		(12/53)22.6

The numbers given in the parenthesis are the number of the tillered plants / the total number of plants that received the respective treatments. In the following discussion, the percentage rather than the actual number of tillered plants is used in order to provide a fairer basis for comparison.

The results showed a complicated interrelationship between light, temperature, soil moisture, and plant variety. In the first experiment, when 16 hour day length was used, 76.8 percent and 57.5 percent of Thatcher wheat tillered under 20° and 25°C. respectively; while not a single Tenmarq plant tillered under either temperature. In the second experiment with day length adjusted at 10 hours a day, 9.6 percent and 25 percent of the Thatcher wheat tillered at 12° and 25°C. respectively; while 94.2 percent and 22.6 percent of the Tenmarq wheat tillered under the same temperatures. Obviously, the response of the tillering of the spring and winter varieties toward light was very different.

The temperature effect was also different for the Thatcher and Tenmarq wheat. In the first experiment, both the percentage of tillered plants and the number of tillers per plant (Table 8) indicate that 20°C. was more favorable than 25°C. for the tillering of Thatcher wheat. No temperature influence could be seen on Tenmarq wheat in the first experiment because of the complete domination of the day length effect. In the second experiment, a greater percentage of Thatcher wheat was able to produce tillers and to produce more tillers per plant at 25°C. than at 12°C., indicating that 12°C. was perhaps too low for proper tillering of this variety, or that it delayed the tillering so that fewer tillers appeared during the period of two months. On the other hand, the Tenmarq wheat had more tillered plants and more tillers per plant at 12°C. than at 25°C. Except for the plants at the lowest soil moisture level, 100 percent of the Tenmarq wheat

Table 8. The average number of tillers per plant produced under different treatments.

Moisture - Variety	D.L. 16 hours 20°C.	D.L. 16 hours 25°C.	D.L. 10 hours 12°C.	D.L. 10 hours 25°C.
A - Thatcher	1.00	0.21	0.00	0.07
- Tenmarq	0.00	0.00	0.00	0.00
B - Thatcher	1.13	0.75	0.14	0.00
- Tenmarq	0.00	0.00	0.00	0.00
C - Thatcher	1.29	1.13	0.00	1.21
- Tenmarq	0.00	0.00	1.87	0.92
D - Thatcher	0.75	0.86	0.20	0.27
- Tenmarq	0.00	0.00	2.50	0.40

tillered, indicating perhaps a favorable temperature for the tillering of this variety. Under natural and experimental conditions, it has been noted by many observers that both spring and winter wheat tend to produce more tillers under short day length than under long day length. Furthermore, the general observation is that the effect of day length is much more influencial on winter wheat than on spring wheat. That is, the reduction of the number of tillers under long day length is much greater in winter wheat than in spring wheat.

In the present study, the results agree with the above observations in that the tillering of winter wheat was decreased by the long day length, but disagree in that more spring wheat tillered under long day length. But it should be pointed out that at the end of two months, the spring wheat plants under 16 hour day length were in a more advance stage of growth than the plants of the same age grown under 10 hour day length. The former were already jointed, booted or headed, while the latter were not. So if the latter plants were allowed to grow to their mature stage, it is still possible for them to have an equal number or more tillers as compared with the long day plants. It should also be pointed out that because of the prematuration of Thatcher wheat under 16 hour day length, almost all the tillers produced by these plants in the first experiment were small and abortive when the main culm had completed its life and was drying. These results, however, do indicate that spring wheat is much less sensitive to day length than winter wheat in regard to tillering.

Hurd-Karrer (25) stated that at equivalent day lengths, more tillers were produced at the high (21°C.) than at the low temperature (12°C.) by both spring and winter varieties in her study. In the present study, this statement is true in regard to Thatcher wheat in both experiments but not to Tenmarq wheat. Whether the difference between 21°C. used by Hurd-Karrer and the 25°C. used in the present study would make such a difference cannot be determined.

The response of tillering to the soil moisture generally followed the trend of other characteristics mentioned before. In the second experiment, the highest percentage of tillered plants and also the highest number of tillers per plant of Thatcher wheat occurred at the highest soil moisture level, in the 12°C. room. Under the same temperature, except at the lowest soil moisture level, 100 percent of the Tenmarq wheat tillered, while the number of tillers per plant was again the highest at the highest moisture level. At 25°C. both varieties had the highest percentage of tillered plants and the highest number of tillers per plant at the field capacity level. This may again be explained on the basis of the increased need of aeration at higher temperature.

In the first experiment, the response of the Tenmarq wheat to soil moisture was again obscured by the effect of the long day length. For the Thatcher wheat, at both 20° and 25°C, as many or more plants tillered and more tillers per plant were produced at the field capacity level.

The Height of Plant

In the second experiment the height of plant was measured at alternate three and four day intervals. These periods of unequal lengths were used because in the routine of affairs they were the most convenient and the only possible scheme. The average heights of the plants at different intervals are given in Table 9 and are graphically represented in Fig. 6 (a, b, c, d) which shows the rate of growth of plants grown under different soil moisture levels at the same temperature. The curves plotted in black ink represent the Thatcher wheat, while those plotted in red ink represent the Tenmarq wheat.

Because the height of the plant was measured to the tip of the leaf which attained the greatest height, it would depend on three factors; namely, the number of leaves, the length of leaves, and the length of the leaf sheath. (This statement holds only for the plants before the jointing stage. Naturally,

Table 9. The periodical growth in height (cm.) of the plants under different treatments. (Result of the second experiment)

