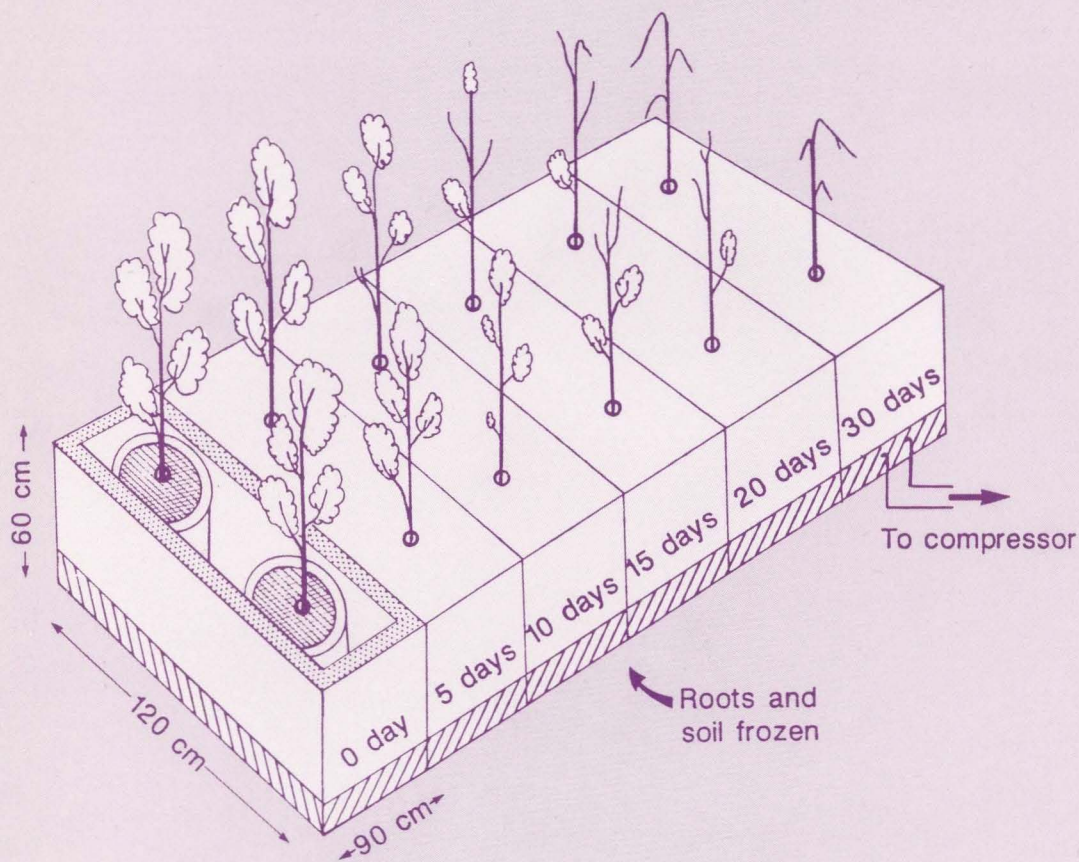# Experiments on the causal mechanisms of dieback on deciduous forests in Quebec

René Pomerleau
With foreword by Allan Auclair and Denis Lachance
Quebec Region • Information Report LAU-X-96

Canada

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René Pomerleau

Dr. René Pomerleau pioneered research into tree diseases in Quebec. After completing specialized studies at the Sorbonne in Paris and at the École nationale des Eaux et Forêts in Nancy, he returned to Quebec and undertook research into the phytopathology of trees. He began his research with the government of Quebec, which he continued for the federal government at the Laurentian Forestry Centre from 1952 until his retirement in 1970.

His interest over the course of his career in the study of mushrooms culminated in the publication in 1980 of a monumental work entitled "Flore des champignons du Québec." This volume, which has rapidly become the "bible" for identifying mushrooms in Quebec, describes over 1400 species of mushrooms.

EXPERIMENTS ON THE CAUSAL MECHANISMS OF DIEBACK ON DECIDUOUS FORESTS IN QUEBEC

René Pomerleau[1]
With foreword
by Allan Auclair and Denis Lachance

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Cette publication est aussi disponible en français sous le titre « Expériences sur les mécanismes du dépérissement des forêts de feuillus au Québec» (N° de catalogue Fo46-18/96F).

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FOREWORD

In an attempt to identify the cause of forest dieback current on sugar maple and other tree species in southeastern Canada, we re-examined earlier research on birch dieback conducted from the late 1940s through the early 1960s. Some of the early work that proved pivotal to our thinking was contained in government reports that had been filed but never published.

Pomerleau's work, originally contained in an unpublished file report entitled *Hardwood dying studies in Quebec. I. Laboratory experiments on white birch seedlings* (1959) is best viewed in the context of his attempt to develop a sound conceptual basis for understanding the dieback phenomenon.

René Pomerleau's **theory** was that dieback episodes on deciduous forests in Quebec were incited solely by anomalous climatic phenomena. It was his observation that the region-wide diebacks since the 1920s had resulted from anomalous winter and/or spring weather. Specifically, the diebacks were incited by deep soil frost penetration in winters of insufficient snowfall or in winters with an intense meltdown of the snowpack.

His **hypothesis** was that the mechanism of crown dieback was frost-kill of the roots, severing of roots by ice lense formation, and/or desiccation of the crown in the spring at a time when the roots were locked in soil ice (i.e., acute frost desiccation).

Thin or wet/poorly drained soils were **enhancing factors** since these conditions resulted both in shallow root systems and inadequate drainage that facilitated the formation of soil ice and frost. Conversely, adequate site drainage and appropriate site and species selection to ensure deep rooting are management options available to minimize the potential risk of dieback.

This study is important for three reasons:

1. It addressed the question of a causal mechanism as identified from extensive forest pathology surveys.

2. It focused on climate - a factor that has proved to be of considerable importance in recent studies on sugar maple dieback.

3. It provided key evidence on the role of climate; that evidence was both unique and crucial to our current concept of how climate acts to initiate dieback.

The lack of sophisticated instrumentation and the rapid development of concepts on tree stress physiology (e.g., cavitation phenomena) may suggest to some that the work is outdated. On the contrary, we view the study as an essential building block for a universal understanding of forest dieback phenomena; moreover, the work is creative, well-focused and meticulously done.

Although editorial changes were made to the original Pomerleau report and metric units substituted for imperial units, its reporting structure and style were only minimally modified. Other related experiments and observations had been conducted by Pomerleau at the time. We considered these a valuable adjunct and added them as appendices together with a compilation of his publications on dieback.

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Allan N.D. Auclair and
Denis Lachance
May, 1990

</div>

ABSTRACT

Symptoms of forest dieback (root mortality, leaf necrosis, chlorosis, wilting, and twig death followed by auxiliary bud development) were experimentally induced in a series of laboratory tests (October 1955-December 1957) on white birch (*Betula papyrifera* Marsh.).

Test results refuted Redmond's (1955) hypothesis that small increases in soil temperature (2°C) had incited high levels of root mortality followed by crown dieback in birch species. A series of four soil temperature x soil moisture factorial tests indicated soil temperature was of little importance even at extremes of 43.3°C provided soil moisture was above minimal requirements. Instead, white birch seedlings proved highly sensitive to moisture stress. Relative to responses at soil field capacity, they showed over 65% stem growth reduction and an 8-fold increase in root mortality with slight soil moisture reductions. Permanent wilting occurred at 7%, and leaf and twig death at 6% soil moisture but, typical of dieback under natural conditions, this was followed by auxiliary bud formation below dead portions of the stem.

Complementary field and growth chamber experiments designed to test hypotheses on the effect of soil frost and soil ice on root mortality and dieback substantiated the importance of anomalous climate as a factor inciting widespread, persistent dieback of tree species in northern hardwoods.

Keywords: Birch (*Betula*), dieback, root mortality, soil temperature, soil frost, northern hardwoods

RÉSUMÉ

Les symptômes du dépérissement des forêts (mortalité des racines, nécrose des feuilles, chlorose, flétrissement et mort des rameaux suivie par la naissance de bourgeons auxiliaires) ont été reproduits expérimentalement dans une série d'essais en laboratoire (d'octobre 1955 à décembre 1957) sur le bouleau à papier (*Betula papyrifera* Marsh).

Les résultats obtenus contredisent l'hypothèse de Redmond (1955) voulant que de petites hausses de la température du sol (2°C) entraînent une mortalité élevée des racines et la mort en cime des bouleaux. Une série de quatre tests factoriels de températures X taux d'humidité du sol indique que la température du sol n'a qu'une faible importance, même à un degré extrême tel que 43,3°C, pourvu que l'humidité du sol se situe au-dessus du minimum requis. En revanche, les semis de bouleau à papier se sont montrés particulièrement sensibles au stress d'humidité. Quant à leurs réactions à la capacité au champ du sol, on a constaté une réduction de plus de 65 % dans la croissance de la tige et une mortalité des racines huit fois supérieure au témoin avec de légères réductions de l'humidité du sol. Un flétrissement permanent s'est produit lorsque l'humidité du sol a atteint 7 %, les feuilles et les rameaux sont morts lorsqu'elle était de 6 %; mais des bourgeons auxiliaires ont alors poussé sous les parties mortes de la tige, comme c'est normalement le cas en milieu naturel.

Des expériences complémentaires sur le terrain et en chambres de croissance, mises sur pied afin de vérifier des hypothèses relatives à l'effet du gel et de la glace sur la mortalité des racines et le dépérissement, ont permis de démontrer que des conditions climatiques anormales pouvaient jouer un rôle important dans le déclenchement d'un dépérissement généralisé et persistant de certaines essences de forêts de feuillus du nord.

Mots clés: Bouleau (*Betula*), dépérissement, mortalité des racines, température du sol, gel du sol, forêts de feuillus du nord.

INTRODUCTION

The important problem of birch dieback has been extensively studied in the eastern provinces of Canada and in the northeastern United States. In several instances, historical notes on this disease have been presented. In this report, no general review of the literature is given. Reference is made to only a few papers dealing directly with climatic influences which may have produced some crown deterioration on birch.

Pomerleau (1944a) concluded from field observations that physical factors, and more particularly anomalous climatic conditions, had been responsible for the extensive and severe dieback on birch. Hawboldt (1952) also confirmed that climatic fluctuations had played a prominent role in this problem. In Nova Scotia, Greenidge (1953) found "indications that the overall water economy of birch has an implicit relationship with the disease levels." Redmond (1955) reported "that small increases in soil temperature above those normally occurring result in increased mortality of rootlets in yellow birch," both in the laboratory and the field. The results of other researchers have been less certain. Using Thornthwaite's method of determining the water balance of soil, Fraser (1957 a, b) showed that a water deficit in the soil occurred in certain years but that considerable annual and seasonal fluctuations in soil temperature had not produced noticeable changes in the health of yellow birch (*Betula alleghaniensis* Britton) trees. Clark and Gibbs (1957) studied the seasonal changes in water content of yellow birch in relation to climatic data but did not find any supporting evidence that the direct action of temperature and drought caused the birch to die back.

The objective of this study was to test the theory that relatively minor soil temperature increases (<2°C) were the most important ecological factor inciting dieback of birch and other hardwoods (Redmond 1955). Although the author had studied the problem of hardwood dieback for more than fifteen years, he carried out laboratory studies only recently. This report includes a complete description of the equipment, methods, and results of four experiments carried out between October, 1955 and December, 1957. The goal was to obtain more precise information on the effects of soil temperature and soil moisture on the dieback of white birch (*Betula papyrifera* Marsh.) seedlings.

METHODS

Since the main objective of this investigation was to determine the effects of soil temperature and moisture on the growth and health of tree seedlings, special attention was given to the control of those two edaphic factors. To achieve this, 12 boxes (Figure 1) were built to contain a volume of soil of 0.37 m² x 15.2 cm deep (4 sq ft x 6 in). Each box was insulated and double-walled. Constant soil temperature was maintained by thermostatic control of electric heating and refrigerant circulation in the water bath surrounding the soil container. Heat was supplied by a 1.22 metre-long (4 ft) flexible immersion heater (220 volts, 1000 watts). The cooling was provided by a serpentine in which oil circulated (Figure 2) at 1.67°C (35°F). The cooling unit was specially built (Figure 3) to bring up a reservoir of oil at the low temperature required and force it to circulate in the pipes with a circulation pump. A bimetal thermoregulator, single-pole, double-throw, with the bimetal element in water was used to control the temperature. Two mercury plunger relays connected to a 6-volt d.c. current were added to control the 230 v.a. current to the heater and the 110 a.c. current to the solenoid valve of the cooling serpentine.

Figure 1. Plant growth equipment used for these experiments. Seedlings were grown under artificial light and in boxes with controlled soil temperature and moisture.

Once properly connected to the cooling system and the electric current, each box was placed under artificial light provided by four banks of 16 fluorescent tubes. The illumination given at 30 cm (1 ft) from the lamps was approximately 538 lumens (500 foot-candles).
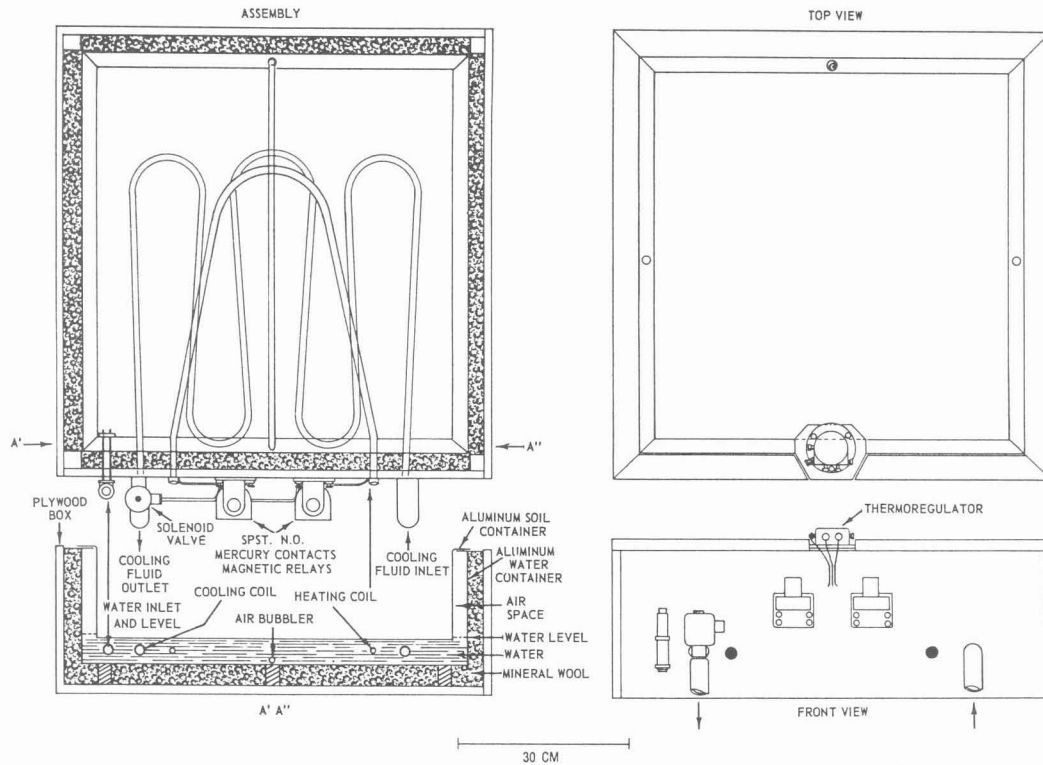
Figure 2. Design of boxes built to keep soil at a constant temperature.
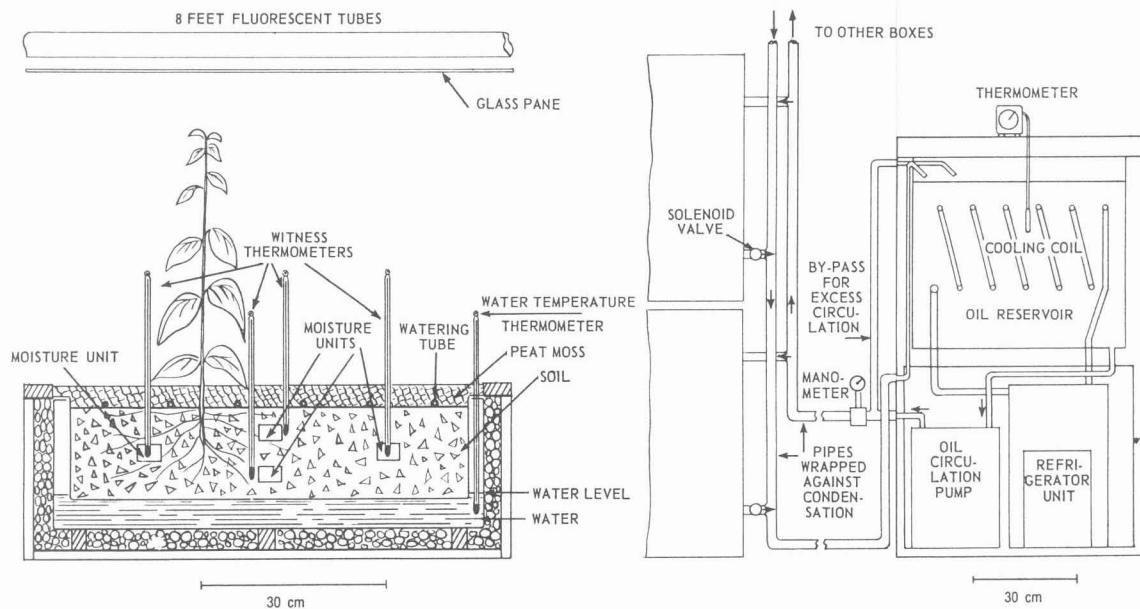
Figure 3. Design of the cooling unit and the plant growth equipment for constant soil temperature and moisture studies.

