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A Study of the Mechanisms and Suppression of Evaporation of Water from Soils

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Texas Water Resources Institute

Texas A&M University

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A STUDY OF THE MECHANISMS AND SUPPRESSION OF EVAPORATION OF WATER FROM SOILS

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Preface

This report concludes Project B-002-TEX of the Texas A&M University Water Resources Institute. Some of the research has been published. Reprints of future publications on this project will be supplied to OWRR as soon as they are available.

Appreciation is expressed to Dr. O. C. Wilke for his suggestions on the project and to Dr. J. R. Runkles, who has furnished much advice and assistance.

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Abstract

Extensive greenhouse experiments were conducted to evaluate chemicals not previously studied extensively for their potential as evaporation suppressants. Included in the studies were crude oil, anionics, cationics, nonionics, silicones, polysaccharide-gum mixtures, oil-latex mixtures, fatty alcohols, and reflectance materials. Of these compounds, only crude oil and crude oil-cationic mixtures were effective in suppressing soil water evaporation significantly when applied to smooth Olton loam wet soil surfaces. The cationics apparently acted as a bond between the cation exchange capacity of the soil. Rates of crude oil studies were 473 l/ha (50 gal/acre) to 9460 l/ha (1000 gal/acre). In some cases the crude oil affected emergence of tomatoes and onions, but did not affect the emergence of cucumbers.

More extensive studies were conducted in controlled environment facilities to determine the mechanisms of suppression by crude oil and to delineate the influence of various soil surfaces and environmental parameters on the effectiveness of the crude oil-treated surfaces. Rates studied included 946, 2038, and 4730 l/ha (100, 300, and 500 gal/acre). Two mechanisms of suppression are apparently involved when crude oil is applied to a smooth wet soil surface. Immediately following application, the mechanism is the same as that when oil is applied to a free water surface. Following this an increase in evaporation occurs, but the rate is much less than that from an untreated soil surface indicating the formation of a

barrier which slows down the movement of liquid water to the soil surface.

The crude oil was most effective on smooth wet soil surfaces and least effective on rough dry surfaces. Crude oil-treated surfaces were effective against wind speeds up to 6.5 m/sec (15 mph) for 3-4 days at rates as low as 946 l/ha (100 gal/acre). As soil temperature was increased from 10° C. to 38° C., crude oil-treated surfaces were less effective in suppressing evaporation due to the increased vapor pressure of the soil water. Varying the light intensity from 0.15 to 0.60 Langleys/min did not influence the evaporation from crude oil surfaces in the controlled environment chamber. This is not surprising since it is net radiation, not solar radiation, which is a part of the energy balance. As was expected, the evaporation losses increased as the vapor pressure deficit of the air was increased from both the untreated and crude oil-treated surfaces.

Field studies to evaluate the practical potential of crude oil in the field were disappointing. Crude oil was sprayed at the rate of 2838 l/ha (300 gal/acre) and floated at rates of 473 to 1892 l/ha (50 to 200 gal/acre) on the surface of irrigation water to apply it to soil surfaces in cotton during the growing season. A savings of moisture due to the application of crude oil was noted. However, there was no consistent increase in the yield of cotton.

Crude oil appears to be an effective evaporation suppressant when applied to a smooth wet soil surface. Further, it is most effective immediately after water applications when the soil water evaporation rate is the highest, and the most economical material reported to date ($3 - $18 per acre or $.06 a gallon for material). However, the application of crude oil to a smooth wet soil surface immediately following water applications is a major problem.

During the field studies, it was noted that rain failed to penetrate the crude oil surface when the land was sloping. This finding is being investigated in another project on the use of crude oil as an aid in water harvesting.

CHAPTER I

INTRODUCTION

The magnitude and importance of evaporation of soil water in arid and semi-arid areas is well known. Studies indicate that up to 99 percent of the precipitation in the Great Plains region may be lost from soil water evaporation (5).

Since the process is irreversible and invisible, it is difficult to investigate. Consequently, the physical processes and mechanisms of evaporation suppression by the various techniques are not completely understood. The soil and atmospheric parameters which influence evaporation are all varying at the same time in the field. Consequently, it is difficult to examine the separate influences of each variable on evaporation. Scientists use controlled environment facilities to overcome this difficulty and thereby save time in field testing suppressants by delineating the conditions under which particular suppressants will be effective.