Temperature Moisture Variety	Days after emergence															
	5	8	12	15	19	22	26	29	33	36	40	43	47	50	54	57	61
6°C.-A-Tha.	2.6	3.9	6.1	7.9	8.8	9.5	9.8	10.0	10.2	11.1	11.6	12.2	12.4	12.6	12.9	13.1	13.4
-Ten.	2.2	3.5	6.4	9.0	9.8	10.3	10.5	10.5	10.5	10.8	10.8	10.8	10.8	10.9	11.0	11.0	11.0
-B-Tha.	3.0	4.8	7.1	9.0	9.5	10.1	10.5	10.7	10.9	13.2	13.6	14.5	14.8	15.0	15.0	15.0	15.0
-Ten.	2.8	4.3	7.2	9.6	10.3	10.8	10.9	10.9	10.9	12.4	12.8	12.8	12.8	12.8	12.9	12.9	12.9
-C-Tha.	3.9	5.6	8.1	10.4	10.8	11.1	11.6	12.3	13.4	18.0	18.4	18.7	19.0	19.4	19.9	21.3	22.7
-Ten.	5.0	7.1	10.4	12.9	13.3	13.5	13.6	13.8	14.3	17.2	17.2	17.3	17.4	17.5	17.5	17.7	18.1
-D-Tha.	5.0	7.1	10.7	13.6	14.2	14.4	14.5	14.7	15.8	20.5	20.7	20.7	20.9	21.8	23.1	25.6	27.0
-Ten.	4.4	6.7	10.5	13.5	13.8	14.1	14.5	15.0	15.7	18.5	18.6	18.8	18.9	19.3	19.5	20.1	20.5
12°C.-A-Tha.	8.7	12.1	13.9	16.4	19.1	23.5	25.3	26.5	27.6	29.7	31.3	33.2	33.4	34.6	35.4	36.5	36.8
-Ten.	6.6	10.7	13.3	16.6	19.2	22.3	23.4	24.2	24.3	24.3	24.4	24.5	24.5	24.6	24.6	24.7	24.7
-B-Tha.	8.1	11.7	13.9	17.5	21.4	26.5	27.7	28.7	31.0	33.8	35.0	35.3	36.9	37.5	37.8	38.4	39.0
-Ten.	8.9	13.5	15.8	20.7	25.4	28.4	28.5	29.0	29.5	29.7	29.7	29.7	29.7	29.7	29.7	29.7	29.7
-C-Tha.	9.0	14.6	17.7	19.8	24.5	30.5	31.7	32.1	33.6	35.7	36.1	36.4	37.4	37.9	38.4	38.8	39.4
-Ten.	10.1	16.1	18.4	22.0	27.5	30.7	30.8	31.3	31.9	31.9	31.9	31.9	32.0	32.0	32.0	32.0	32.0
-D-Tha.	7.3	12.0	13.9	18.5	23.1	26.2	26.9	29.1	32.9	34.8	35.4	37.2	38.7	39.0	39.6	41.4	43.5
-Ten.	9.4	14.0	15.9	21.4	25.5	28.0	28.3	29.2	29.8	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0
25°C.-A-Tha.	13.9	15.8	18.3	21.3	22.4	22.5	24.1	24.9	26.6	28.4	29.6	29.8	30.1	30.2	30.6	31.8	
-Ten.	15.6	19.2	22.3	25.7	28.3	29.2	31.2	31.7	31.9	32.0	32.9	33.9	35.1	36.3	36.5	36.7	
-B-Tha.	15.5	17.4	22.8	27.0	28.9	30.3	31.0	31.0	33.7	33.7	35.8	36.2	36.5	36.5	36.8	37.1	
-Ten.	16.1	19.4	28.4	34.2	36.5	36.7	37.8	38.2	38.5	38.6	38.7	38.8	38.9	39.0	39.2	39.3	
-C-Tha.	16.5	19.1	26.5	27.8	30.0	31.2	32.5	34.1	35.5	37.5	38.5	38.7	38.9	39.0	39.3	39.5	
-Ten.	16.4	20.7	30.1	34.3	35.5	38.0	39.4	39.4	39.5	39.5	39.8	40.1	41.0	41.4	41.5	41.5	
-D-Tha.	15.2	17.6	24.6	26.1	27.0	29.0	29.6	30.3	32.1	33.1	34.0	34.7	35.8	36.3	36.3	36.7	
-Ten.	16.3	22.3	30.3	33.5	34.7	36.6	37.5	38.1	39.2	39.4	39.6	40.0	40.3	40.8	40.8	40.9	
34°C.-A-Tha.	10.9	11.9	12.3	12.3	12.5	12.9	13.2	13.7	15.8	16.2	17.0	17.6	18.1	18.6	19.2	19.2	19.7
-Ten.	12.3	14.5	15.4	16.6	19.1	20.4	21.7	22.0	22.5	22.8	23.5	23.7	23.8	24.0	24.5	24.5	24.6
-B-Tha.	11.2	12.4	12.7	13.5	14.9	15.6	16.2	16.6	17.9	18.0	19.2	19.4	20.0	21.2	22.0	22.3	22.5
-Ten.	13.3	15.9	16.4	18.2	22.2	23.8	24.5	25.2	25.9	26.2	26.6	26.8	26.8	26.9	27.1	27.1	27.3
-C-Tha.	15.3	16.4	16.5	16.8	17.2	17.2	17.8	18.1	19.1	20.2	21.7	22.3	22.3	22.6	22.6	23.2	23.5
-Ten.	18.2	18.2	19.2	21.2	22.0	23.4	25.3	25.4	26.0	26.2	26.2	26.2	27.0	27.0	27.7	27.7	27.7
-D-Tha.	16.8	17.6	17.8	18.3	18.5	18.7	19.0	19.4	21.4	22.0	22.7	23.0	23.3	23.3	23.4	23.7	23.8
-Ten.	17.9	18.9	19.4	20.9	23.5	24.0	24.1	24.4	25.0	25.2	25.2	25.2	25.2	----	----	----	----