During an experiment, all plants were subjected to the same period of illumination, which was between 12 and 20 hours per day. The light source was at 55.88 cm (22 in) from the soil surface, but when the plants had grown the entire length, the experiment was ended. Glass shields and a ventilation system were used to eliminate the heat developed by lamps and ballasts.

In the first three of the four experiments, each box was filled to a depth of 15.24 cm (6 in) with soil from the top-soil layer of a white birch stand located in Laurentian Park. Another white birch stand was used for the last experiment. All the soil was well-mixed and screened before being used to fill the boxes.

To measure soil moisture, a number of fibreglass soil moisture units (Berkeley Scientific Company) were placed in the soil. For the first experiment, two or three units were placed at 7.62 cm (3 in). This number was increased to six per box during the third and fourth experiments to obtain a better representation of the moisture at 7.62 cm (3 in) (four units), at 2.54 cm (1 in) (one unit), and at 12.7 cm (5 in) (one unit). Resistance was measured and recorded with a conductivity bridge (Industrial Instruments Co., New Jersey). In order to determine the relationship between soil unit resistance and soil moisture content, several calibrations were carried out in special boxes according to the method recommended by the manufacturer. The curves presented here (Figure 4) are the results of calibration of a number of units in the two soils used. Readings on the curve of a given resistance in ohms provided the soil moisture percentage.

To maintain soil moisture at the required level, distilled water was added after the resistance reading when needed. For the first experiment, a perforated plastic tube was placed in the soil of each box at a depth of about 7.62 cm (3 in). This procedure was soon found to be inadequate for young seedlings with a very superficial root system. For all other experiments, seven rigid plastic tubes with perforations were placed at the surface of the soil. They were connected with a large rubber tube to a suspended bottle (Figure 1). This system allowed a measured amount of water to be evenly distributed on the surface of the soil when needed.

The plants used for the experiment were obtained by the germination of white birch seeds collected around Quebec City. Before being planted in the box, seedlings were grown in soil under artificial light until they had reached a length of 2.54-5.08 cm (1-2 in). Seedlings of approximately the same size were planted. For the first experiment, 49 plants were used. That number was reduced to 35 and finally 25 in the fourth experiment. It was soon realized that the surface of the soil must be well-insulated from the air to avoid

temperature fluctuations and soil surface evaporation. Therefore, 5.08 cm (2 in) of peat moss were added over the soil when the plants were long enough.
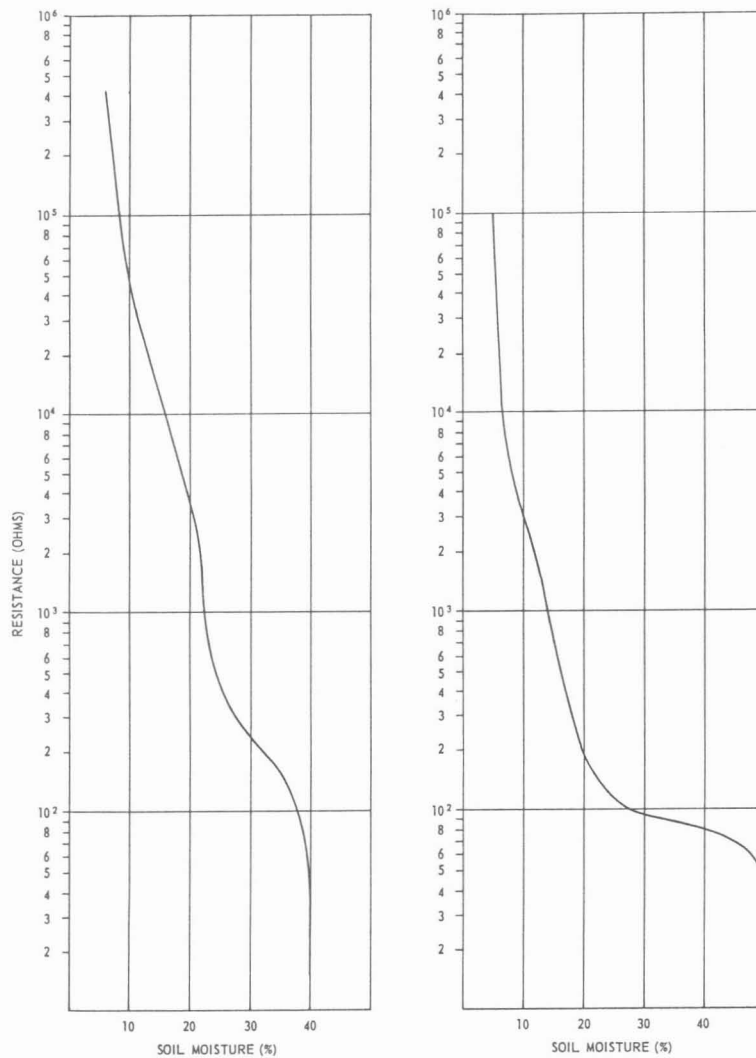
Figure 4. Curves of two soils representing a soil moisture percentage in relation to resistance of Coleman units.

Room temperature and moisture fluctuated quite extensively around growth equipment and this caused some fluctuation in soil temperature. Nonetheless, the results obtained with the present set-up should certainly provide very useful information on the effect of soil moisture and temperature on tree seedlings. All plants were grown at the same air temperature and humidity. Through the use of air fans placed in windows, fluctuation was controlled by a thermostat. Air temperature was recorded by two thermographs and two sets of minimum and maximum thermometers.

First experiment: varied soil temperature (initial trial)

To initiate this experiment, a set of six boxes was filled with a fine sandy loam from the top soil of a white birch stand. That soil had a moisture equivalent of 23.5 and a wilting percentage of 11.4 as determined by the cryoscopic method with a dilatometer (Foote and Saxton 1916, 1917a, b).

White birch seeds were placed in the soil for germination on October 15, 1955 and seedlings were planted in the boxes on November 15, 1955. The experiment lasted from November 15, 1955 to February 27, 1956. During the first 43 days, the soil temperature was maintained at about 21.1°C (70°F). Temperature fluctuations were frequent at that time because thermoregulators and relays were not properly arranged. From December 29, 1955 to February 22, 1956, the temperature of each box was set at a given level which was maintained as far as possible within narrow limits. Soil moisture was maintained almost at field capacity (around 1000 ohms) or 36 percent for a period of 52 days, then gradually lowered to about 20 percent (around 10 000 ohms) until the end of the experiment.

All the boxes were kept at a temperature of about 21.1°C (70°F) for the period of the establishment of white birch, and after 40 days, soil temperature was changed and maintained at a given level for each box for almost two months. Soil moisture was kept at almost field capacity during the establishing period, then gradually lowered to about 20 percent. Air temperature fluctuated within certain limits, but the average maximum was at about 25.6°C (78°F) and the minimum at about 19.4°C (67°F).

Second experiment: varied soil temperature (revised trial)

Because many alterations to the growth equipment were needed, a second but similar test was begun in the fall of 1956. A new crop of white birch seedlings was germinated from September 25 and planted on November 6, 1956. This time, only 35 plants were grown in each of six boxes. Temperature and soil moisture were maintained at the optimum level for the period of root system establishment, which lasted 37 days. Over the 125-day growing period, light was provided 20 hours a day. The test period lasted 46 days. The soil was the same as in the first experiment.

Third experiment: lethal soil temperature, varied soil moisture

During February 1957, a third series of tests was initiated. White birch seeds were planted on January 9 and grown under artificial light in soil boxes until planting on February 27. This time, only 35 plants were grown in each box. The experiment lasted from February 27 to May 31. The period of light was 18 hours per day with the same illumination intensity as for the previous experiments. With 12 boxes instead of six, as in the two previous tests, the experiment had two aims: (1) to determine the lethal soil temperature, and (2) to test the effect of soil moisture on white birch seedlings. Results of the two parts of the experiment are presented separately.

Part A, Lethal Soil Temperature: During the establishment period, which lasted from February 27 to April 11, the seedlings were grown at approximately the optimum temperature of 20°C (68°F) and at field soil moisture capacity (about 39.3%). The soil temperature was then adjusted in Boxes 1 through 6 to obtain an average as shown in Table 1. Throughout the test period (April 17–May 26), the soil moisture was maintained above 20 percent. Air temperature (Table 1) was about the same for the entire room and fluctuated within reasonable limits.

Table 1. Growth, dry weight, and root mortality of white birch seedlings in relation to soil temperature and moisture - third experiment, part A: February 26, 1957 to May 31, 1957

Parameter	Date	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6
Average stem length	April 11	1.09	1.40	1.84	1.53	1.17	0.43
(cm)	May 23	10.86	7.16	9.33	21.96	31.11	31.80
		±5.24	±4.07	±3.24	±9.05	±10.33	±11.27
Average dry weight of	May 31	0.51	0.38	0.62	1.40	2.17	1.54
stem and leaves		±0.30	±0.17	±0.38	±0.96	±1.44	±0.97
(g)							
Root mortality		13.8	0.46	0.94	1.09	0.01	0.00
(%)							
Average soil temperature	Feb. 26 – April 12	20.1	20.3	20.3	19.8	19.9	19.4
(°C)	April 17 – May 23	-	-	37.0	31.9	25.9	20.4
	April 17 – April 20	46.2	41.9				
	May 20 – May 30	41.4	38.6				
	April 27 – May 30	19.4	20.1				
Average soil moisture	Feb. 26 – April 10	39.3	39.1	39.2	39.3	39.5	39.4
(%)	April 17 – May 23[a]	-	-	26.7	24.1	22.9	24.0
	April 17 – April 21	22.9	37.1				
	April 27 – May 19	33.8	34.8				
	May 21 – May 26	21.8	25.9				
Average air temperature	April 17 – May 26						
(°C)	(maximum)	30.3					
	(minimum)	23.0					
Amount of water added	Feb. 26 – April 10	20	19	19	20	19	19
(L)	April 11 – May 23	30	20	27	41	56	37

a In Boxes 1 and 2, the temperature was raised above the lethal level between April 12 and April 22. A new planting took place on April 24.

Part B, Varied Soil Moisture: The second part of the third experiment was carried out to test soil moisture effects on the birch seedlings. The same soil and planting methods were used during the same period as in Part A but soil moisture over the April 4–May 31 growth period was varied, ranging on average from about 15% in Box 7 to 32% in Box 12 (Table 2 and Figure 5).

Table 2. Growth, dry weight, and root mortality of white birch seedlings in relation to soil temperature and moisture – third experiment, part B: February 26, 1957 to May 31, 1957

Parameter	Date	Box 7	Box 8	Box 9	Box 10	Box 11	Box 12
Average stem length	April 11	2.19	1.75	2.89	1.52	1.71	1.56
(cm)	May 31	5.0	5.1	6.0	11.0	27.2	31.5
		±2.56	±2.65	±2.88	±4.65	±9.60	±9.86
Average dry weight of	May 31	0.28	0.28	0.34	0.61	1.90	2.16
stem and leaves		±0.14	±0.11	±0.18	±0.38	±1.30	±1.46
(g)							
Root mortality	May 31	15.6	3.9	6.5	5.7	1.6	0.7
(%)							
Average soil temperature	Feb. 27 – April 12	20.2	20.4	19.9	19.7	19.8	19.6
(°C)	April 17 – May 31	21.1	21.1	20.8	20.5	21.6	20.4
Average soil moisture	Feb. 27 – April 8	39.1	39.4	39.2	39.3	39.3	38.6
(%)	April 4 – May 31	15.6	16.5	17.5	21.3	24.4	32.0
Average air temperature	Feb. 27 – April 12						
(°C)	(maximum)	26.6					
	(minimum)	19.8					
	April 17 – May 31						
	(maximum)	30.3					
	(minimum)	23.0					
Amount of water added	Feb. 27 – April 7	18	19	19	19	14	14
(L)							

Fourth experiment: combined soil temperature x soil moisture

Knowing the general behaviour of the white birch seedlings under a variety of soil temperatures and soil moisture conditions, the next logical step was to determine the combined effects of soil temperature and moisture on the same plants. To achieve this, two groups of six boxes were planted with 25 white birch seedlings and maintained at the same soil temperature and moisture for 40 days. Then, the soil temperature of six boxes was lowered to about 15.6°C (60°F) while the other set was kept at about 21.1°C (70°F). At the same time, soil moisture was fixed at a given level in each box, as shown in Table 3 and Figure 6, in such a way that one box at about 21.1°C (70°F) and another one at about 15.6°C (60°F) were maintained at approximately the same moisture percentage. That, of course, was
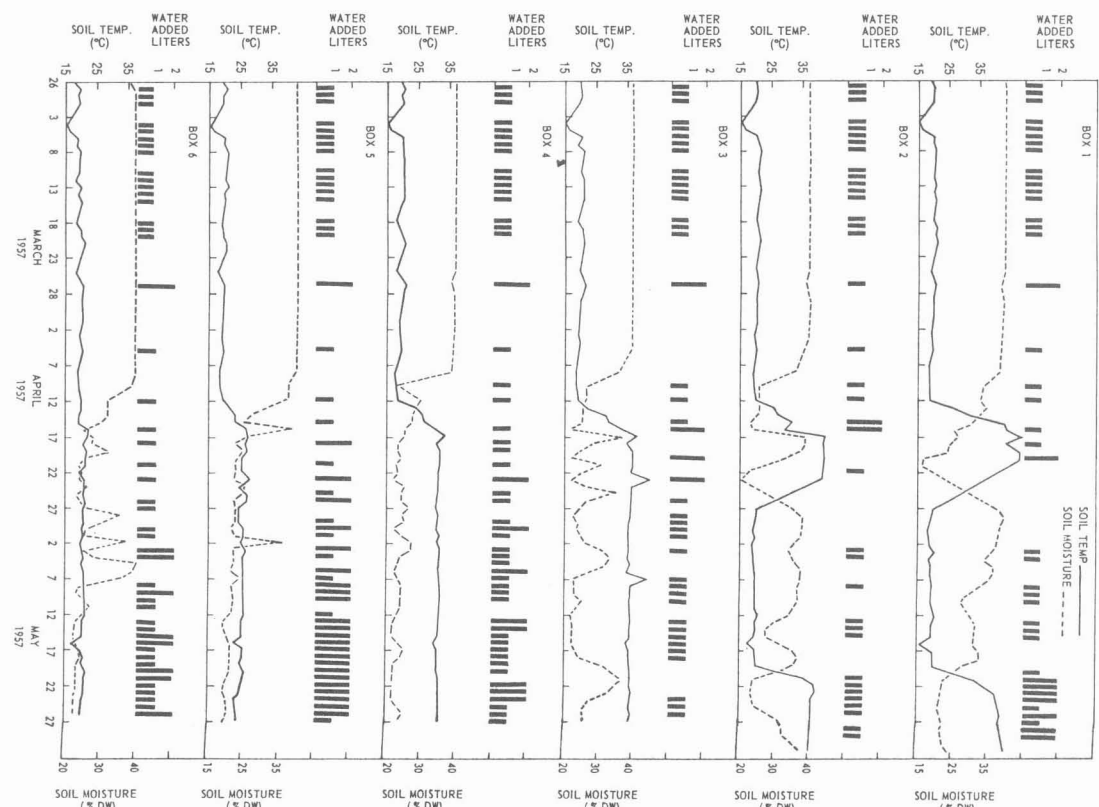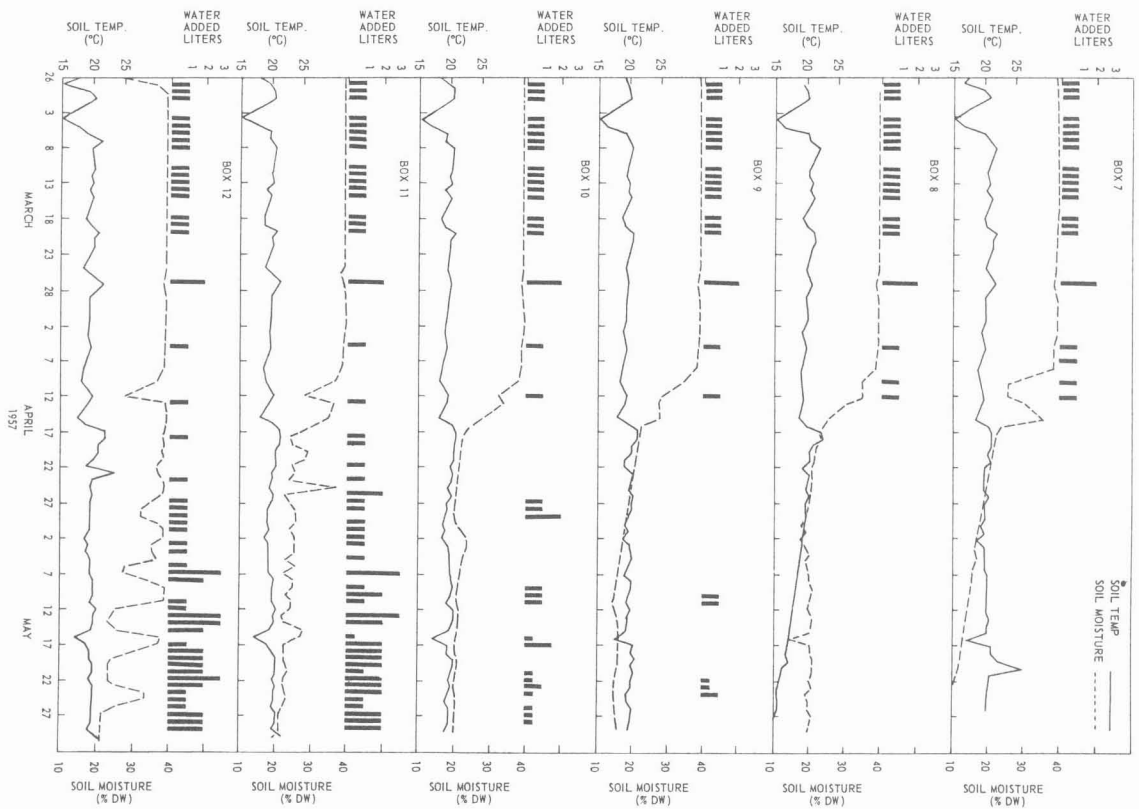
Figure 5. Soil moisture and temperature, and amount of water added in twelve boxes during the third experiment.