Materials which will suppress soil water evaporation and are economical to use are currently not available except for relatively small acreages of high value crops. Since evaporation is a major consumer of water in the Southern High Plains of Texas during periods immediately following rainfall and irrigations, it was deemed worthwhile to undertake a study of possible new approaches to suppressing soil water evaporation. The study was divided into three phases: (1) Greenhouse studies to evaluate a large number of compounds and materials not previously investigated as to their potential as evaporation suppressants, (2) Studies in a controlled environment of the more promising compounds and materials from the greenhouse studies to delineate the mechanisms of suppression and the soil and aerial environment conditions under which they would suppress evaporation and (3) Field studies to evaluate the more promising materials from the controlled environment studies.

During the initial screening of potential evaporation suppressants, it was found that crude oil was effective in suppressing evaporation of water from soil. Since this fact had not been previously reported, deviations were made from the initial proposal so that the phenomena could be investigated in more detail. It is the purpose of this report to present the results of these investigations.

CHAPTER II

GREENHOUSE STUDIES

Most greenhouse studies are rather empirical in nature in that environmental conditions are not usually well controlled or in many cases even recorded. However, such studies can be used to investigate major differences due to a treatment. The reasons for major differences can then be studied in more detail under controlled conditions. Using the greenhouse to experiment with major parameters, one can make better use of the facilities involved in the controlled environment. For these reasons, it was decided to undertake a series of greenhouse experiments to screen various materials which had received little testing to determine their potential as soil water evaporation suppressants. It is the purpose of this section of the report to present the results of these experiments.

Methods and Materials

Black polyethylene containers, 20 centimeters in diameter and 18 centimeters tall, were filled with soil from the 0-15 centimeter surface layer of an Olton loam soil to a bulk density of approximately 1.35. Soil in the containers was saturated by allowing the containers to stand in water for 4 hours. The containers were then covered with polyethylene and allowed to drain. Evaporation was determined by weighing the pots periodically following the application of the treatments of the different experiments indicated in Tables 1, 2 and 4-9.

The temperature in the greenhouse varied from 15.6° to 30.0° C. (60-85° F.) and the relative humidity from 30 to 60 percent. No attempt was made to correlate the atmospheric and soil conditions with soil water evaporation and plant growth.

At the end of the second experiment, the moisture content of the surface layer and the lower layer of soil in each pot was determined gravimetrically. Estimates of soil strength were made by determing the amount of pressure required to push a penetrometer 2.5 cm into the surface of the treatments. Three penetrometer measurements were made in each pot.

Results and Discussion

Experiment 1 - Evaluation of Crude Oil, Surface Active Chemicals, Silicones, Latex, and Polysaccharide-gum Mixtures as Evaporation Suppressants.

All treatments in Experiment 1 are listed in Table 1. Cumulative evaporation loss for the crude oil-treated containers are shown in Figure 1. All treatments which contained crude oil had slower initial rates of evaporation. There was little difference during the first 8 days between the 1419 and 4730 l/ha of crude oil in decreasing evaporation. This suggests that crude oil rates less than 1419 l/ha may decrease evaporation. The addition of an anionic at the rate of 90 kg/ha to the 1419 l/ha rate of crude oil further decreased the rate of evaporation. Since no positive results were obtained when the anionic was added alone (Figure 2), it appeared that the anionic served as a penetrating agent for the oil. However, this was not a closely controlled test and further testing was necessary before any statements could be made concerning the crude oil-anionic mixtures. Data for the cumulative evaporation data of all treatments are located in Table A-1 of the Appendix. It can be readily seen that the only materials which significantly decreased soil water evaporation were those discussed above. Polyethylene oxides are water soluble nonionics which may form films that will not absorb moisture at humidities less than 80 percent. The materials were included in this study to see if solutions of the material would form a film on the soil surface which would decrease evaporation. However, none of the materials or mixtures of the materials decreased evaporation.

Table 1. Treatments evaluated in Greenhouse Experiment 1.