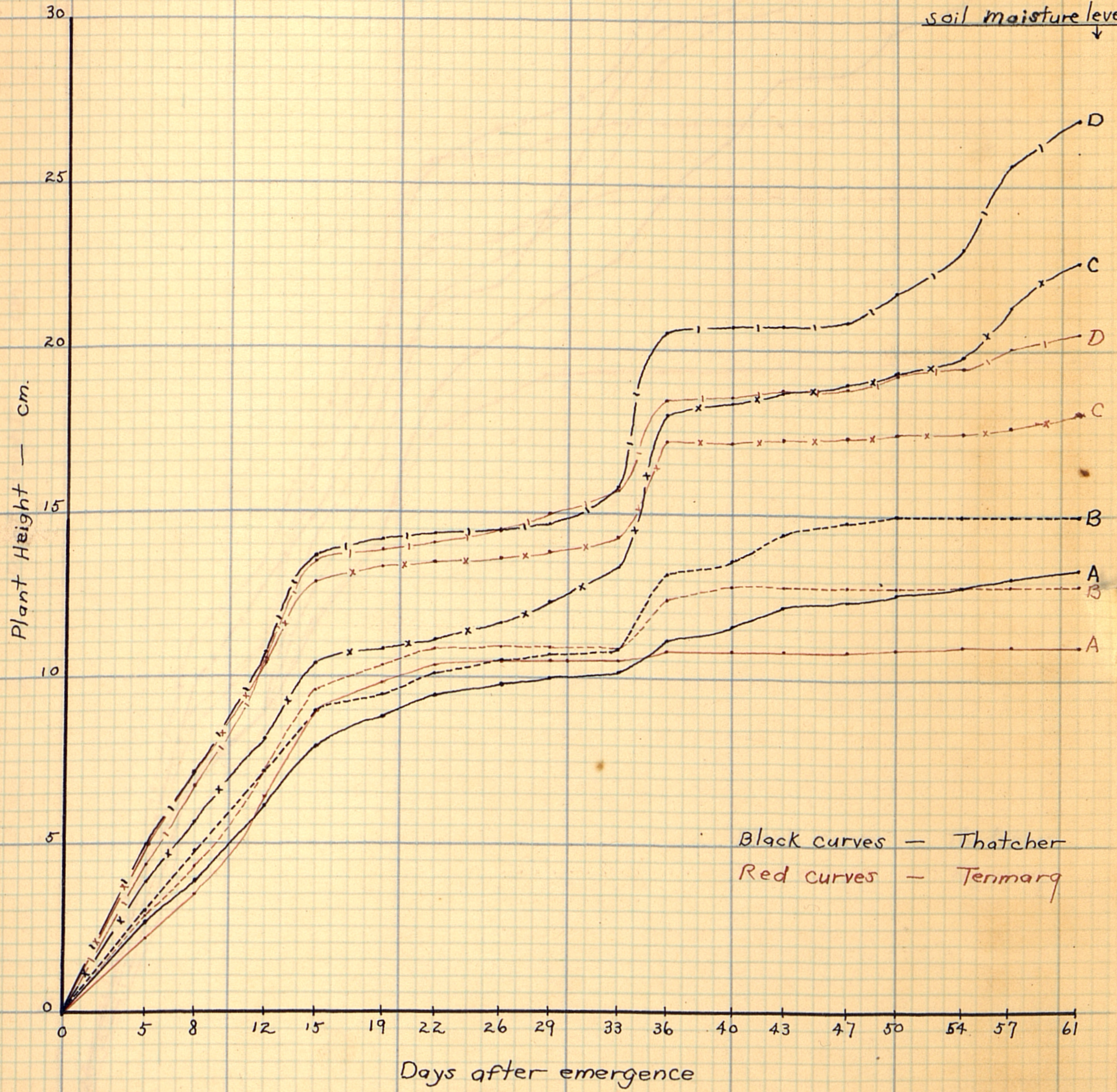

Fig. 6.a. A graph showing the periodical growth in height of the plants grown at different soil moisture levels under 6°C. (result of 2nd expt.)

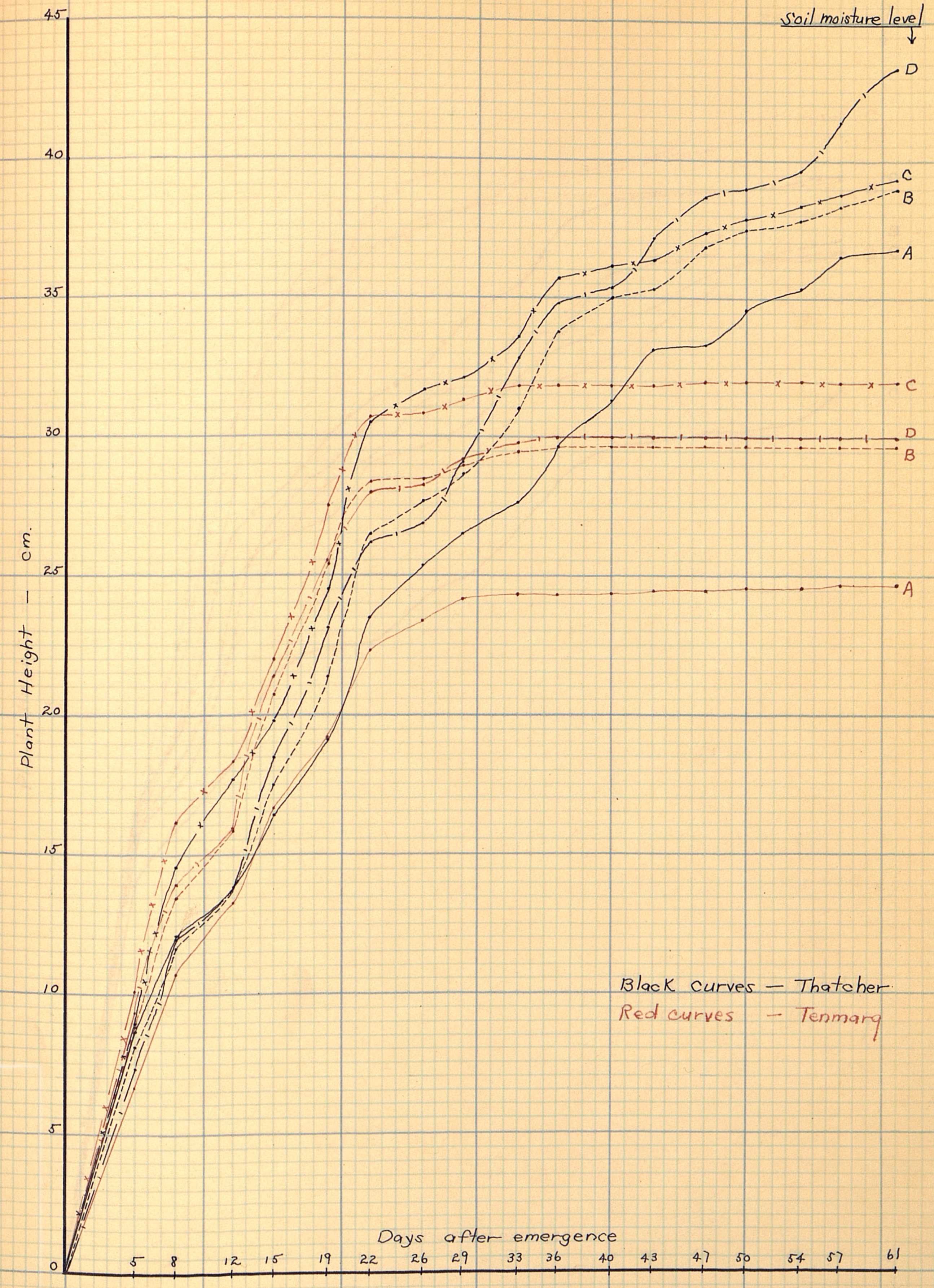

Fig. 6 b. A graph showing the periodical growth in height of the plants grown at different moisture levels under 12°C. (result of 2nd expt.)