done by measuring resistance every day and by adding the amount of water needed. Evidently, it was rather difficult to keep the moisture percentage within a close range, and moisture distribution was not uniform from top to bottom in the dryer boxes. In Boxes 6 and 12, a moisture level below the wilting point was reached before water was added. Consequently, average soil moisture could not be determined.

After a period of about one month of observation, the soils were allowed to dry to obtain the total wilting of all plants. The length of that period varied with the soil temperature and moisture at the time of last watering.

Table 3. Growth, and dry weight of white birch seedlings in relation to soil temperature and moisture - fourth experiment: August 1, 1957 to November 27, 1957

Parameter	Date	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6	Box 7	Box 8	Box 9	Box 10	Box 11	Box 12
Average stem length	Sept. 10	17.9	19.2	19.1	17.9	17.4	17.9	20.1	20.4	19.4	17.5	18.3	20.4
(cm)	Oct. 29	35.2	33.4	34.0	33.3	28.9	29.8	42.1	37.6	36.6	35.8	30.3	32.7
	Nov. 27	35.5	33.4	34.2	33.7	28.9	34.2	42.1	37.6	36.7	36.2	30.7	32.7
		±6.94	±4.54	±4.29	±8.25	±5.50	±5.38	±5.63	±6.98	±6.40	±5.49	±4.64	±6.34
Average dry weight of	Nov. 27	2.17	2.23	2.03	1.95	1.58	1.78	2.70	2.69	2.38	2.34	1.94	1.66
stem and leaves		±0.71	±0.67	±0.64	±0.70	±0.43	±0.51	±0.88	±0.86	±0.74	±0.58	±0.64	±0.68
(g)													
Average soil temperature	Aug. 1-Aug. 16	21.2	21.4	21.2	21.0	20.6	21.1	21.2	21.4	20.9	20.9	20.9	21.9
(°C)	Aug. 21-Oct. 15	16.2	16.3	16.5	15.9	16.3	16.4	20.6	20.8	20.5	20.3	20.2	20.8
Average soil moisture	Aug. 1-Aug. 16	31.1	28.4	27.7	31.2	25.5	31.9	29.5	27.2	28.1	35.0	31.3	28.6
(%)	Sept. 16-Oct. 15	23.4	13.3	12.6	9.2	6.5	6.4	18.1	12.6	8.7	8.2	6.3	6.2
Average air temperature	Aug. 21-Nov. 27												
(°C)	(maximum)								27.8				
	(minimum)								20.0				
Amount of water added	Aug. 1-Aug. 20	8.25	8.25	8.25	8.25	8.25	8.25	8.25	8.25	7.25	7.25	7.25	8.25
(L)	Aug. 21-Oct. 15	47.0	44.0	37.0	28.0	21.0	17.0	64.0	58.5	49.0	39.0	30.5	22.0

BOX NO.1 AVERAGE TEMP. 16.2°C AVERAGE MOISTURE 23.4 %	BOX NO.7 A.T. 20.4°C A.M. 18.1 %
BOX NO.2 A.T. 16.3°C A.M. 13.3 %	BOX NO.8 A.T. 20.7°C A.M. 12.6 %
BOX NO.3 A.T. 15.9°C A.M. 12.6 %	BOX NO.9 A.T. 20.3°C A.M. 8.7 %
BOX NO.4 A.T. 16.3°C A.M. 9.2 %	BOX NO.10 A.T. 20.2°C A.M. 8.2 %
BOX NO.5 A.T. 16.4°C A.M. 6.5 %	BOX NO.11 A.T. 20.4°C A.M. 6.3 %
BOX NO.6 A.T. 15.7°C A.M. 6.4 % an LESS	BOX NO.12 A.T. 20.8°C A.M. 6.2 % AND LESS

Figure 6. Distribution of boxes according to average soil temperature and moisture A.T. = average temperature; A.M. = average moisture.

RESULTS

First experiment

White birch grew optimally at a soil temperature of about 20.3°C (68.5°F). However, at 27.6°C (81.6°F), seedlings were healthy and grew only a little less than at the optimum soil temperature providing the soil moisture was maintained above the minimum level.

Seedlings growing at lower soil temperatures of 18.1°C and 16.1°C (64.6 and 61.0°F) grew much less than at the optimum or higher temperatures. This poor development was attributed mainly to the unsatisfactory watering device used during the first experiment. In a cool soil, the superficial root system could not easily reach the water and the soil surface was not covered.

It was learned in the first test how to use the equipment, the corrections to be made, and how to grow white birch under artificial light. It was also found that white birch could grow in soil temperatures as high as 30°C (86°F) without dying or showing any sign of weakness if enough water was available.

Daily moisture and temperature readings and the amount of water added each day are presented in Figure 7; minimum and maximum daily air temperatures are shown in Figure 8. The aim of the first experiment was to evaluate the effects of soil temperature on the
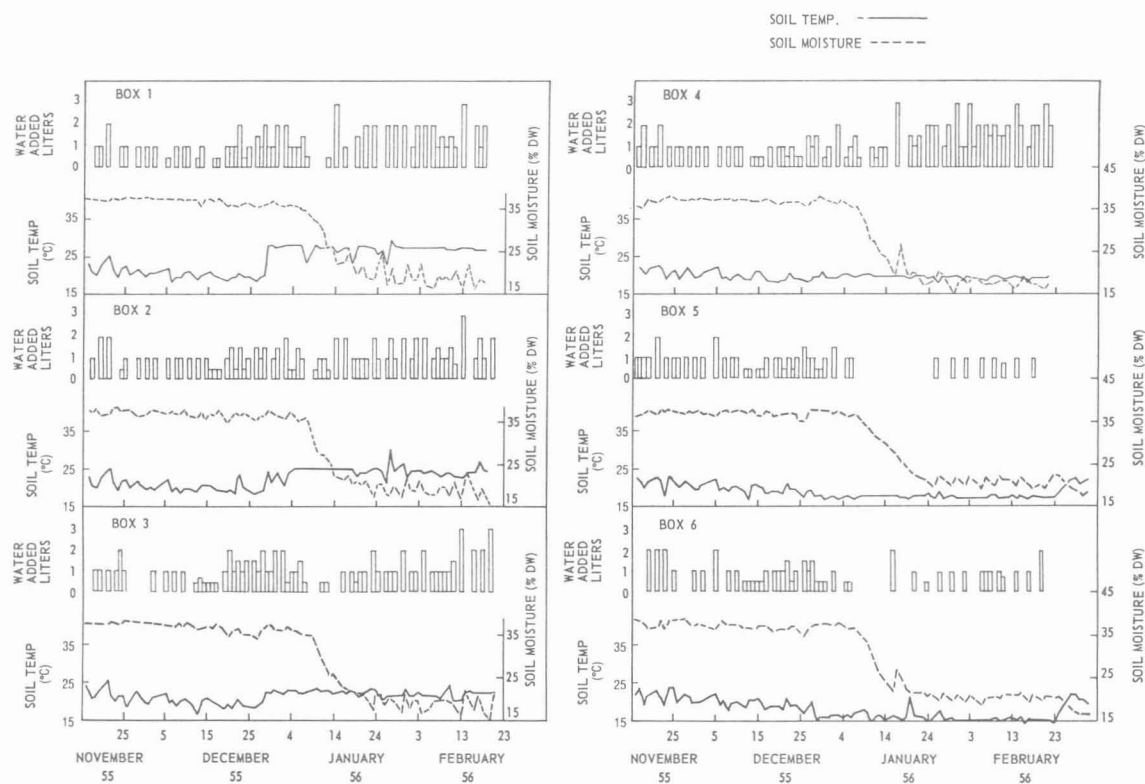
Figure 7. Soil moisture and temperature, and amount of water added in six boxes during the first experiment.
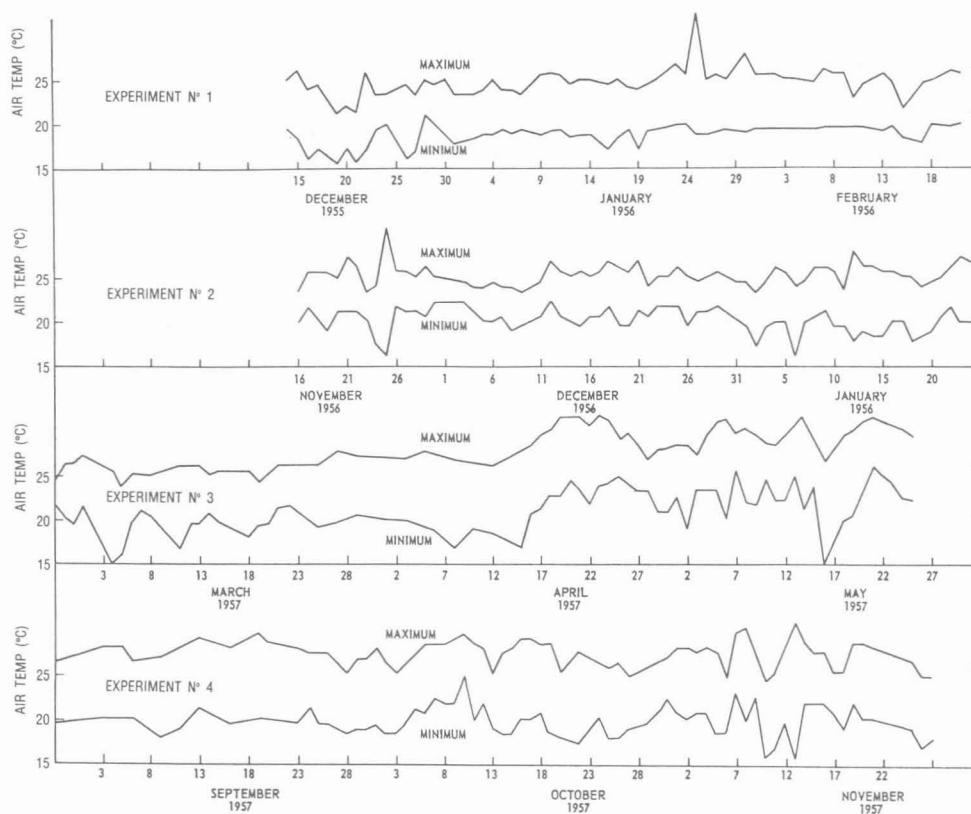

Figure 8. Daily minimum and maximum air temperature for the four experiments.

growth and health of white birch seedlings. During the experiment, only the general condition of plants was noted; their lengths and dry weights were measured at the end of the test. Data of this first test are summarized in Table 4.

Table 4.   Growth, and dry weight of white birch seedlings in relation to soil temperature and moisture - first experiment: November 15, 1955 to February 23, 1956

Parameter	Date	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6
Average stem length	Jan. 25	16.46	16.46	18.03	23.22	5.94	10.18
(cm)	Feb. 23	22.60	26.32	26.16	25.65	-	-
Total dry weight of stems and leaves (g)	Feb. 23	52.17	57.55	62.87	82.37	-	-
Total dry weight of roots (g)	Feb. 23	26.34	30.97	30.94	42.54	-	-
Average total root length (cm)	Feb. 23	180.34	133.32	133.32	215.38	-	-
Average soil temperature	Nov. 15 - Dec. 27	20.8	20.9	20.6	20.8	20.8	20.5
(°C)	Dec. 28 - Feb. 23	27.6	25.1	22.8	20.3	18.1	16.1
Average soil moisture	Nov. 15 - Dec. 27	37.0	37.0	36.9	37.2	37.1	37.2
(%)	Dec. 28 - Feb. 23	20.3	19.7	20.0	19.2	21.3	21.1
Amount of water added	Nov. 15 - Dec. 27	23.5	21.0	21.6	24.5	24.5	23.0
(L)	Dec. 28 - Feb. 23	36.3	33.2	39.5	41.5	13.2	18.6
Average temperature (°C)	Dec. 28 - Feb. 23 (maximum)	25.4	-	-	-	-	25.4
	(minimum)	19.7	-	-	-	-	19.7

Second experiment

Data on the controlled factors are presented in Figure 9 and growth is illustrated in Figure 10 and in Table 5. With the exception of an accidental rise in temperature on January 21, 1957 in Box 1, soil temperature and moisture were maintained at required levels throughout the experiment. In all boxes, white birch seedlings grew very well until the end of the experiment (Figure 11). The end of the experiment was determined by the maximum height available under the light system. It was evident, however, that the optimum soil temperature was at about 20 or 20.6°C (68 or 69°F). Below this temperature, growth was reduced but the plants continued their development. Above the optimum, growth continued at a reduced rate (Figures 12, 13) but was still quite vigorous in soil at temperatures averaging 34.7°C (94.5°F) over more than one month provided moisture was kept above the critical point.
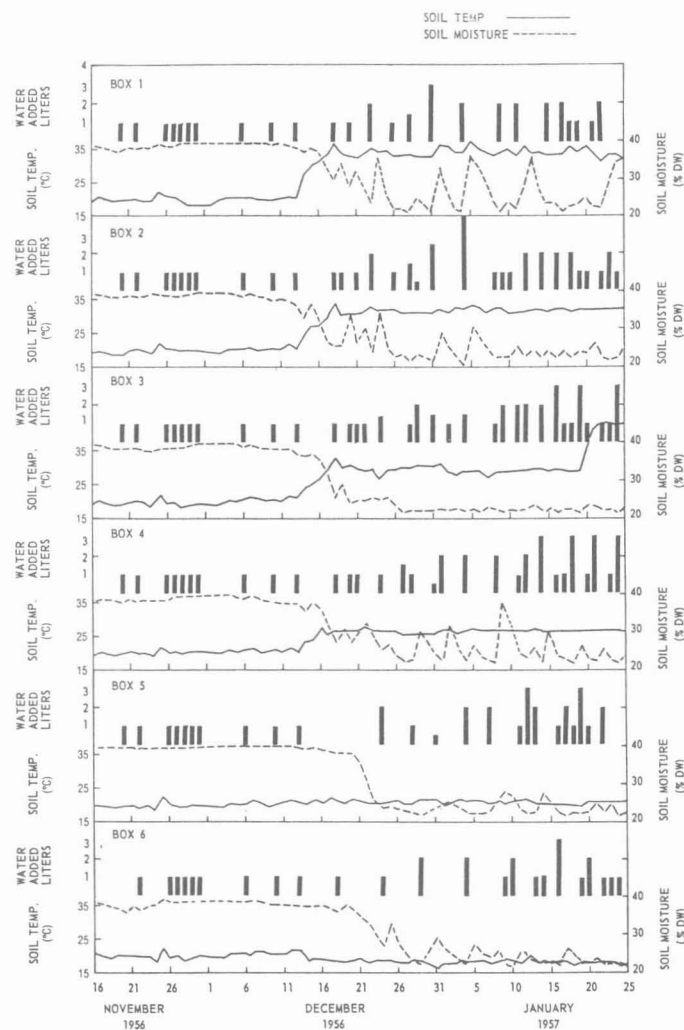
Figure 9. Soil moisture and temperature, and amount of water added in six boxes during the second experiment.