Treatment	Rate Per Hectare
A - Crude oil[1/]	1419 l
B - Crude oil	4730 l
C - Crude oil and anionic[2/]	1419 l and 90 kg
D - Control	none
E - Polyethylene oxide (Type I)[3/]	45 kg
F - Polyethylene oxide (Type I)	180 kg
G - Polyethylene oxide (Type II)[4/]	45 kg
H - Polyethylene oxide (Type II)	180 kg
I - Polyethylene oxide (Type III)[5/]	45 kg
J - Polyethylene oxide (Type III)	180 kg (applied as a powder)
K - Control	none
L - Silicone (Type I)[6/]	45 kg
M - Silicone (Type I)	180 kg
N - Silicone (Type II)[7/]	45 kg
O - Silicone (Type II)	180 kg
P - Polyethylene oxide (Type I) & Silicone (Type I)	45 kg and 45 kg
Q - Polyethylene oxide (Type I) & Silicone (Type II)	45 kg and 45 kg
R - Polyethylene oxide (Type I) & Pseudo-plastic polysaccharide	45 kg and 45 kg
S - Polysaccharide-gum Mixtures[8/]	45 kg
T - Polysaccharide-gum Mixture & Silicone (Type I)	45 kg and 45 kg
U - Polysaccharide-gum Mixture & Silicone (Type II)	45 kg and 45 kg
V - Oil-latex Mixture[9/]	1182 l
W - Anionic	90 kg
X - Hexadecanol[10/]	180 kg
Y - Control	none

Footnotes on next page

Table 1. Treatments evaluated in Greenhouse Experiment 1. (Footnotes)

1/ Crude oil from the Anton-Irish oil field courtesy of Service Pipe Line Co., Lubbock, Texas.

2/ Petro®-S (alkylnapthalene sulfonate) manufactured by Petro Chemicals Co., 1825 East Spring Street, Long Beach, California.

3/ Polyox WSR N-80 manufactured by Union Carbide Corporation, Chemicals and Plastics Development Division, New York, N. Y.

4/ Polyox WSR 35 manufactured by Union Carbide Corporation, Chemicals and Plastics Development Division, New York, N. Y.

5/ Polyox Coagulant manufactured by Union Carbide Corporation, Chemicals and Plastics Development Division, New York, N. Y.

6/ Silicone R-20 manufactured by Union Carbide Corporation, Silicones Division, New York, N. Y.

7/ Silicone R-28 manufactured by Union Carbide Corporation, Silicones Division, New York, N. Y.

8/ Dacagin manufactured by Diamond Alkali Corporation, Cleveland, Ohio.

9/ Unisol 91 manufactured by the International Synthetic Rubber Co. Ltd., Brunswick House, Brunswick Place, Southhampton, England.

10/ Hexadecanol, practical grade, J. T. Baker Chemical Co., Phillipsburg, New Jersey.