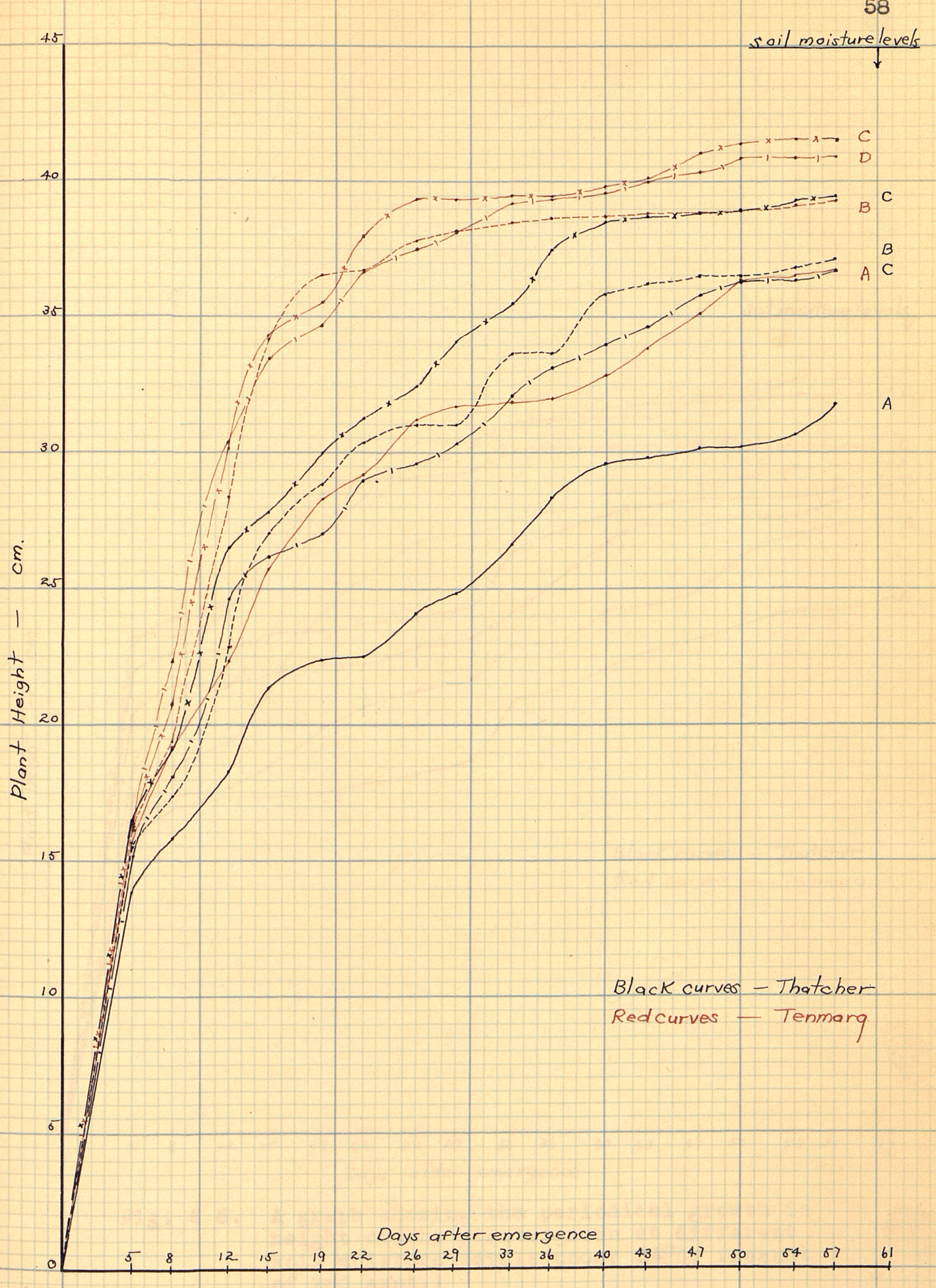

Fig. 6 c. A graph showing the periodical growth in height of the plants grown at different soil moisture levels under 25°C. (result of 2nd expt.)

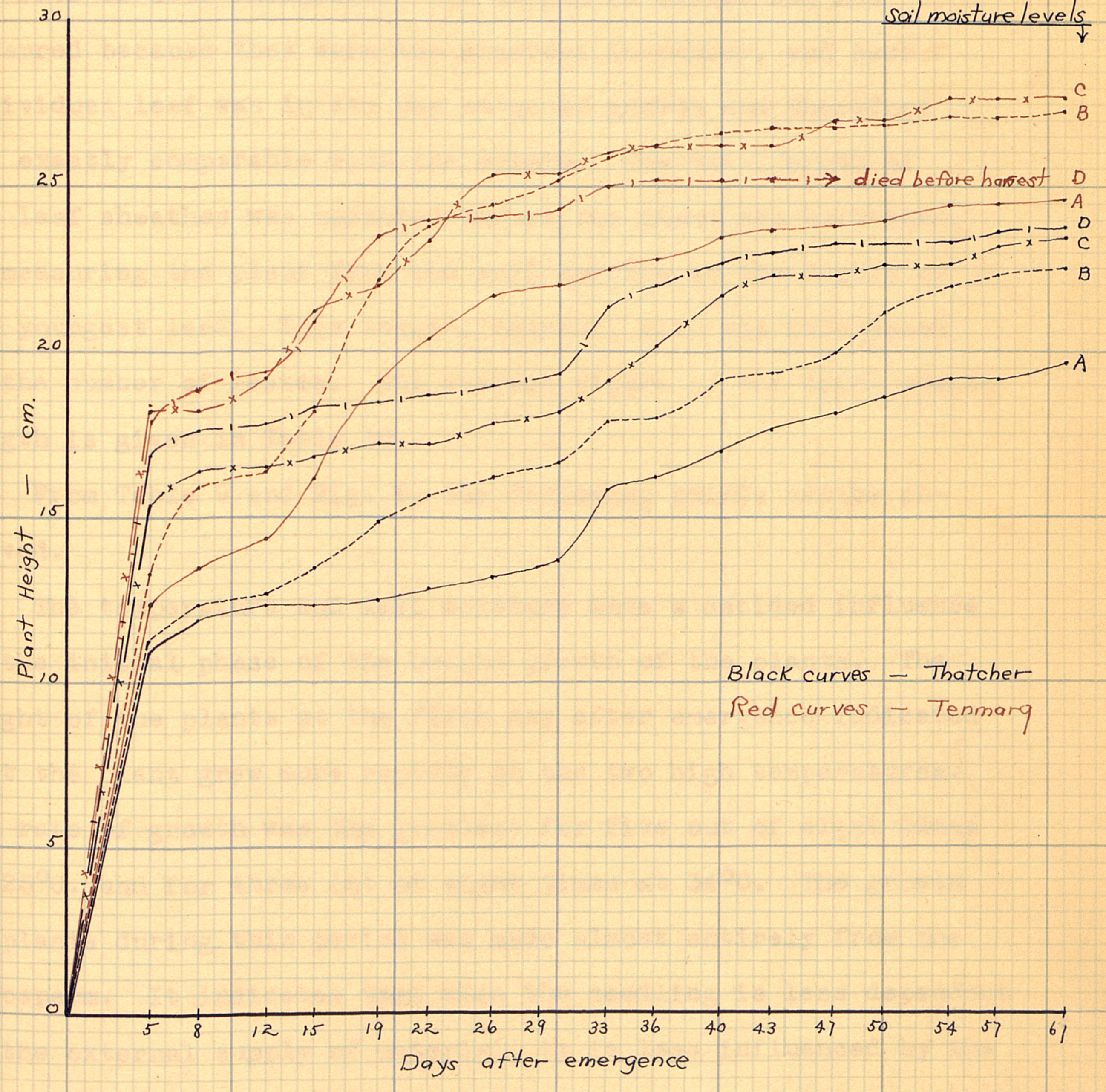

Fig. 6 d. A graph showing the periodical growth in height of the plants grown at different soil moisture levels under 34°C. (result of 2nd expt.)