Table 5.   Growth, dry weight, and root mortality of white birch seedlings in relation to soil temperature and moisture
- second experiment: November 7, 1956 to January 25, 1957

Parameter	Date	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6
Average stem length	Dec. 14	2.11	2.50	2.52	2.50	4.25	3.70
(cm)	Jan. 25	21.94	27.60	31.87	32.63	35.27	24.84
		±7.9	±9.6	±7.8	±8.2	±10.6	±8.1
Average dry weight of	Jan. 25	1.02	1.16	1.49	1.48	1.94	1.30
stems and leaves		±0.63	±0.75	±0.71	±0.83	±1.07	±0.71
(g)							
Root mortality		99.47[a]	11.50	13.50[b]	0.48	0.91	1.67
(%)							
Average soil temperature	Nov. 11 – Dec. 13	20.5	20.3	20.3	20.5	20.2	20.1
(°C)	Dec. 17 – Jan. 25	34.7	31.9	29.6	22.3	20.9	18.3
Soil moisture	Nov. 11 – Dec. 13	38.9	38.5	38.6	38.6	39.4	37.9
(%)	Dec. 24 – Jan. 25	26.4	24.1	22.6	24.6	23.2	24.1
Average air temperature	Dec. 17 – Jan 25						
(°C)	(maximum)	25.9					
	(minimum)	20.3					
	(mean)	23.1					
Amount of water added	Nov. 11 – Dec. 16	10	10	10	11	10	9
(L)	Dec. 17 – Jan. 25	26.25	31.25	36.00	32.00	30.75	21.0

a On January 21, 1957, due to an accident, the temperature in Box No. 1 climbed to 54.4°C (130°F) one night. All plants were killed.
  The mean temperature given for that box does not include that unusual rise.
b The temperature in Box No. 3 was raised to 43.3°C (110°F) for ten days at the end of the experiment.
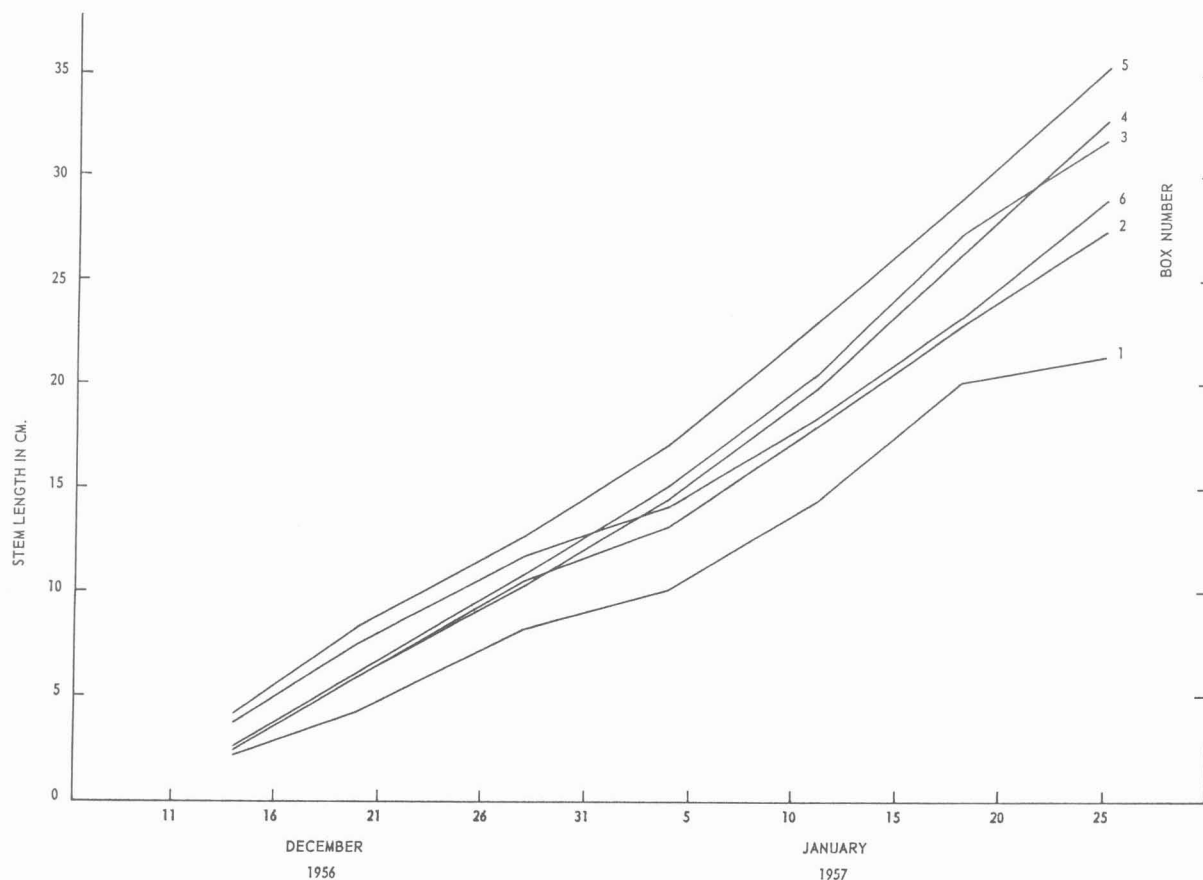
Figure 10. Growth of white birch seedlings in six boxes maintained at different temperature levels during the second experiment.

With the exception of Box 1, where a sudden rise in temperature occurred one night and killed the roots of all plants, the percentage of dead rootlets remained low. Root mortality was determined by examining from 3 000 to 4 000 root tips per box. The root system of a number of plants from each box was examined and photographed (Figure 14). With the exception of birch seedlings growing at about 35°C (95°F), the root development appeared to be similar in the five other boxes.

Figure 11. White birch seedlings after 25 days at different soil temperature levels. (Second experiment). Temperatures are indicated on the white cards.

Figure 12. White birch seedlings after 42 days at lower temperature levels. (Second experiment). Temperatures are indicated on the white cards.

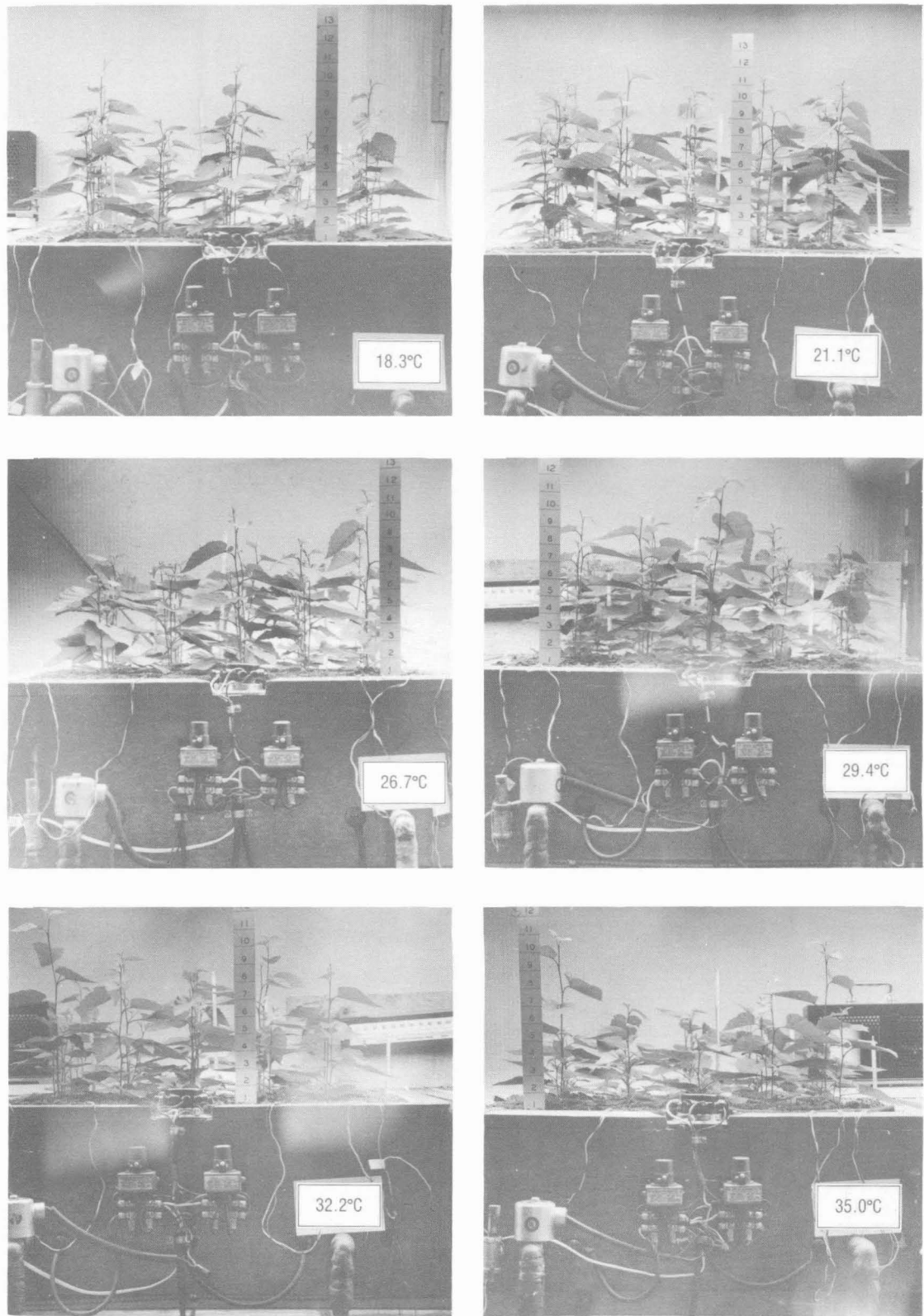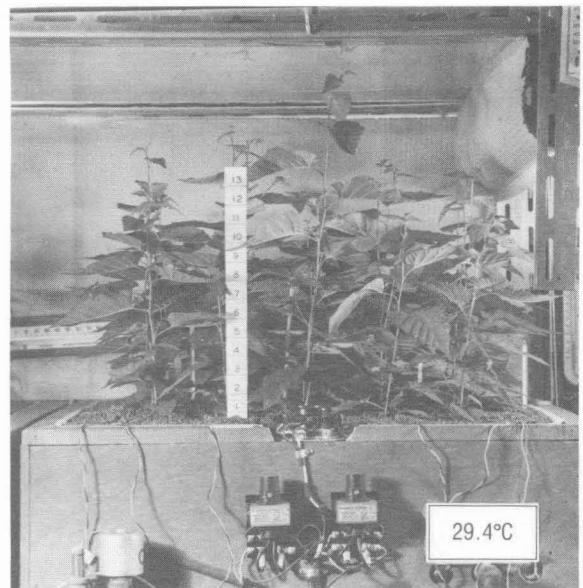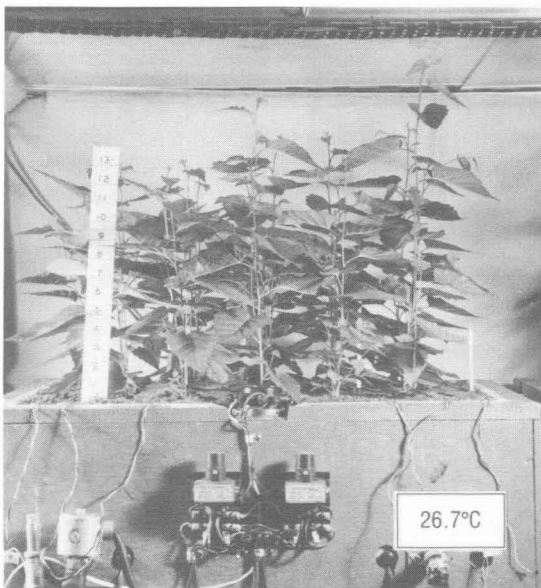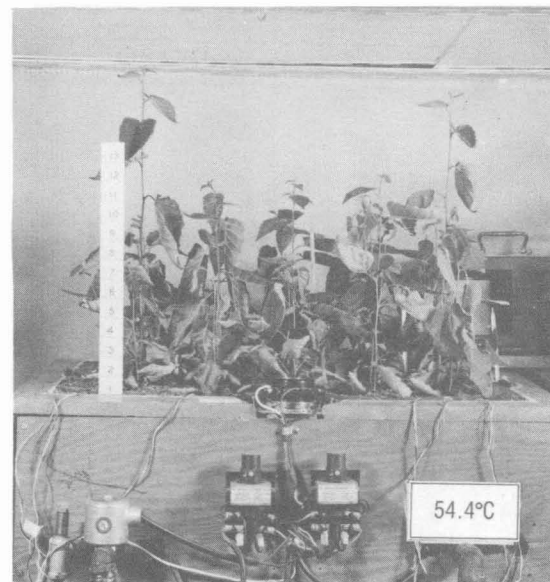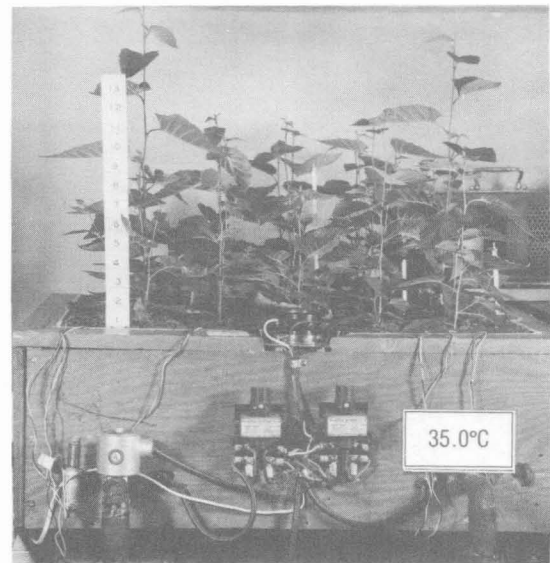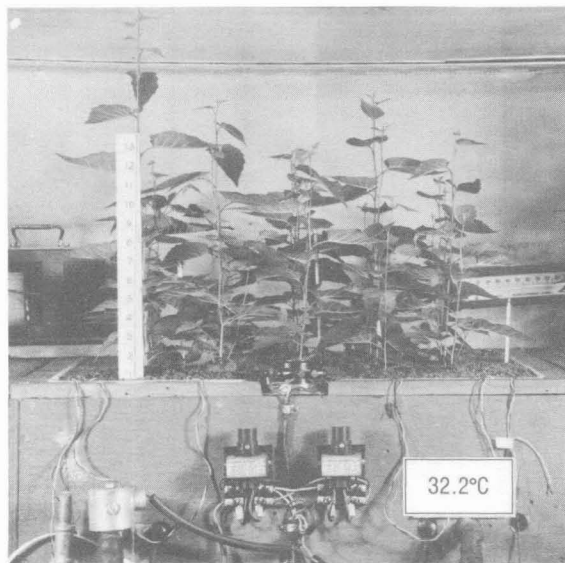**Figure 13.** White birch seedlings after 42 days at higher temperature levels. (Second experiment). Temperatures are indicated on the white cards.
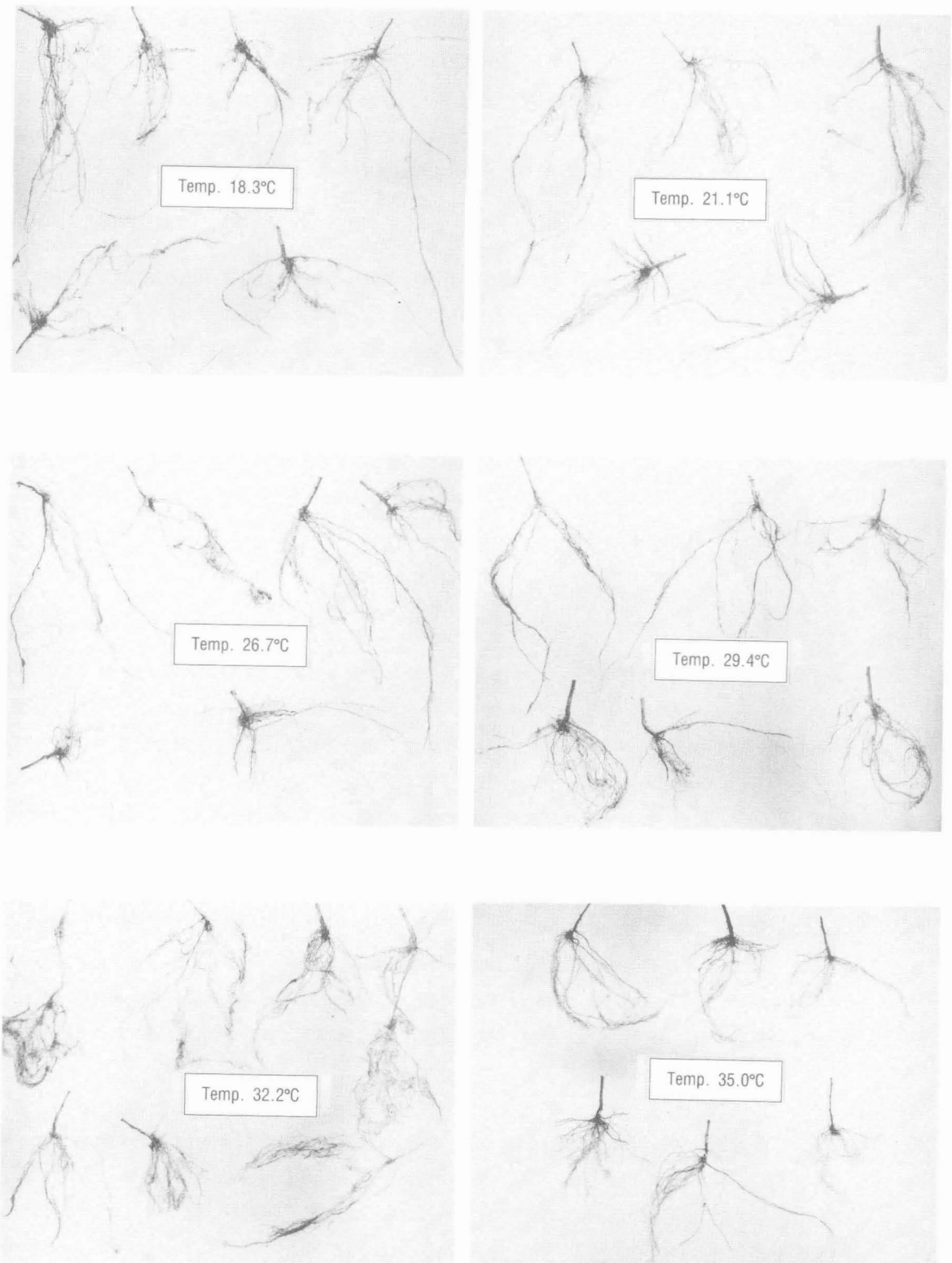
Figure 14. Root systems of white birch seedlings grown at different soil temperatures for 42 days. (Second experiment).