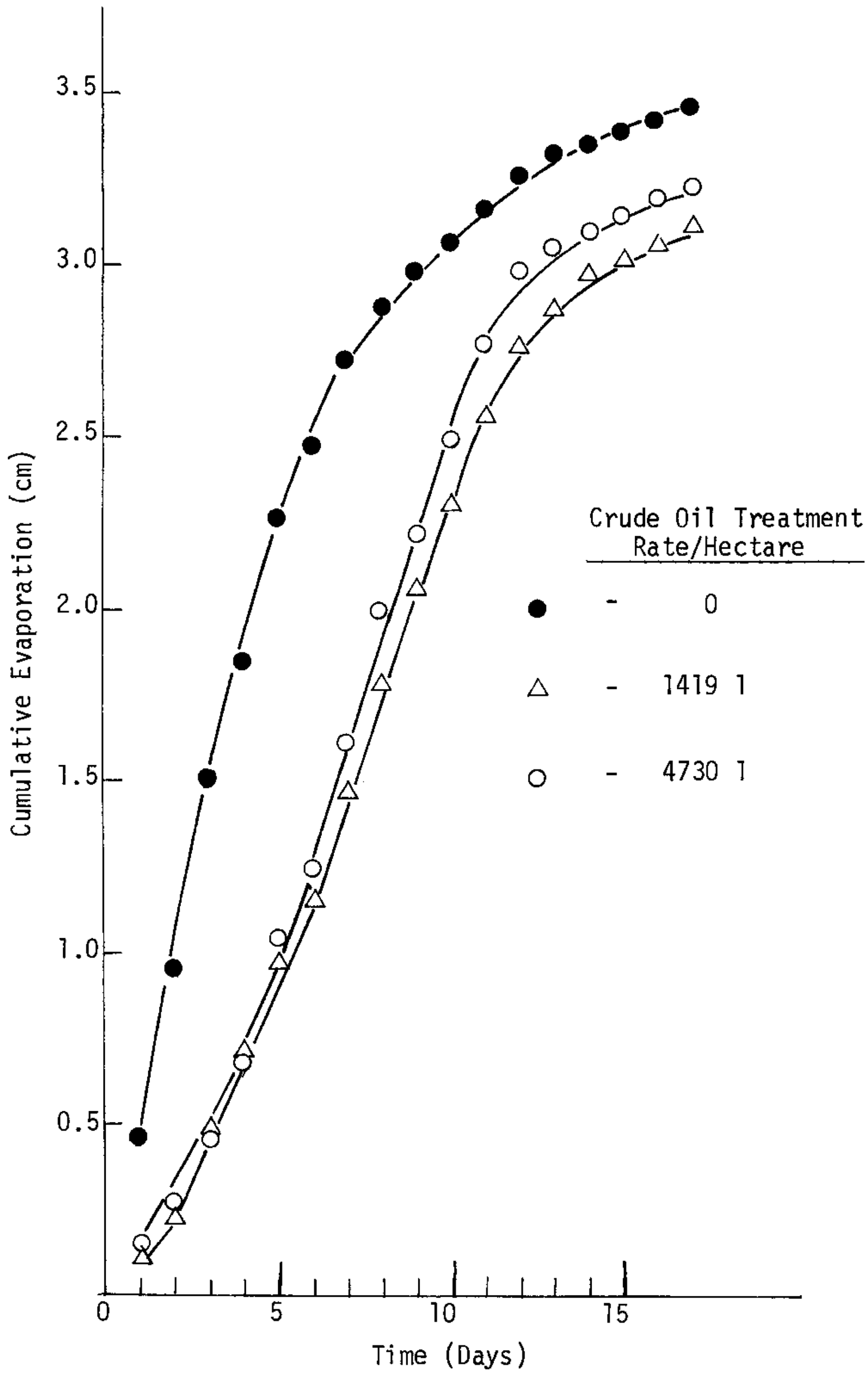

Figure 1. Cumulative evaporation from Olton loam soil treated with crude oil.