a plant with more leaves, longer leaves and longer sheathes would be taller, but these three factors are not necessarily accompanying each other, as they respond differently toward the temperature, soil moisture and perhaps other factors. The number of leaves could be referred to the discussion of the rate of leaf emergence. The length of leaves was not measured because they were too numerous in number, and each individual leaf was in its own stage of growth and therefore not exactly comparable with the others. The total length of the leaf sheathes was measured before the plant was harvested, by measuring the plant from the soil surface to the ligule of the youngest leaf. This length, however, also was influenced by the number of leaves. The average figure of the total sheath length is given in Table 10.

From Table 9 and Fig. 6, the following points can be observed.

The temperature and soil moisture have a decided influence on the initial phase of the height growth of the plants. The height of the plants at the fifth day after emergence indicated that the plant grew more rapidly at the two high temperatures. The rate of growth was the greatest for five out of eight times at 25°C. and for three out of eight times at 34°C. The growth of plants during this period was made almost entirely from the endosperm. It indicates that when the seedling is less dependent on the external supply of material, it is less influenced by the adverse temperature or other conditions.

For all the soil moistures and temperatures, the curves tend to taper off at earlier or later stages, and to a more or less extent, the tendency was most prominent for the 6°C. and the 34°C. plants, quite prominent for the 12°C. Tenmarq wheat, and much less prominent for the 12°C. Thatcher wheat and the 25°C. plants. This tendency of tapering marked the point beyond which, for some reason or another, the plant could not grow with the same rate as it had so far. In both 34°C. and 6°C. plants, the turning point corresponded approximately to the completion of the growth of the first leaf of the plant. At 12°C., Tenmarq began to slow down at the 22th the 26th day point, indicating that the initial growth rate of the plant was not significantly reduced till that time (Fig. 6b). After the 33th day point, the plants at all moisture levels made very little growth, the probable reason of which will be further discussed. The rate of growth in height of the Thatcher wheat grown at 12°C. and both varieties grown at 25°C. did not show any prominent lagging till the end of the experiment. This indicates that under these temperatures, the plants received a much less check on their growth in height.

Consideration is now given to the behavior of the plants in regard to the growth in height under different treatments.

On referring to Fig. 6 a, it can be seen that both varieties grown at 6°C. increased regularly in height with increase in soil moisture. Tables 6 and 10 show a steady increase in number of leaves and total length of sheath. Under this circumstance, the common limiting factor the plants received is the low temperature.

Table 10. The average total length (cm.) of the leaf sheathes of the plants under different treatment (result of the 2nd experiment.)

Moisture - Variety	Temperature °C. 6	12	25	34
A - Thatcher	3.90	13.35	9.12	6.05
- Tenmarq	3.17	5.45	6.67	4.95
B - Thatcher	4.38	14.18	10.07	6.36
- Tenmarq	3.81	6.29	7.85	5.04
C - Thatcher	6.28	14.78	11.94	7.14
- Tenmarq	4.73	7.29	8.44	5.24
D - Thatcher	7.61	15.96	10.58	6.23
- Tenmarq	4.98	6.65	8.04	----

The plants grown at a low soil moisture content received also the limiting effect of the soil moisture. In addition to this, the winter wheat, Tenmarq, at all soil moisture levels, in fact, under all conditions showed a consistently shorter total sheath length. Therefore the plants grown at 6°C. show (a) consistently lower height as compared with the plants grown at the higher temperatures, (b) an increased height with the increase in soil moisture, and (c) a consistently greater height of Thatcher wheat over the Tenmarq wheat at all moisture levels.

Another particular feature that can be noticed in Fig. 6 a is that almost all the curves showed an upturn at the 36th day point. An explanation is herewith given. The refrigerating machine of the 6°C. room somehow stopped work at the morning of August 25th, which corresponded to the 34th day after the emergence of the plants, and was not repaired until the afternoon of the 26th. During this period, the temperature of that room went up to above 25°C., causing a sudden rapid growth of the plants. Although it interrupted the regularity of the experiment, it is of interest to notice that the effect of a sudden rise in temperature on the growth of plants consistently became greater with the increase of the soil moisture. This means that with the same increase of heat, the plants with an abundant water supply were able to make more growth than those with a low water supply. Again, the effect was more prominent for Thatcher wheat than for Tenmarq wheat. In fact, the Tenmarq wheat at the lowest soil level made almost no response at all toward that 'suddenly arrived warm day', while an increase of as much as 4.7 cm. was made by the Thatcher wheat at the highest moisture level during the three day interval. It gives some idea about how a dormanting wheat crop will respond to an incidental warm day during the winter or early spring on soils with different moisture content.

In the 12°C. room (Fig. 6b) the Thatcher and Tenmarq wheat showed very little difference in their height during the first twenty-two days. Thereafter, the Tenmarq wheat showed a gradual leveling off of the growth in height, while the Thatcher wheat kept on growing. Table 5 indicates that under this temperature, the Tenmarq wheat has produced more leaves than the Thatcher wheat. So it is not the actual slowing down of the plant activity that caused this leveling off of the growth rate of Tenmarq wheat but rather that a different form of growth resulted. Table 10, however, shows a remarkable difference in the total length of sheath between the two varieties at this temperature, this for Thatcher was 13.35, 14.18, 14.78, and 15.96 cm. for the soil moisture A, B, C, and D respectively; while the corresponding figures for Tenmarq were only 5.45, 6.29, 7.29, and 6.65 cm. An observation of the Tenmarq wheat at this temperature showed a crowding between the upper leaves, notably the 4th, 5th, and 6th, at their bases, which was caused by the failure of the leaf sheathes of those leaves to elongate to any great extent. Under any condition, the 4th and 5th and later leaves of the wheat plant are successively shorter than the lower leaves (4). Therefore, when their sheathes failed to grow, the emergence of the new leaves materially did not help increase the plant height. As it appears in Table 9, the Tenmarq wheat under this temperature (12°C.) made only a negligible amount of growth after the 33rd day. Again, if we examine Table 5, we will find that this date corresponds approximately with the emergence of the 4th leaf and approximately marks the full growth of the 3rd leaf, the longest leaf of the plant.