The amount of water added to each box to maintain the soil moisture at the same level was high in the box with soil at 29.4°C (85°F) and lower at 32.2, 35, 22.2, 20.6, and 18.3°C (90, 95, 72, 69 and 65°F). That would indicate that at 29.4°C (85°F), plant activity was greater than at higher or lower temperatures although examination of growth, size, and dry weight had already shown that the optimum temperature was between 20 and 21.1°C (68 and 70°F).

The second experiment, carried out with improved equipment and techniques as compared to the first, provided useful information on the behavior of birch seedlings under a wide range of soil temperatures. It also showed that white birch can grow in soil maintained at an average temperature of 35°C (95°F) with a few peaks of 43.3°C (110°F) without dying. In Box 3, the temperature was raised to 43.3°C (110°F) (Figure 13) for a week at the end of the experiment and the plants were not killed although rootlet mortality increased a little. Evidently, 54.4°C (130°F) (Figure 13), even for a few hours, was fatal to the birch seedlings.

Third experiment

Part A: When the soil temperature of Box 1 was raised to an average of 46.2°C (115.2°F) and a maximum of 48.9°C (120°F) at a depth of 7.62 cm (3 in) and 51.1°C (124°F) at 12.7 cm (5 in), all plants were killed. In Box 2, the temperature was raised to an average of 41.7°C (107°F) and a maximum of 42.2°C (108°F) was reached at 7.62 cm (3 in), and 45.6°C (114°F) at 12.7 cm (5 in). All plants were killed at that point also. The plants were then removed and the soil newly planted on April 25 with seedlings kept aside from the same lot. After the new crop had reached a fair size, the temperature was again raised. Between May 21 and May 30, temperatures in Box 1 reached an average of 41.1°C (106°F) and a maximum of 41.7°C (107°F); in Box 2, they reached an average of 38.3°C (101°F) and a maximum of 39.4°C (103°F). Plants in Box 1 were partly killed after nine days at temperatures above 40.6°C (105°F). In Box 2, however, plants were still living after a ten-day exposure at 38.3°C (101°F).

The growth of seedlings in other boxes maintained at lower soil temperatures (Figure 15) confirmed what had been found previously; namely that the optimum soil temperature for growth of white birch seedlings was close to 20°C (68°F). That species, however, can continue its development at temperatures up to 37.8°C (100°F), but at a lesser rate. This is provided soil moisture does not decrease to the critical point. Examination of roots from 15 seedlings also revealed that rootlet mortality was insignificant except in plants exposed at soil temperatures above 38.3°C (101°F) (Table 1).

Figure 15. Growth of white birch seedlings in six boxes maintained at different temperature levels during the third experiment, Part A.

Part B: The results presented in Table 2 and Figure 16 clearly indicated that white birch seedlings attain the best growth when the soil is maintained almost at the field capacity. When the moisture percentage was reduced, growth decreased accordingly. The percentage of growth reduction according to the average soil moisture is presented in Table 6.

Table 6. Growth reduction of white birch seedlings according to the average soil moisture

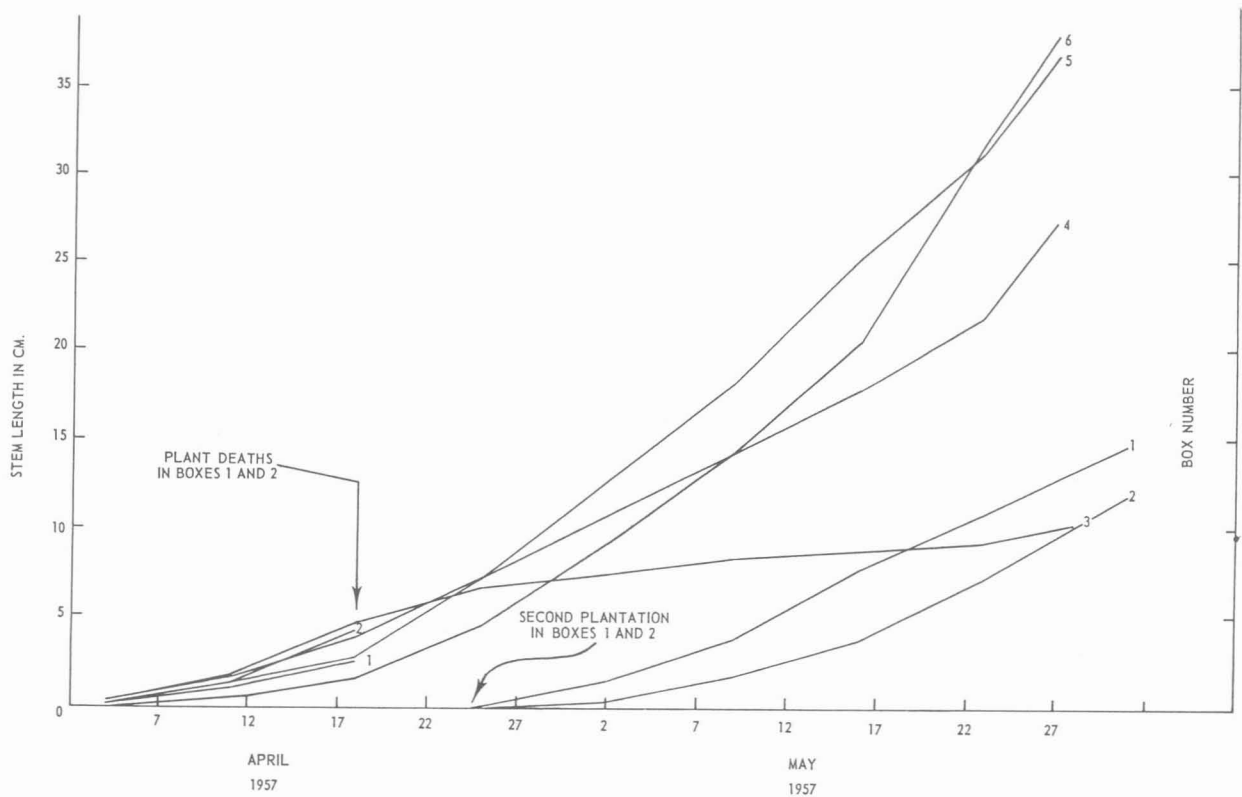| Box No.	Soil moisture percentage	Growth reduction percentage
12	32.0	0
11	24.4	13.7
10	21.3	65.1
9	17.5	80.9
8	16.5	83.9
7	15.6	84.1
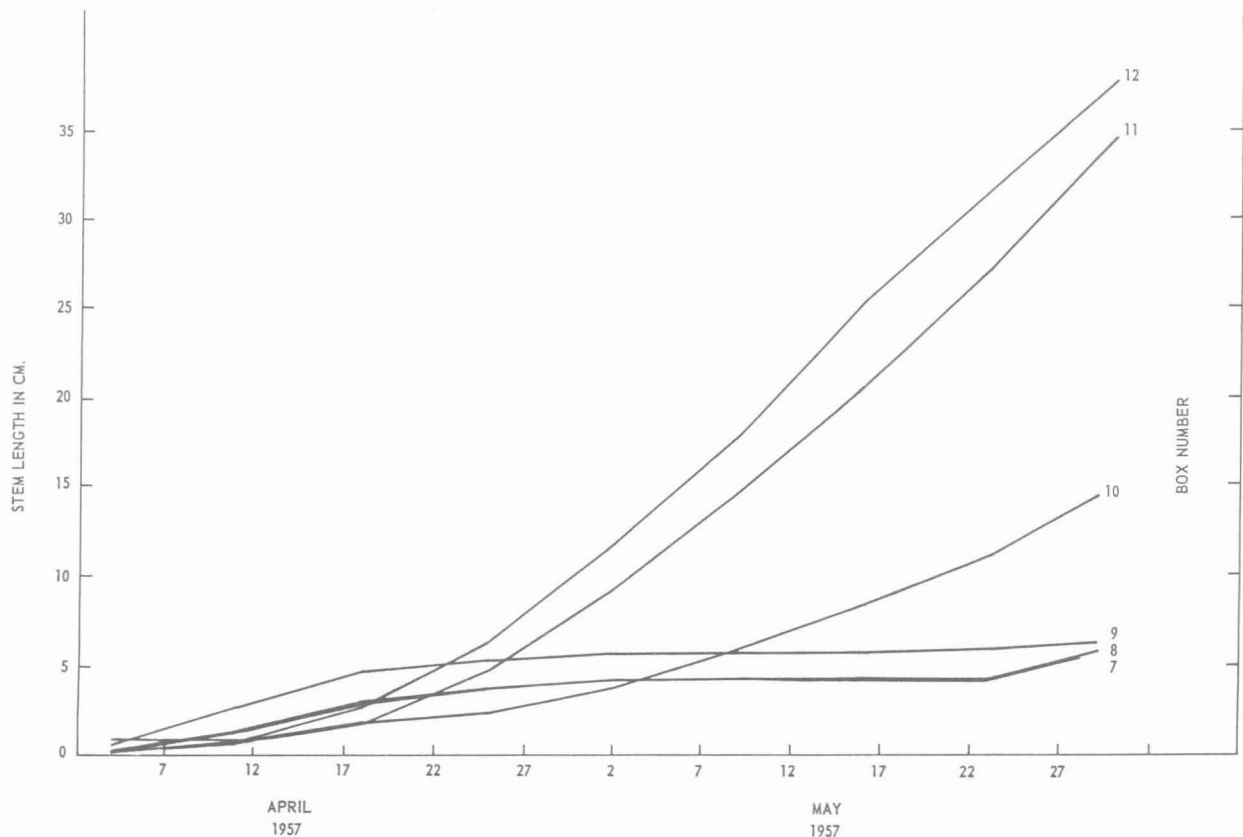
Figure 16. Growth of white birch seedlings in six boxes maintained at different moisture levels during the third experiment.

A soil moisture of less than 24% is a poor condition for white birch seedlings, and below that point, growth almost ceases (Figure 17). This is indicated by the percentage of rootlet mortality at the end of the experiment; by the chlorotic leaves that occurred in Boxes 7, 8 and 9 on May 2; and by the wilted leaves that appeared before May 23 in Boxes 7 and 8. This experiment, therefore, provided clear indications of the moisture stress condition of the soil for white birch and of a permanent wilting close to 11% of soil moisture as already found by the cryoscopic method. To keep plants in a perfect growing condition, 49 L of water were required for a period of 50 days. When only 13 L, 5 L, or 2 L were given for the same period, growth was slowed down and leaf chlorosis and wilting were quite apparent.

The third laboratory experiment clearly revealed the sensitivity of white birch seedlings to soil moisture variations and the effects of water deficiency close to the wilting point.
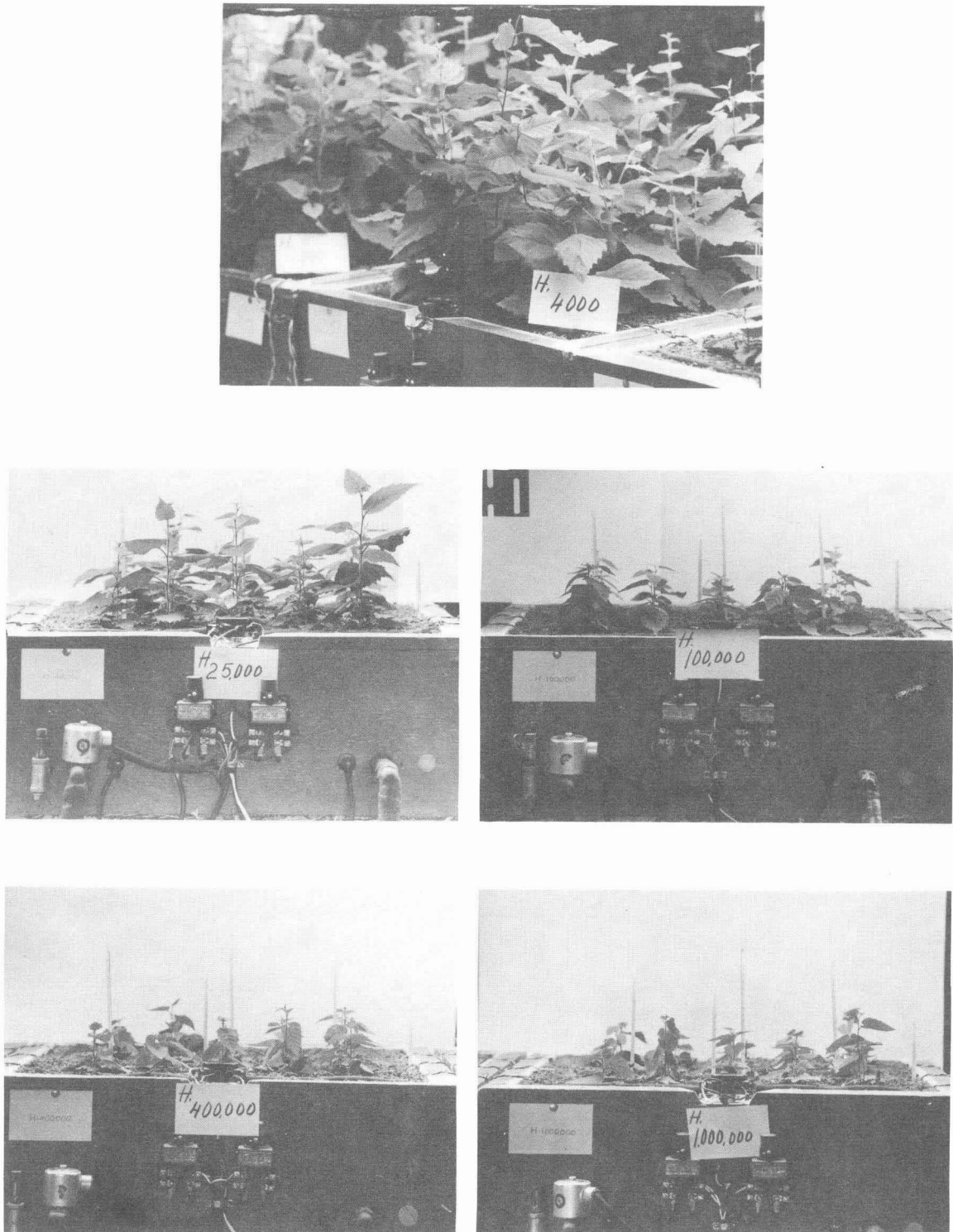
Figure 17. White birch seedlings grown at different moisture levels over 42 days. The white cards indicate resistance in ohms.