On the other hand, the Thatcher wheat made a notable elongation of the leaf sheathes of the 4th, 5th, and 6th leaves, which sent each new leaf to a greater height than the next older one. By this means, its height showed a steady increase till the end of the experiment.

The crowding of the upper leaves, together with the earlier tillering of the Tenmarq wheat gave it a short and bushy appearance in contrast with the mostly single stemmed, tall, upright Thatcher plants. Morphologically, these features constituted at least a part of the common impression of the observers about dormancy of the winter wheat.

The response of the plant height toward the soil moisture at 12°C. was in general in agreement with the top dry weight, the number of leaves and the total length of the leaf sheath. For Thatcher wheat, the plant height increased from the lowest moisture level to the highest, but the height of the plant at the highest soil moisture level stayed below that of the field capacity plants until the 40th day point, then sprang up. For Tenmarq, the height of plant increased with the soil moisture until the field capacity level. The plants grown at the highest moisture level were shorter throughout than plants grown at field capacity.

In the 25°C. room, (Fig. 6c) at every soil moisture level, the Thatcher wheat was shorter than the corresponding Tenmarq wheat almost from the very beginning to the end of the experiment. It was also shorter than or about equal to the same plants in the 12°C. room, while the Tenmarq wheat at this temperature was much taller than at 12°C. (Fig. 6b).

As shown in Table 6, both varieties produced more leaves at 25°C. than at 12°C. In accordance with this, the 25°C. Tenmarq wheat plants had a greater total length of leaf sheathes than the 12°C. plants, but, on the contrary, the total length of the leaf sheath of Thatcher wheat was much greater at 12°C. than at 25°C. This indicates that under this relatively high temperature, for some reason, the leaf sheath of this variety failed to make as much elongation as it did at a lower temperature, resulting in a shortening of the total plant height in spite of its having more leaves. The total sheath length of Thatcher wheat at 25°C., however, was still considerably greater than that of the Tenmarq wheat, (Table 10), but the latter produced very long leaves at this temperature, which helped to build up the total plant height on a shorter total leaf sheath length.

These facts indicate that the different features of the same sort of organ of the same plant, viz. the number of leaves, the length of leaf sheathes, and the length of leaves, respond different from one another, and these features also respond differently or even contradictorily among different varieties. This at least constitutes one of the reasons why the growth form of the wheat plant is so variable under natural environment. A plant breeder or an agronomist can always notice at once in his experimental plots the morphological differences among his testing varieties. Upon analysis, one will find that these obvious differences to ones naked eye are really the summation of the various simple individual items, part of which are those mentioned above. Each of those items responds differently toward the environment and has significant bearing on the later stages of growth of the plant. They deserve to receive more attention and study although they seem to be as simple as things could be.

In regard to the response of the plants under this temperature (25°C.) toward soil moisture, the result was again in agreement with the data of other characters. For both varieties, the plant grown at the highest moisture level had failed to lead in height. It was second to the field capacity plant for Tenmarq and stood in third place for Thatcher. Under both 12° and 25°C., the curves for moisture B, C, and D show a closer association while the curve for moisture A was always left wide apart from the others, indicating that under moderate temperatures, the wheat plant is adapted to a quite wide range of soil moisture content from the fairly dry soil to the saturated soil.

In the 34°C. room, (Fig. 6d) the plants at all soil moisture levels were shorter than the corresponding plants grown at 12° and 25°C. The plants had short leaves, short leaf sheathes, a sickly appearance, a lack of tillering and were light in weight. It is true that these plants were taller than the 6°C. plants during all the experimental course, but if we examine Table 9 and compare Fig. 6 a and 6 d, we will find that as the soil moisture became more and more favorable to the low temperature plants, the height of the plants in the 6°C. room increased, approaching the 34°C. plants. At the highest moisture level, the Tenmarq plants grown at 34°C. all died, while the Thatcher wheat plants were surpassed in height by the plants grown at 6°C.

Fig. 6 d shows that at this temperature, the Tenmarq plants grown at all soil moisture levels were taller than the corresponding Thatcher plants. In fact, even the shortest Tenmarq plants in this room, those grown at the lowest soil moisture level, were taller than the tallest Thatcher plants. The curves of Thatcher wheat show a sharp leveling off at the 5th and 8th day period. After that time the progress of the growth was very slow. The curves of Tenmarq show a moderate leveling off at the 5th day point too, but the growth kept on at a moderate rate until the 26th day point where they show a further flattening, and from there on, the rate of increase in height was about the same for both varieties till the end of the experiment. Thus, it seems that although the spring wheat is adapted to a milder temperature during the seedling stage under natural conditions, the results of the experiment show that the response of the plant height toward high temperature was still in favor of winter wheat. Summarizing, the Thatcher wheat was taller than the Tenmarq wheat at the two lower temperatures, but shorter at the two higher temperatures. Although the height of plant is not a good indication of the successfulness of the plant growth, the relative reduction in height of the spring wheat definitely indicates its lack of adaptability to the high temperatures during the early growing period.

The response of plant height at 34°C. toward soil moisture also can be seen in Fig. 6 d. For Tenmarq, the plants grown at the lowest moisture level remained constantly the shortest. The plants grown at the highest moisture ceased to grow at the first part of the second month and finally died. The plants grown at moisture B and C showed little difference in their height during the whole course of the experiment. For Thatcher wheat, the height of plant increased from the lowest moisture level clear to the highest moisture level. This rather disagreed with the data of other characters and the general impression we obtained so far that the plants at the high temperature were more susceptible to the high soil moisture. No appropriate explanation could be given except that the special nature of the data of the 34°C. plants should be recalled.

The Death Rate of the Plants Grown at 34°C.

Table 11 shows that under a day length of 16 hours, the Thatcher wheat was exceedingly susceptible to high temperature at all soil moisture levels. This was primarily due to the forcing effect of the long day length which drove the spring wheat toward reproduction and greatly cut down its vegetative metabolism. This effect on plants which were already under an unfavorable food balance induced by the high temperature, materially hastened the death of the plants. The Tenmarq wheat was much less sensitive to the forcing effect of the long day length, therefore its death rate was considerably lower than Thatcher.

Under 10 hour day length, the difference in death rate between the two varieties was much smaller, as compared with the results obtained under 16 hours.

The relation between the death rate and the soil moisture content was not consistent for the two experiments. But there was a general indication that the death rate was the highest at the highest moisture level and lowest at the intermediate level.

The death of the plants apparently was caused chiefly by

Table 11. The death rate of the plants grown at 34°C.