Fourth experiment

During the period of establishment, from August 1st to September 10, seedlings in all boxes grew at about the same rate. Differences up to that date were due to factors other than soil temperature and moisture. Differences were more evident after changes were made to the temperature and moisture (Table 3). On October 29, birch seedlings in Box 7, grown at the optimum temperature and at a high moisture percentage, had the best growth. The growth rate gradually decreased and even remained static in boxes with lower moisture percentages. In Boxes 8, 9, 10, and 11, plants became chlorotic and began to wilt before the end of the second period. The same effect was observed on plants in Boxes 5 and 6, but much later.

Figure 18. Wilting period of white birch seedlings in twelve boxes during the fourth experiment.

The first part of this experiment confirmed the results obtained previously (third experiment – Part B), but new facts were observed during the last period of the experiment. Results are presented in Table 7 and Figures 18, 19, 20, 21, 22, 23, and 24.

Table 7. Soil drying and white birch seedlings wilting period in relation with soil temperature and moisture, from September 20 to November 27, 1957

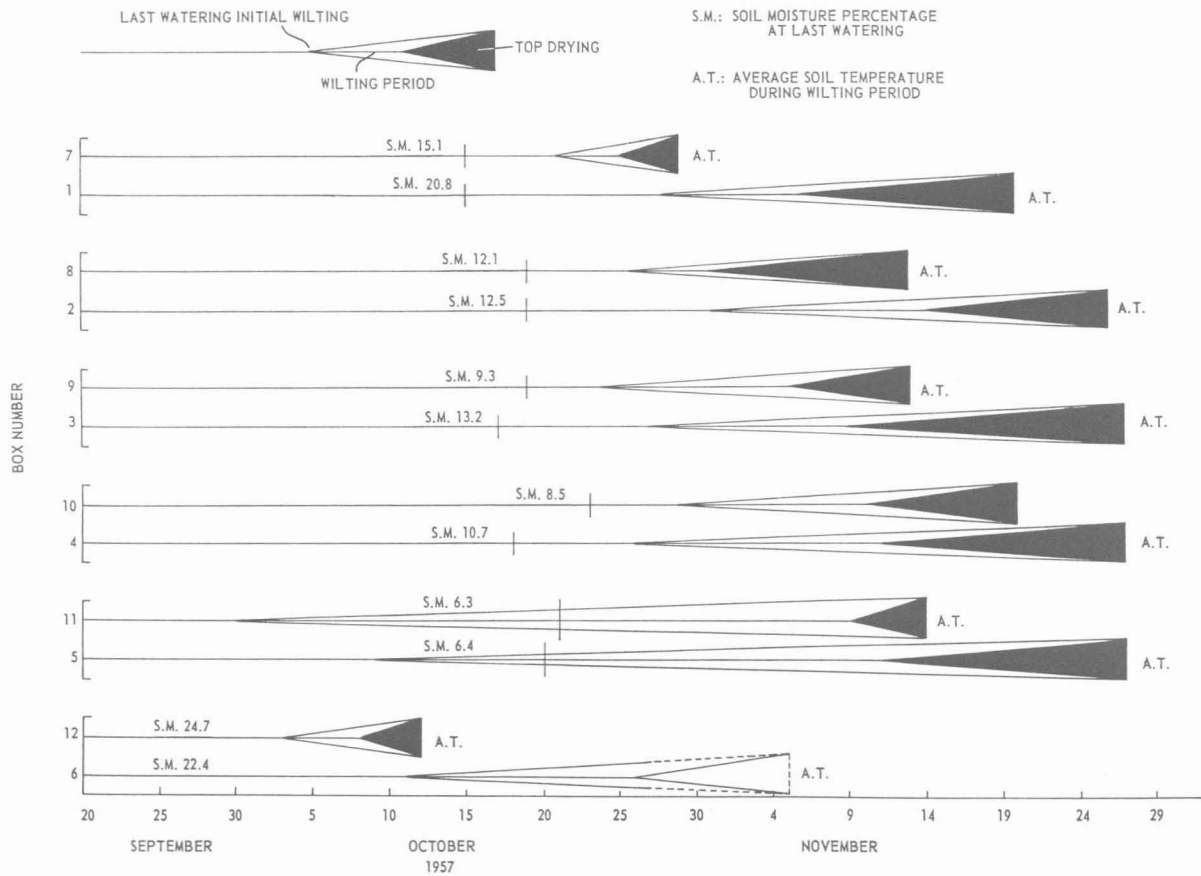| Box no.	Date of last watering	Average soil temperature (°C)			Moisture at last watering (%)			No. of days between last watering and			No. of days of wilting	No. of days difference due to soil temperature	
		7.62cm	12.7cm	2.54cm	7.62cm	12.7cm	2.54cm	Initial wilting top drying	Initial top drying	Last top		since last watering	since initial wilting
7	Oct. 15	20.4	20.5	20.6	15.1	15.6	18.1	6	10	14	8		
1	Oct. 15	15.9	13.8	16.4	20.8	18.8	18.0	13	22	36	23	22	15
8	Oct. 19	20.7	21.1	20.6	12.1	9.1	20.2	7	13	24	17		
2	Oct. 19	16.3	15.5	16.1	12.5	15.5	20.3	12	26	38	26	14	9
9	Oct. 19	20.3	20.6	20.2	9.3	6.7	20.1	5	17	25	20		
3	Oct. 17	15.6	15.0	15.9	13.2	6.3	11.0	8	21	39	31	14	11
10	Oct. 23	20.2	20.5	19.8	8.5	12.8	13.7	6	18	28	22		
4	Oct. 18	15.8	15.0	16.1	10.8	6.9	9.1	3	19	35	32	7	10
11	Oct. 21	20.4	20.1	19.8	6.3	6.8	10.7	-[a]	19	24	45		
5	Oct. 20	16.3	15.4	16.5	6.4	6.1	16.8	-	21	37	51	13	6
12	Sept. 20	20.6	20.7	20.7	24.7	18.0	17.1	12	18	22	10		
6	Sept. 20	15.7	15.4	16.2	22.4	24.5	24.8	21	36	-	-	-	-[b]

a Water was added in Boxes 11 and 5 after the initial wilting.
b Water was added in Box 6 before the last top drying.

In Boxes 6 and 12, soil was left to dry after the last watering on September 20 so that the soil moisture level would be low enough to cause a complete wilting of seedlings. Watering of the other boxes was stopped by groups of two on October 15, 19, 21, and 23. In each box, the initial leaf drooping (I.L.D.), initial top drying (I.T.D.), and last top drying (L.T.D.) were the criteria adapted to measure the effects of drought. The moisture stress condition of the soil was usually determined by the permanent wilting percentage and the ultimate wilting percentage. In this case, the permanent wilting percentage could not be determined because a saturated atmosphere was not applied to the boxes. The ultimate wilting percentage (Taylor et al. 1934, Meyer 1956), being the extreme drought condition where all leaves of a sunflower plant were wilted, represented the end of the wilting range. In this study, the basal leaves were the first to droop and wilt. Wilting extended upward to the last upper leaves and finally to the younger leaves of the terminal bud. When the last little leaf and the stem tip drooped and dried, the last visible drought condition was reached. That stage, however, did not necessarily include the complete death of the plant, as it was found later on. Furthermore, the above phenomena did not occur at the same time on every plant in every box. Therefore, the date of the first sign of leaf drooping was noted. Afterward, the date of top drying of every plant was also recorded until all seedlings were apparently dead.

Figure 19. Soil moisture and temperature, and amount of water added in Boxes #1 and 7 during the fourth experiment.

Figure 20. Soil moisture and temperature, and amount of water added in Boxes #2 and 8 during the fourth experiment.

Figure 21. Soil moisture and temperature, and amount of water added in Boxes #3 and 9 during the fourth experiment.
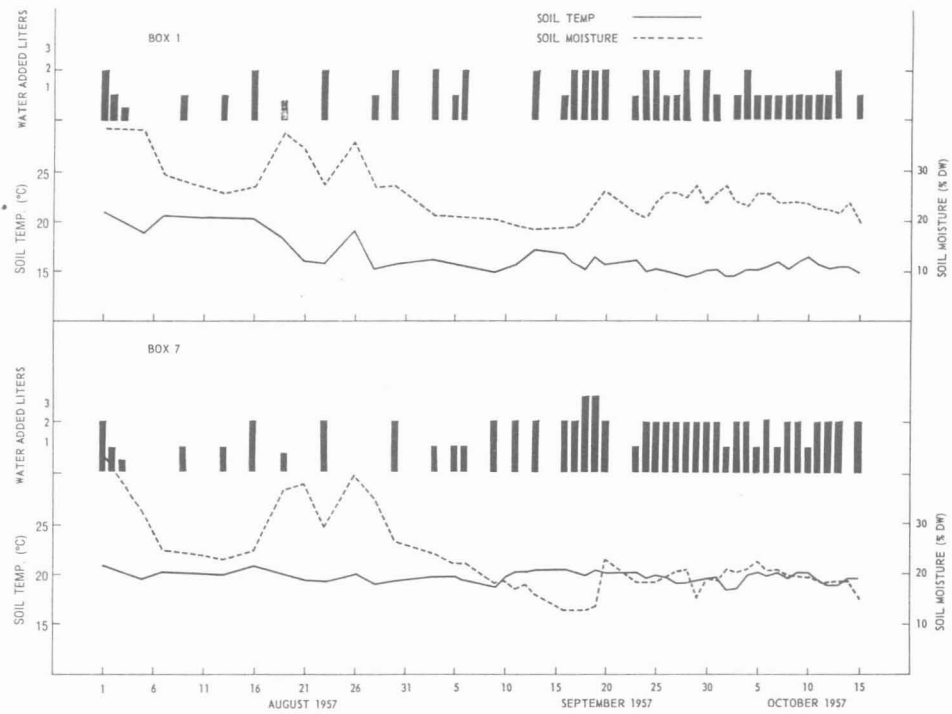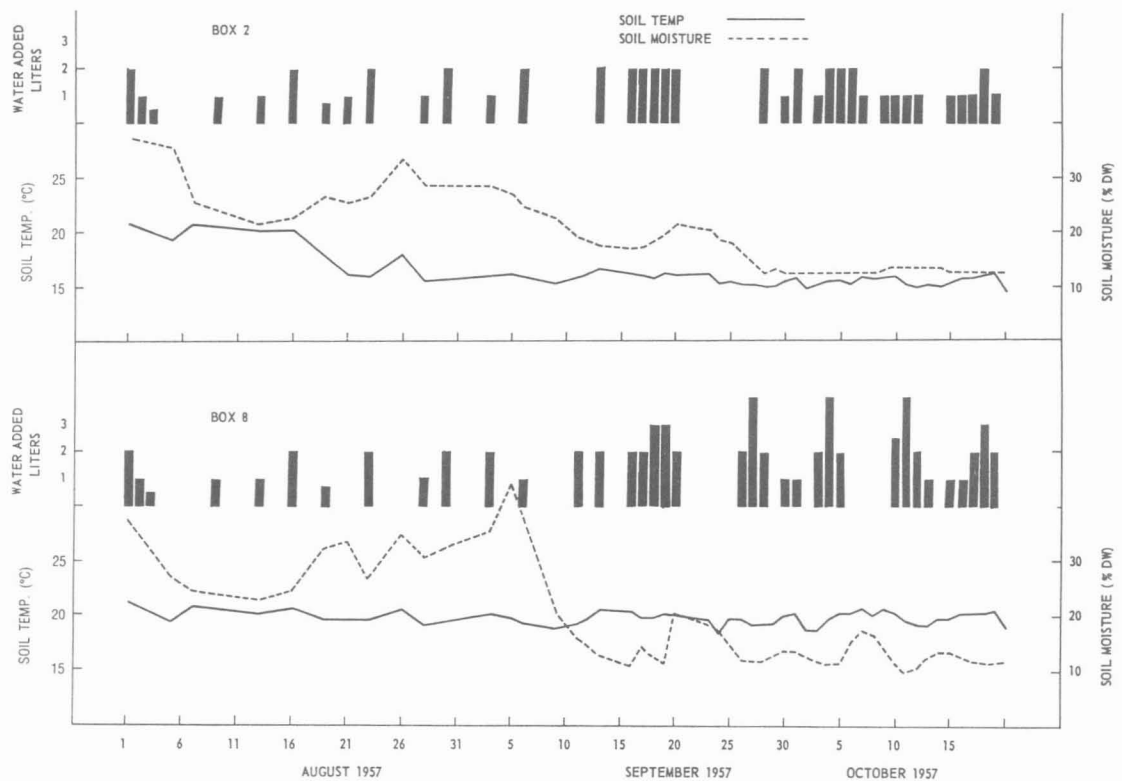

Figure 22. Soil moisture and temperature, and amount of water added in Boxes #4 and 10 during the fourth experiment.
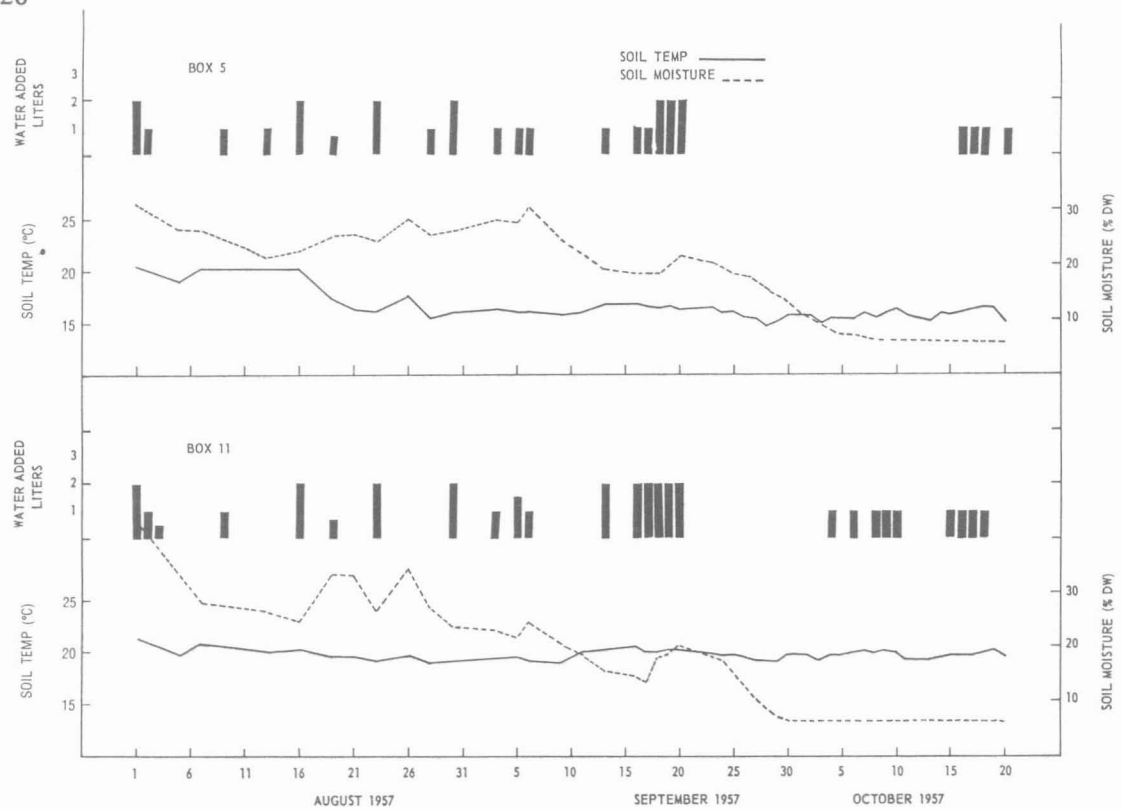
Figure 23. Soil moisture and temperature, and amount of water added in Boxes #5 and 11 during the fourth experiment.
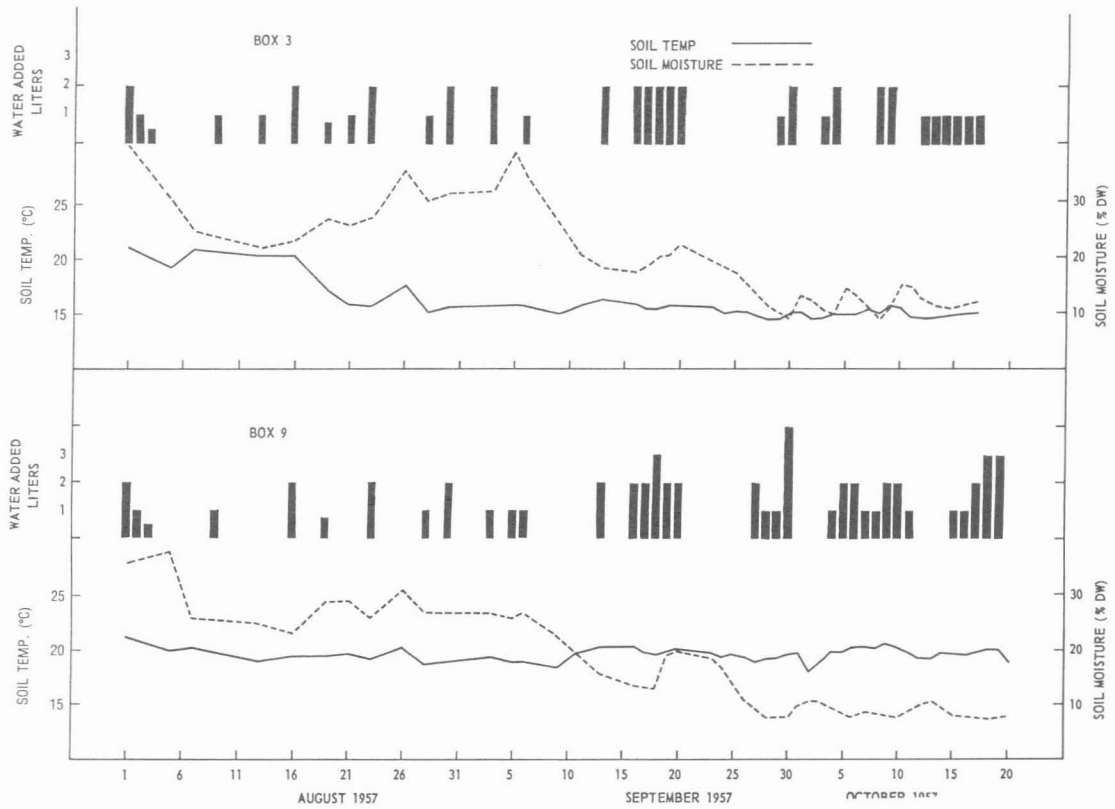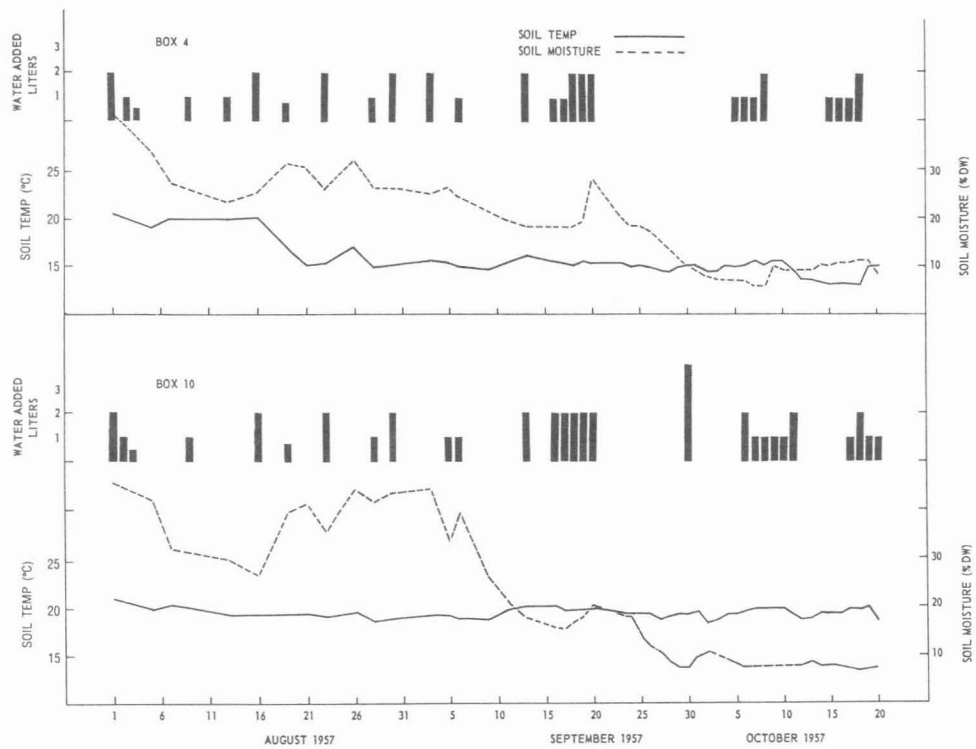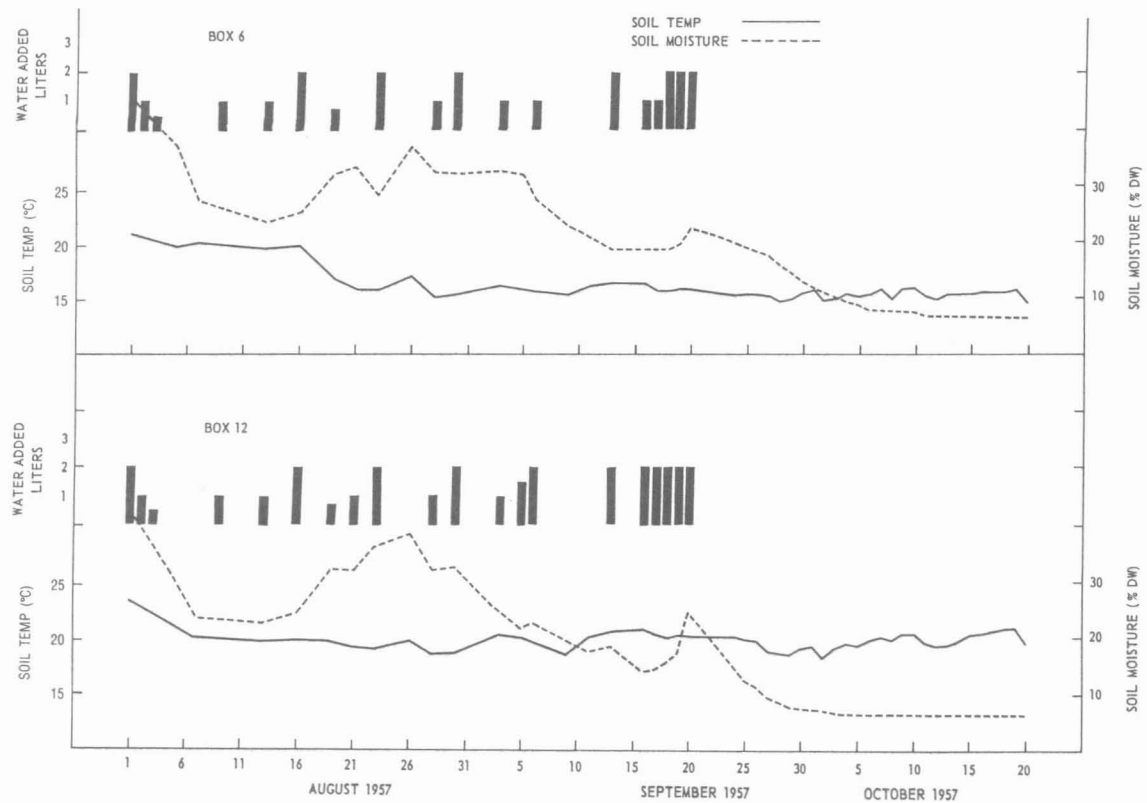

Figure 24. Soil moisture and temperature, and amount of water added in Boxes #6 and 12 during the fourth experiment.

In Figure 25, these milestones are indicated on resistance curves of the fibreglass units (average of four units). The same indications are presented on curves of soil moisture percentages in Figure 26. The wilting period is illustrated in Figure 18. The results, also listed in Table 7, provided the following information:

(1) In the soil used, the first signs of wilting occurred when the soil moisture percentage was lowered to about 7 percent (700 000 ohms).

(2) The first plant with a dried top appeared when the soil moisture was at about 6.4 percent.

(3) Most seedlings were apparently dead at a moisture level of 6 percent or a little lower.

(4) In boxes maintained at about 15.6°C (60°F), the wilting period began from three to nine days later than in those kept at about 20.6°C (69°F).

(5) The length of the wilting period lasted between six and 15 days longer in cool boxes than in warm ones.

(6) The difference in time from the last watering to the first wilting, between cool boxes and warm ones, varied between three and 21 days.

(7) The difference in time between the last watering and the initial top drying ranged between 10 and 36 days, and 39 days at the last top drying.

(8) The wilting period was shorter in boxes kept warm and at a high level of soil moisture than in cool boxes, or in boxes kept at a low soil moisture percentage for a period of about one month.

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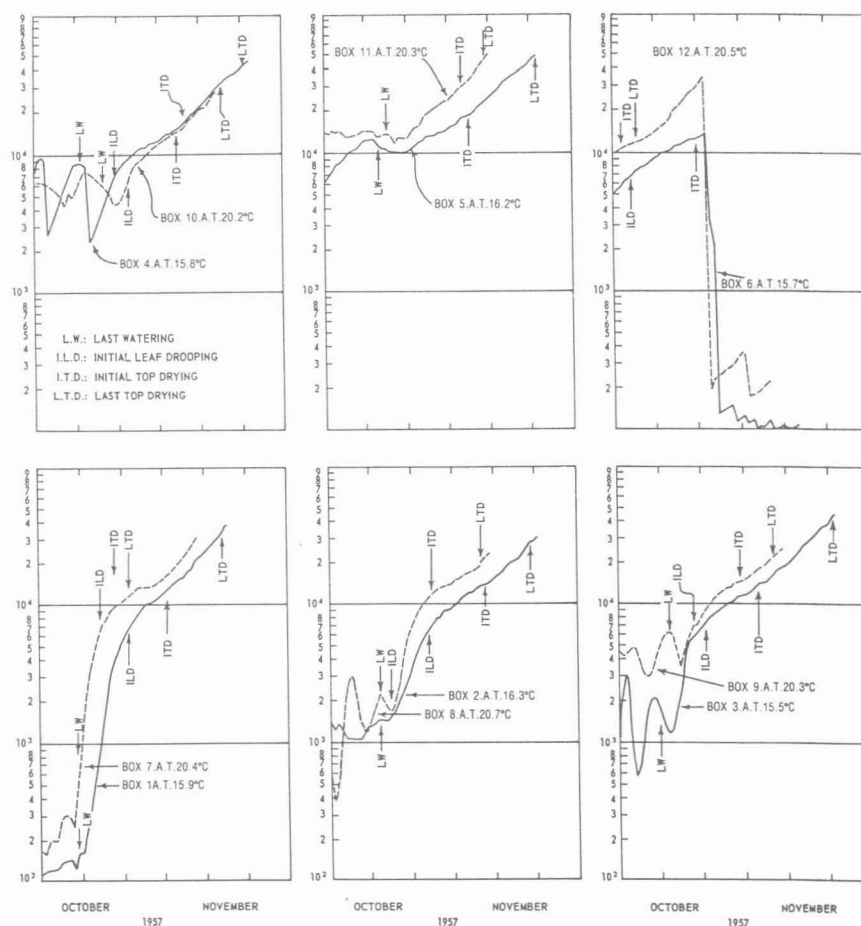
Figure 25. Fibreglass unit resistance (ohms) (average of four units per box) in twelve plant growth boxes.

As well as the above results, this experiment also revealed other interesting facts. In Boxes 6 and 12, the soil was rapidly exhausted of its available water until plants were all dried in Box 12, which had a soil temperature of about 20.6°C (69°F). Eighteen days later, when the first top drying signs were seen on a few plants in Box 6, both boxes were generously watered to bring moisture percentage up to field capacity. Almost one month later, none of the plants in Box 12 had revived. In Box 6, three seedlings did not recover, but the others (Figure 26) resumed their growth. The most interesting occurrence was the production of auxiliary buds below the dead top on three of the plants (Figure 27). Those plants exhibited real dieback symptoms: dead tops with new leaves or shoots growing below the dead part. Partially wilted leaves, and leaves with a variety of necrotic lesions or mottling were also found on affected plants. Sometimes auxiliary buds were produced below the humus line and new shoots were formed.
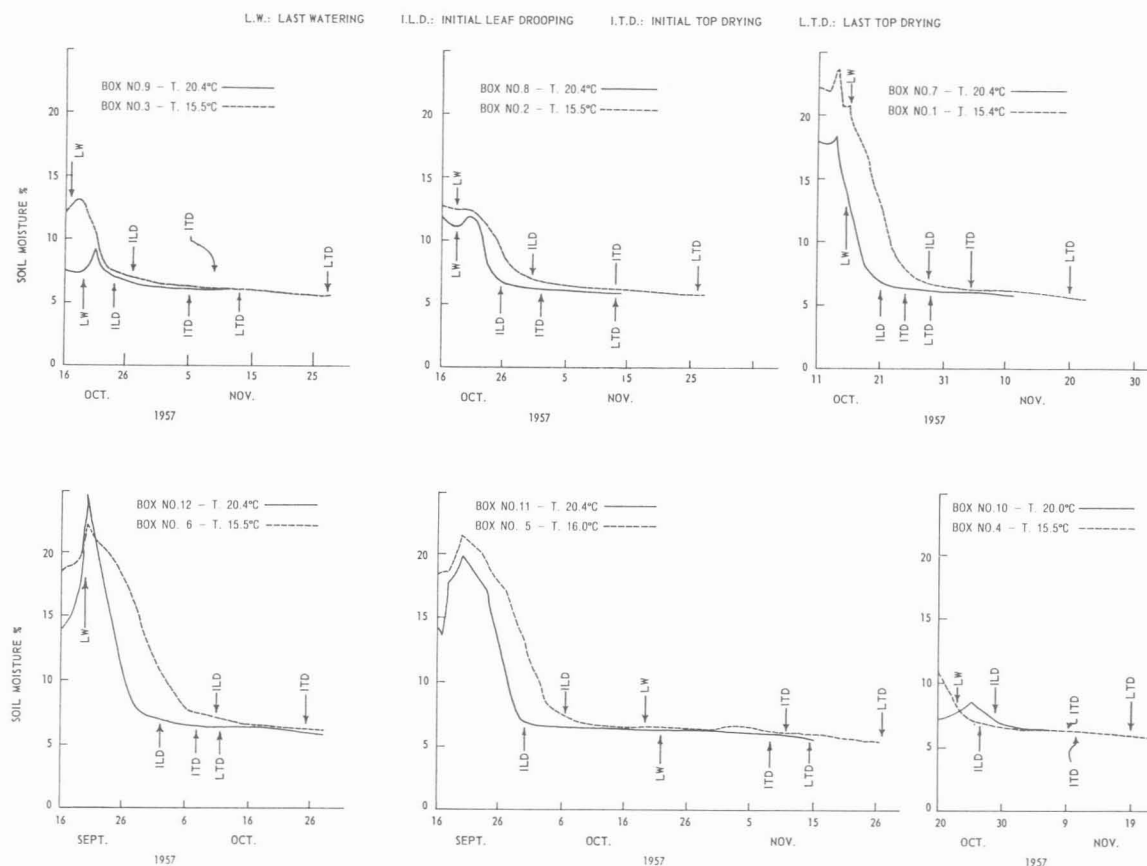
Figure 26. Soil moisture percentage during drying period in twelve plant growth boxes.

These results clearly indicated that white birch seedlings, though apparently dead or showing wilted and even dried tops, could recover from a prolonged soil moisture deficit. Recovery was evidently dependent on the time between top drying and watering. Such a test also demonstrated that plants growing in soil kept at about 20.6°C (69°F) were completely dead when the soil was watered to field capacity 15 days after the last top drying.

In the fourth series of tests, it was not found very useful to redetermine the percentage of dead rootlets in every box since it had previously been shown that significant rootlet dying occurred only in extreme drought and temperature conditions. The depth of rootlet distribution, however, was evidently an important factor in determining how they were affected under field conditions. To that end, four soil cores, 1.91 cm (3/4 in) in diameter, were cut and removed by a tube from every box. Soil cores were cut in 1-cm (3/8 in) sections, and the number of rootlets present at each level was determined with a stereoscopic microscope. Counting of these rootlets did not show that any significant differences were caused by temperature or moisture.

Figure 27. White birch seedlings that recovered from a wilting period before top drying. The lower right picture shows new auxiliary buds low on the stem.

DISCUSSION

The four laboratory experiments carried out on white birch seedlings under controlled soil temperature and moisture conditions yielded very useful information on the behavior of that tree species. During these tests, the method of raising white birch seedlings under artificial conditions, beginning with seed collection, germination, and growth to a height of 40 cm (15.7 in), was modified. The proper handling of equipment and soil moisture units was also determined.