Moisture-variety	16 hr. day length		10 hr. day length	
	Plants germinated	Plants died	Plants germinated	Plants died
A - Thatcher	15	12	15	9
- Tenmarq	15	8	14	1
B - Thatcher	15	13	15	1
- Tenmarq	15	7	14	1
C - Thatcher	15	14	15	8
- Tenmarq	15	1	15	10
D - Thatcher	15	15	15	8
- Tenmarq	15	9	15	15

the unbalanced photosynthesis / respiration ratio of the plants grown under the adverse temperature condition. Death is more sure if the plant is further subjected to other unfavorable factors; too low or too high moisture, and long day length.

GENERAL DISCUSSION

The results of this experiment appear to be simple and fundamental. By analyzing the degree of growth of the individual plant characters, the experiment furnishes some information as to actually how the plants respond to temperature and soil moisture conditions.

In the first place, it appears that temperature is by far more powerful in influencing the growth of the young wheat plants than soil moisture. The cardinal temperatures for the wheat plant evidently are fixed, while the cardinal soil moistures shifted according to the temperature. The difference between the lower and higher cardinal soil moistures becomes less as the temperature increases. This is due chiefly to the shifting of the maximum soil moisture, and perhaps also the optimum soil moisture to a certain extent, toward the side of low level. Cannon (10) stated that the critical oxygen concentration for root growth is greatest at the highest temperature and least at the lowest temperature. This experiment, shows that the top part of the plant responds in a similar way. At high soil moisture levels, the plant growth showed no or little decrease when the temperature was low, but when the temperature increased, a greater and greater reduction was observed. This fact is generally true for the dry weight of the top, the rate of leaf emergence, the number of leaves, and the height of the plant.

In the second place, the results reflect the fundamental principles of the effect of temperature and soil moisture on plant growth. Every bit of growth requires food and energy. The amount of growth made by the plant therefore marked to an extent the ability of the plant to elaborate and accumulate food material besides the amount required for the maintainance of life processes. The ability of a plant to accumulate food depends, on one hand, on the proper development and functioning of its root system which must be able to afford a liberal amount of water and nutrient material needed by the top and, on the other hand, on the proper balance between the anabolism and catabolism of its aerial parts. The failure of any one of the two balances will lead to the same result, that the plant will not be able to accumulate enough food reserves for further growth, giving subnormal development and in the extreme cases, the premature death of the whole plant. For an annual economic plant like wheat, time becomes another factor to be considered. The growth of the plant at any stage of its life must not be so slow that the late growth will be retarded.

The results of this experiment point out that the significance of temperature and soil moisture on the growth of the wheat plant lies in their being the main factors controlling the two above mentioned balances. A brief outline is marked along which the plant responded through a temperature range of from 6° to 34°C., with minor but significant variations with the changes in soil moisture. When the seedlings were started and grown at a low temperature of 6^oC. the top / root ratio was the lowest and roots should not have any trouble in supplying nutrients to the tops. The photosynthesis / respiration ratio was theoretically high. So far as the 'balances' are concerned, the plants were in a very good situation. But the difficulty appears in an exceedingly low growth rate. Although the relative proportion of the root and shoot was favorable, both root and shoot had a low absolute amount of growth. Although photosynthesis was in a favorable condition relative to respiration, the absolute amount of photosynthesis was too low. At the end of two months, both varieties produced only three or four leaves, no tillers, and a very light weight. From the practical point of view, therefore the low temperature at the early start of the plant growth is still undesirable.

With the increase of temperature, the top / root ratio increases while the photosynthesis / respiration ratio decreases. Superficially, this appears to be unfavorable to the plant's food economy. But, only if the top / root ratio does not exceed the limit beyond which the root will no longer be able to afford the necessities of the top, the increase in the absolute amount of growth of the top is desirable. When heading and maturing time comes, most of the food material contained in the grain is drawn from the leaves and stems; only the plant with a big crop of the aerial parts could afford an abundant supply of food to be stored in the grains. It is evident then what we actually want is a high net amount of reserve food per plant which will be available for further growth or for grain development, whatever the top / root ratio may be. The greater dry weight, the greater rate of leaf emergence, the greater number of tillers, etc. are all the expressions in one way or another of a good state of balance within the plant.

Once the 'balances' are so upset by the further increase in temperature that the aerial part can no longer obtain enough material from the relatively reduced root system for its further growth or the anabolism is overwhelmed by the catabolism, a gradual reduction of the amount of reserve food will occur and finally the death of the plant will result. The growth condition of the plants in the 34°C. fully demonstrated such a tendency.

At all temperatures, an increase in soil moisture tends to increase the top / root ratio. But its effect on the plant at different temperatures varies. At low temperatures, an increase in soil moisture increases the absolute amount of top growth and therefore may either be beneficial or does no apparent harm to the wheat plants. At low temperatures, the temperature itself is on the side favoring the low top / root ratio, so even when the high soil moisture tends to increase the top / root ratio, the balance between the top and root will not be badly disturbed. At high temperatures, the high soil moisture becomes more and more detrimental, because at these temperatures, the top / root ratio is already high because of the temperature effect; when this is accentuated by the high soil moisture, the top and root relation is thrown into a still more unfavorable condition. An abundant food accumulation is therefore impossible and gradual exhaustion will probably follow.

In the third place, the results show the individuality of the plant characters in their response to the environmental factors. The optimum temperature and soil moisture for top growth are different from those of root growth. A high rate of emergence of leaves alone does not confirm the suitability of the environment to the leaf growth, because the size of the leaves may be either smaller or larger when the rate of leaf emergence is slower. Also the height of the plant is not in direct proportion to the weight of the plant, because a plant can grow to great height by the stimulation of the environment on a single character like the length of leaf sheath or the length of the leaf blade. Again, even the parts of the same organ, the leaf sheath and the blade, do not show a parallel response to the environmental conditions. Because of such a high individuality of the various characters it is rather difficult to state, in a strict sense, exactly which temperature or soil moisture is best suited for plant growth. For practical purposes, reference will have to be made to the yield for the final determination. Yet when doing so, it should be realized that the yield is the result of the interactions of all these characters which respond individually.

In the fourth place, the results show the interrelation between the internal factors of the plant and the external factors of environment. The most striking differences between the Thatcher wheat, the spring variety, and the Tenmarq wheat, the winter variety, are their responses to day length, of their tendency to tiller and time of heading and the responses of their length of leaf sheath and leaf blade to temperature.

Finally, the results suggest the critical period of the wheat plant growth as the point when the endosperm is exhausted and while the young seedling has little root absorption and photosynthetic action. Since the growth is cumulative, the effect of the environmental factors at this critical period has a profound influence on the later growth. Similar to the statement made by Alsberg and Griffing (2) and Bakhuyzen (4), it could be said that the failure of the proper development of the second or third leaf due to the incidental attack of an unfavorable temperature or moisture condition at this critical period would reduce or delay the growth of the fourth leaf, and so on. Under field conditions, numerous young seedlings must have perished in this manner. With the unexpected changes in weather conditions, a plant which germinated one or a few days after another may unluckily encounter unfavorable weather at its critical period, while the former may narrowly escape it. These weakened plants are obliged to be the ones that are defeated in later competitions. In regions with rapid weather changes, the yield of the whole crop may be influenced by this sensitive relationship between the crop and the environment.

SUMMARY

This experiment was planned to study the influence of temperature and soil moisture on the growth of the young wheat plant. The experiment was conducted in a suite of four refrigerating rooms of the Chemistry Department of Kansas State College and artificial light was used for growing the plants.

Thatcher and Tenmarq wheat were grown under 16 different combinations of temperature and soil moisture for a period of two months. The temperatures used were 6°, 12° (in the first experiment 20°C.), 25°, and 34°C. The soil moisture levels used were slightly above the wilting coefficient, intermediate between wilting coefficient and field capacity, field capacity, and 7 percent above field capacity. The experiment was repeated. In the first experiment, 16 hour day length was used, while in the second experiment, the day length was reduced to 10 hours, but the light intensity was increased. The following characters were observed and the data analyzed: top dry weight, root dry weight, rate of leaf emergence, percentage of plants that tillered, number of tillers per plant, height of the plant, and total length of the leaf sheaths.

(1) Top dry weight. Under a 10 hour day length, the top dry weight of both varieties increased from 6° to 25°C. and decreased at 34°C. Both varieties at 6°C. and Thatcher wheat at 12°C. increased in dry weight with the increase of the soil moisture up to the highest level. For the rest of the combinations, the greatest top dry weight was shifted to the field capacity level.

Under a 16 hour day length, the results were less consistent, but the general order was not altered. The Tenmarq wheat had a similar dry weight as the Thatcher wheat 6° and 34°C., but a significantly greater top weight than Thatcher wheat at 20° and 25°C. This was due to the fact that Thatcher wheat under these two temperatures and day length was forced to head prematurely.

(2) Root dry weight showed a lower optimum temperature and a lower soil moisture level than the top dry weight. The top root ratio generally increased with temperature and soil moisture, but reductions occurred when the treatments were such that the top growth was also greatly reduced.

(3) Rate of leaf emergence. Under a 10 hour day length, both varieties had the greatest rate at 25°C. For Thatcher wheat, the plants grown at 34°C. came second and those grown at 12°C. third; for Tenmarq wheat, those grown at 12°C. second and those grown at 34°C. third. The plants grown at 6°C. always had the lowest rate. Both varieties grown at 6°C. and the Thatcher wheat grown at 12°C. showed an increase in the rate of leaf emergence with the increase of soil moisture content up to the highest level. The plants under the other treatments all had the greatest rate at field capacity.

(4) The percentage of tillered plants. Under both 16 and 10 hour day lengths, no plant tillered at 6° and 34°C. at the end of the two months. Under 10 hour day length, 9.6 percent of the Thatcher wheat and 94.2 percent of the Tenmarq wheat tillered at 12°C.; and 25.0 percent of Thatcher wheat and 22.6 percent of Tenmarq wheat tillered at 25°C. At 12°C. the percentage was generally the highest at the highest soil moisture level, while at 25°C., it was the highest at the field capacity level.

Under a 16 hour day length, 76.8 percent and 57.5 percent of the Thatcher wheat had produced abortive tillers at 20° and 25°C. respectively, the highest percentage being attained at the field capacity level. None of the Tenmarq wheat plants had tillered at either temperature under 16 hours day length.

(5) The number of tillers per plant. Under 10 hour day length, the greatest number of tillers per plant for both varieties was obtained at the highest soil moisture level under 12°C. and at the field capacity level under 25°C. Under 16 hour day length, only the Thatcher wheat grown at 20°C. and 25°C. had tillered, and those tillers were abortive and were not considered as fair indication of the tillering ability of the plants.

(6) The height of plant was measured from the base of the plant to the tip of the leaf which attained the greatest height. (under 10 hour day length).

a) The height of plant during the young plant stage was thought to be influenced by three plant characters; the number of leaves, the length of leaves, and the length of the leaf sheath. Failure of plants to increase in height after certain stages of growth was due either to the failure of the leaf sheath to elongate to an appreciable extent and the habitual shortening of the successive younger leaves, or to the actual retarding of leaf development and leaf blade elongation.

b) The initial phase of the height growth of the plant (made from the reserve food of the kernel) was shown to have a higher optimum temperature than that after the seedling had become independent.

c) Both varieties grown at 6^{o} and $34^{o}C$. showed a leveling off of the ratio of growth in height at a relatively early stage. Tenmarq wheat grown at $12^{o}C$. showed the same tendency but at a later stage. Thatcher wheat grown at $12^{o}C$. and both varieties at $25^{o}C$. showed a fairly steady increase in height until the end of the experiment.

d) The tallest Thatcher wheat was obtained at $12^{o}C$. where it had greatly lengthened leaf sheathes. The tallest Tenmarq wheat was obtained at $25^{o}C$. where it produced extra long leaves. The plants grown at $6^{o}C$. were always the shortest, and those at $34^{o}C$. the second shortest.

At $6^{o}C$. the plant height increased consistently with the increase of the soil moisture. At $12^{o}C$. the height of both varieties grown at the highest soil moisture stood second to the field capactiy plants till the forty-third day. This order continued to the end of the experiment in the case of Tenmarq, but in the case of Thatcher, the plants grown at the highest soil moisture level finally became the tallest among its group. At 25^{o} and $34^{o}C$. the tallest plants of both varieties were those grown at field capacity level.

(7) The heat resistance. Both varieties had a high death rate when grown at $34^{o}C$. Under 10 hours day length the death rate of Thatcher wheat is higher than that of Tenmarq wheat at low soil moisture levels, but lower at two high moisture levels. Under 16 hour day length, Thatcher wheat had a much higher death rate than Tenmarq at all soil moistures.

(8) The results of this experiment suggest the following points:

a) The injurious effects of the plants to high soil moisture increase with the increase of temperature; and these effects are not only shown by the roots but by the tops as well.

b) The temperature affects the plant growth decisively in two lines, namely, the balance between the top and root growth, and the balance between the anabolism and catabolism of the whole plant. Soil moisture exerts a modifying but less significant effect.

c) Plant characters respond more or less individually toward the environmental factors.

d) A critical period probably exists when the endosperm is exhausted while the young seedling is yet unstable in its photosynthesis and root absorption. At this period, effect of adverse environmental factors is more likely to be fatal to the plant.

e) The Thatcher wheat is more susceptible to high temperature but less susceptible to high soil moisture than the Tenmarq wheat.

(9) The results of this experiment are only applicable to the conditions of the experiment and are only suggestive regarding plants grown under natural conditions.

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