The effects of soil temperature were the first factor considered in three of the experiments. It was found that white birch could grow in soil maintained for quite a long period at 37.8°C (100°F) without being killed although the optimum temperature was located between 20 and 21.1°C (68 and 70°F). Above or below these temperatures, growth was reduced, but seedlings were not killed and rootlets were little affected except when exposed to unusually high temperatures. This, of course, was difficult to reconcile with Redmond's laboratory and field findings on yellow birch. He felt that a rise of 2°C (3.6°F) would increase rootlet mortality on yellow birch to 60 percent, and that a 6 to 7°C (10.8 to 12.6°F) increase would kill all rootlets in 100 days. That statement certainly does not apply to white birch seedlings grown under well-controlled soil moisture conditions, or to plants that showed vigorous growth in our equipment. Where white birch seedlings are concerned, the possible deleterious effects of soil temperature as a single factor unrelated to moisture stress have little importance since high lethal temperatures rarely occur under field conditions.

With regard to soil moisture, a set of tests (third experiment, Part B) showed that white birch seedlings are very sensitive to water deficiency. Growth was considerably reduced in soil kept for almost two months at various moisture levels below field capacity. Complete wilting and apparent wilting occurred when the permanent wilting percentage was passed. This fact was stressed in the fourth experiment, but the main finding of these tests was the importance of soil temperature and the length of wilting and drying periods. A difference of about 5.6°C (10°F) in soil temperature shortens soil drying and wilting periods by as much as 22 days. It was also found that well-developed plants grown under optimum soil temperature and moisture conditions will reach the ultimate wilting point much faster than those grown in soil kept at a low moisture level. Since the first signs of wilting and the ultimate wilting points occurred at a given moisture percentage, the difference in time of wilting was evidently due to the fact that well-developed plants have a greater evaporating power than less active plants with a smaller leaf surface.

The last finding of these experiments concerns the recovery of birch seedlings after a more or less intense wilting. From a preliminary test, it is evident that white birch seedlings may recover even when all leaves are withered and the top is bent and dry. After soil moisture was brought up to field capacity, plants that had only a few flaccid but still living leaves at the top revived almost immediately. A number of seedlings with dry tops produced new side shoots (Figure 27) sometimes quite a bit lower down the stem, and only a few of them did not recover. This very strongly resembles dieback as it occurs naturally in the field. It also suggests that disease symptoms could be reproduced at will in the laboratory or the greenhouse by manipulating the soil moisture conditions. This could also be done in the forest.

The results also show the path to follow for future experiments to be undertaken. For birch and other hardwood tree species, it is important to determine the length of the critical period after which the plant can recover when water is again available. It is also expected that this period varies with soil and air temperatures, moisture, and air turbulence. This last group of environmental factors can be investigated only in the laboratory when rooms with controlled air temperature and moisture are available.

These experimental results suggest that dieback symptoms could be produced by the partial wilting and drying of the foliage during soil moisture stress periods. Such periods would occur when the soil temperature increases during a dry spell. Evidently, hot and dry air would also intensify evaporation, exhaustion of the soil's water supply, and eventually the wilting of trees if rainfall could not restore the soil moisture level. It is also obvious that depth of rooting plays an important role in the phenomenon.

Repetition of such periods of stress for two or more successive seasons is another aspect of the problem. It would therefore be most important to determine when such stress periods occurred in the past, and try to relate such periods to dieback of birch species. The effects of a variety of environmental alterations should also be closely followed in the field.

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APPENDIX 1

Observations on the etiology and cause of dieback on deciduous tree species in Quebec[1]

1. A dieback on black ash (*Fraxinus nigra* Marsh.) in the 1920s was not documented first-hand and knowledge of it was based on memory 20 years after the episode (Pomerleau 1944b). The cause of the dieback in 1925 or earlier may relate to no or little snow accumulation. Climate records should be checked to verify if the winters of 1922 or 1923 were open winters (see Auclair 1989).[2] Dieback symptoms similar to those of the 1920s were evident on white ash, Manitoba maple, and on various ornamental trees in southern Quebec over the 1934-1936 period. Recovery and/or progression of dieback on ash after 1925 was not documented. The dieback in 1934-1936 probably related to events in 1932 affecting sugar maple in southern Quebec and birch species in New Brunswick in the same year.

2. The sugar maple dieback in the 1930s was related to the open winters in 1932 and 1933; deep soil frost (e.g., 1.5 m (5 ft) in depth) in the absence of snow cover resulted in root damage.

3. The birch dieback became severe in Quebec in 1937 and especially over the 1941-1944 period; 1943 and 1944 were probably open winters, but this, as with other years, needs to be verified from climate records. In contrast with New Brunswick, birch trees in Quebec did not show recovery after 1945; in fact, they worsened over the 1946-1949 period. Recovery occurred only in and after 1950.

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1. Based on discussions with Dr. René Pomerleau at his present address, June 23, 1987. Discussions were confirmed in subsequent letter correspondence on Oct. 16, 1987 and Aug. 25, 1988.

2. Auclair, A.N.D. 1989. The variability of snowcover as a factor in forest decline. Proc. of the 46th Eastern Snow Conf., June 8-9, 1989, Quebec, Quebec, Canada.

APPENDIX 2

Comments on the cause of the current dieback of sugar maple in Quebec[1]

Since the end of the summer of 1982, there have been reports in the media on the increased mortality of maples in southeast Quebec. It would seem that the causes, if not new, are at least unknown. In fact, such devastation occurs sporadically in the northeastern regions of North America, and since 1923, I have observed generalized diebacks on ash, maples, birch, and other deciduous species, first in the Bois-Francs area and then throughout southern Quebec from 1934 on.

Concurrent with the major birch decline of 1943 and subsequent years, maple and ash showed the same signs of weakness and died in great numbers. Early on, I understood that insects and other parasites were not the primary cause of these problems and at most attacked only moribund subjects. I was also aware of declines in birch and other deciduous trees that had been left standing after cuts of conifers over large parts of the northeastern U.S., an affliction associated with the sudden exposure of the soil to the sun during the summer. These symptoms also appear along newly opened roads and when circumstances affect the root system. However, the sudden occurrence of generalized decline over vast areas, as was the case after 1943, cannot be explained by local interference, epidemics, or increases in populations of insect pests.

Over this period, I was able to show a close relationship between the intensity of damage and the depth of the root system. This disease is aggravated when the soil is wet or thin as at the top of a hill. Through later research into climatic conditions affecting superficial roots, I came to understand that major declines followed winters where there was no protective blanket of snow (as in 1922, 1942, and especially 1943 and 1944).

We artificially produced these conditions by removing the snow in maple and birch stands after each snowfall. We were able to induce the formation of an ice lense that was more than 1 m deep and a soil vertical displacement of at least 50 cm (19.7 in). When this happens, rootlets are often broken or encased in ice even after the snow thaws, sometimes until the beginning of the growing season. Without a large part of their active root systems, trees cannot absorb water needed for leaf production and growth, and so begin to die at the crown, proceeding downward depending on the severity of the disease. In the worst cases, the

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1. Based on an unpublished article titled "Le dépérissement des érables", January 1983 by René Pomerleau.

afflicted subjects die after a season, or one or two years later, especially if the same conditions recur the following winter. In many other cases, the disease evolves more slowly, and secondary infections prolong the decline until the tree dies. Finally, those that are the least affected recover gradually, developing a new root system and a normal crown once dead branches fall.

In an article published on February 14, 1980, Le Soleil reported that in the village of Saint-Ferdinand d'Halifax (Bernierville), the ground was frozen to a depth of 1.8 m (6 ft), water intakes were plugged with ice, and villagers and agricultural establishments were transporting water from nearby rivers to supply their homes and water their animals.

In a letter to the newspaper, I predicted that the snowless winter would have severe consequences on the forest, on orchards, and even on pastures. This prediction was proved true by the subsequent high mortality of apple trees and by the dieback and death of maples in the Estrie, Bois-Francs, and Beauce regions. Countering or predicting this disease is a difficult if not impossible problem. In theory, improved drainage to lower the water table will favor deeper rooting and prevent the formation of ice lenses that can damage roots or trap them in an icy cement.

APPENDIX 3

The effect of snow removal on the development of dieback in a maple-birch stand in Quebec[1]

Pomerleau's hypothesis, based on extensive field observations of forest diebacks, was that they were caused by the absence of snow cover sufficiently deep to prevent deep soil frost penetration.

To verify his hypothesis that deep soil frost resulted in root damage and mortality, Pomerleau conducted a field experiment to reproduce the effects of snowless winters on soil temperatures and on tree response. Experimental plots were established in September 1953 in a maple-birch hardwood forest on the Université Laval campus (Quebec City), and in September 1954 at the Duchesnay Experimental Forest, 25 km northwest of Quebec City. In each case, a pair of circular plots about 9.1 m (30 ft) in diameter were delimited. All trees in the plots were numbered and described. Coleman thermocouples (fibreglass cells) were placed in the soil at various depths up to 1.27 m (50 in). These were read periodically using a conductivity bridge to give resistance and temperature.

Following this preparation, at each snowfall, the snow in the experimental plot (but not in the control plot) was removed (starting in December and continuing through the spring) and placed around the outside of the plot. The results indicated:

a) Soil freezing extended into the soil to a depth of about 1.27 m (50 in) where the snow had been removed. On the control area, the soil was not frozen after eight weeks or more under the mantle of deep snow; soil temperature at a depth of 2.54 cm (1 in) was 0.3°C (32.5 °F).

b) Ground surface heaving, caused by the formation of ice lenses, was evident to about 45.6 cm (18 in.) above pre-winter soil surface levels on the experimental plot but not on the control.

c) On the experimental plot, but not on the control, soil thaw was abnormally late; soil temperature began to rise in late June, first at the base of the ice lense and then at the soil surface directly beneath the litter.

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d) In places on the experimental plot where the ground had thawed and the surface was depressed, ice was visible, particularly around the tree roots.

e) On the experimental plot, superficial roots and rootlets were frequently broken. Some young birch and maple were falling down because of broken roots.

f) Observations on the condition of trees were continued through August of the following year in each case. By July or August, tree crowns within the experimental plots showed signs of dieback and mortality (Figure 1). Initial composition on the plots at both sites was approximately as follows: sugar maple (+50%); yellow birch (30-35%); white birch, beech, and red oak (15-20%).
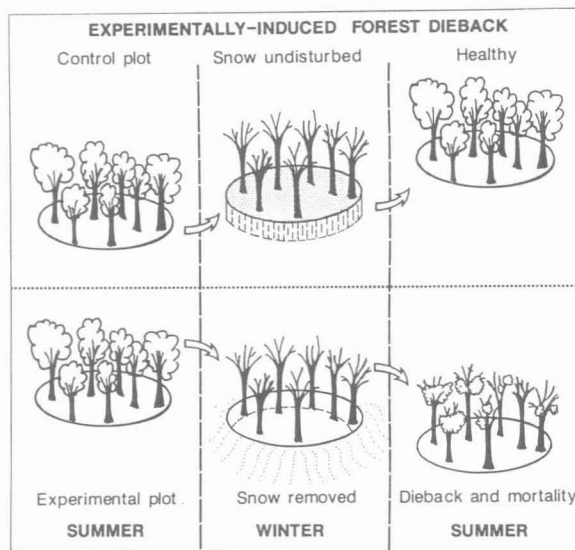

Figure 1. Snow removal experiment conducted in a sugar maple/yellow birch stand from September 1954 through August 1955 at the Duchesnay Experimental Forest, 25 km northwest of Quebec City. Tree conditions, air temperatures, soil temperature to 130 cm, and soil heaving were measured throughout the treatment period on control and experimental plots, each about 10 m in diameter.

Discussion[1]

At the beginning of the 1940s, a wide-scale catastrophe hit the forests of Canada, leading to the death of numberless birches in Quebec and the Atlantic Provinces. I estimated the loss of yellow and white birch at about 1400 million m^3. The distressing spectacle of these trees with their dried crowns, and later the many skeletons showing the presence of the disease, brought the importance of tree diseases in our country to the attention of the public and foresters.

In my research into the causes of this sudden widespread dieback, I demonstrated that this disease could not be attributed to an insect or a parasite such as a fungus, bacterium, or virus despite the findings of most researchers, foresters, entomologists, phytopathologists, and ecologists. Based on numerous detailed observations, I formed the hypothesis that only climatic factors could explain this disaster. Accordingly, I attempted to back this up with well-established experimental findings. The relationship between root depth and the degree of decline observed when soil freezing was artificially induced (either through removal of snow outdoors or the use of invented equipment in the laboratory) led to this explanation. This explanation had not previously been considered and has not since been refuted.

In certain winters (as in 1925, 1932, 1938, and especially in 1942-1944), the soil in northeastern North America had no protective blanket of snow as a result of low precipitation or significant thaws. Consequently, it froze to a depth of 1.27 m (50 in) and the root systems of superficially rooted trees, especially in birches growing on wet or thin soils, deteriorated in the frozen soil because the ice lense raised the roots.

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1. The Discussion was extracted from an updated (1988) curriculum vitae titled "Titres et Travaux de René Pomerleau" in a section on "Principal Bio-ecological Studies: Dieback of birch and other deciduous species".

APPENDIX 4

Acute frost desiccation as a mechanism inducing dieback in birch species in Quebec[1]

A laboratory experiment was performed in the late 1950s to verify the effect that deep soil frost (see APPENDIX 3) concurrent with cold temperatures has on inciting crown dieback. Yellow birch seedlings (about 0.9 - 1.2 m (3-4 ft) in height) were planted in large pots in the spring (May 1958); these were grown through the summer with the pots buried in the soil. In the fall (October 1958), these potted trees were placed above the ground surface and left to freeze so that by winter the soil and the roots had completely frozen. In this condition, the trees were transferred to the lab and placed in an insulated wooden container (about 5.5 m (18 ft) long, 1.2 m (4 ft) wide and 0.76 m (2.5 ft) high, with mineral wool insulation between double walls) divided into six compartments. In each compartment, two potted seedlings were positioned as a pair; the stems in each case protruded through a small hole in the box cover into the air maintained at room temperature. The soil and tree root temperature within the first compartment were maintained at room temperature. In each successive compartment, the cover was removed after 5, 10, 15, 20, and 30 days, respectively, the soil temperature being kept below 0°C (32 °F) by a freezing element. The results were:

a) In the first and second compartments, completely normal green foliage developed.

b) In compartments held at 10, 15, and 20 days of soil frost, dieback in the foliage appeared through the course of the experiment and became increasingly intense.

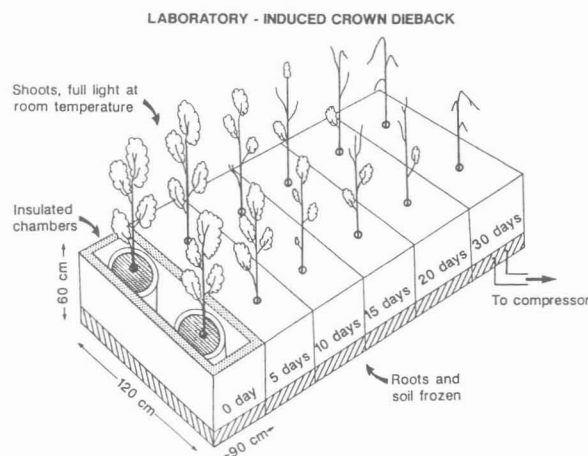c) In the compartment with 30 days of soil frost, the seedlings had died by the end of the experiment (Figure 2).

Figure 2. Laboratory acute frost desiccation experiment conducted on six pairs of yellow birch seedlings. While shoots were maintained at room temperature under fully lighted conditions, soil and roots were maintained below 0° C over periods varying from 0 to 30 days. Increasingly severe dieback and mortality occurred with 10 days or more of soil frost.

1. Based on discussions with Dr. René Pomerleau at his present address, June 23, 1987. Discussions were confirmed in letter correspondence on October 16, 1987 and August 25, 1987.

Conclusion: Results indicated that trees with roots embedded in frozen soil are killed by desiccation when the crown is subject to summer-level temperature and light conditions for sufficiently long periods. The primary mechanism of dieback in hardwoods is aberrant winter climate, specifically cold air temperatures (below root frost-resistance thresholds) concurrent with the lack of sufficient winter snowcover to prevent the development of deep soil frost; this results in both root mortality and in desiccation of trunk and crown in the spring. In future studies, the moisture content of the trunk, branches, and leaves under conditions of deep soil frost need to be measured with appropriate equipment not available in the above field and laboratory experiments.

APPENDIX 5

List of selected publications on the dieback of deciduous tree species in Quebec[1]

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Pomerleau, R. 1953d. Spread vs. intensification on dying in hardwood species in Quebec. Pages 50-51 *in* Rept. of the Symp. on Birch Dieback, Can. Dept. of Agric., Ottawa, Ont.

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1. Abstracted from updated (1988) curriculum vitae entitled "Titres et travaux de René Pomerleau".

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