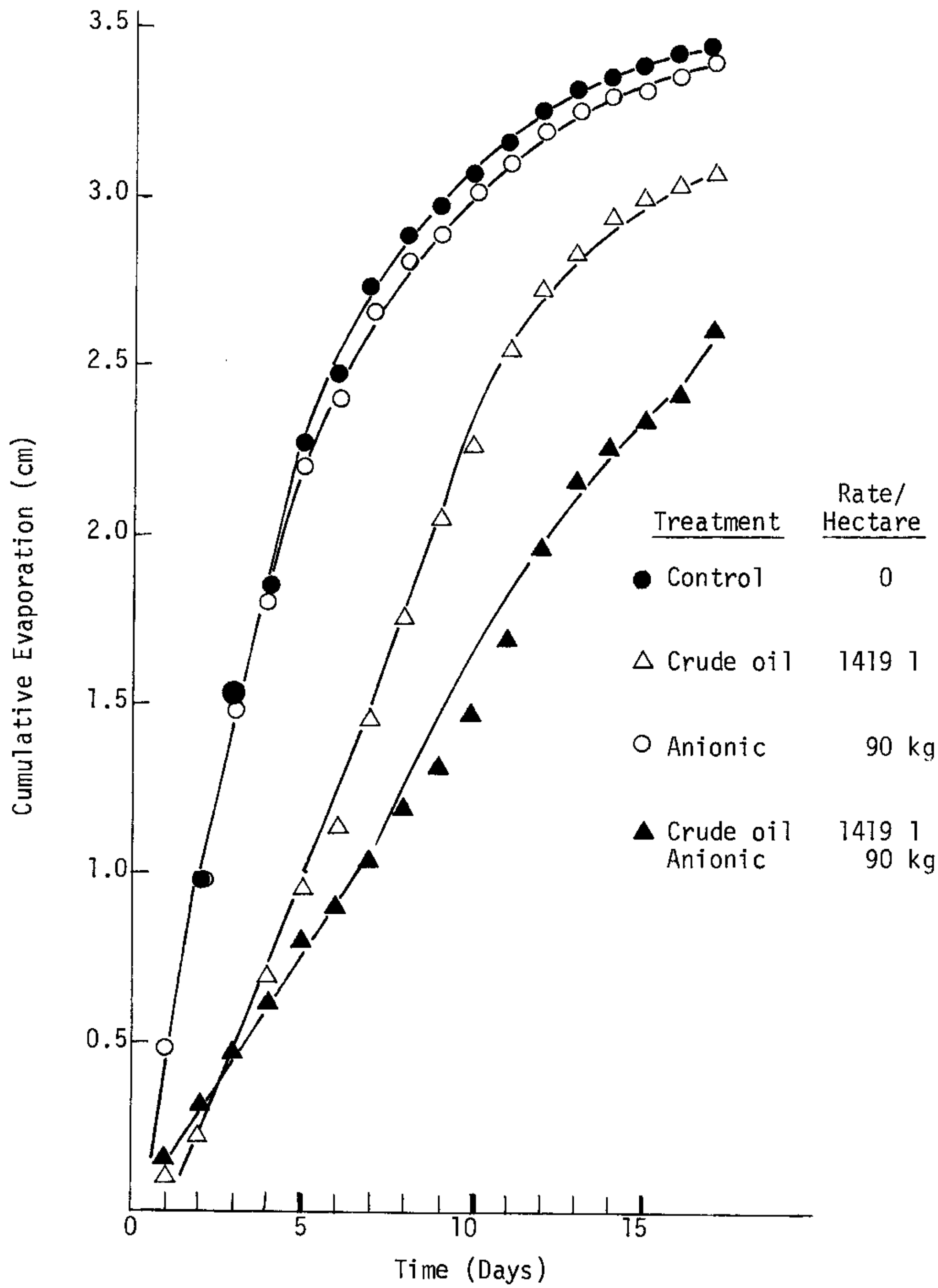

Figure 2. Cumulative evaporation from Olton loam soil treated with crude oil, an anionic, and crude oil-anionic mixture.

Myers (9) has reported that silicones make soil surfaces water repellent in his water harvest studies. They were included in this study to see if they would make water surfaces water repellent and reduce evaporation. However, none of the materials or mixtures of the materials were effective in reducing evaporation.

Polysaccharide-gum mixtures are inert spray gel agents that are used to reduce physical spray drift. The materials were used in this study to see if they would aid other compounds in reducing evaporation. The materials did not aid in decreasing the evaporation rate.

Oil-latex mixtures have been used throughout the world in vegetation establishment in sandy soils. It is thought that one of the reasons they were effective is their ability to suppress evaporation. However, the mixture did not suppress evaporation in this study.

Fatty alcohols and surfactants have been reported by Law (7) and others to suppress evaporation from sand and sandy loam soils. They were not effective in suppressing evaporation from the loam soil used in this study. As indicated by Law, the materials are less effective as the clay content is increased. It is probable that evaporation suppression with these soils would require higher rates of the fatty alcohols and surfactants.

Experiment 2 - Further Evaluation of Crude Oil and Surface Active Chemicals as Evaporation Suppressants.

In Experiment 1, the major decrease in soil water evaporation occurred in containers treated with crude oil. Some further suppression was obtained when a surface active chemical (anionic) was added to the crude oil. It was, therefore, decided to undertake a study involving the crude oil and the three major groups of surface active agents; anionics, cationics, and nonionics, to see if further suppression of evaporation could be obtained by mixing the materials with crude oil.

The various mixtures used are shown in Table 2. Cumulative evaporation curves of the treatments treated with crude oil and surface active chemicals separately are shown in Figure 3. There was increased suppression due to crude oil as the rate of crude oil application was increased. Only the cationic of the surface active chemicals was effective in decreasing evaporation where it was used alone. Of the mixtures of surface active agents and crude oil, only the crude oil-cationic mixture decreased evaporation over crude oil alone (Figure 4). The evaporation loss of the crude oil-anionic loss was about the same as crude oil alone while the loss from the crude oil-anionic mixture was greater than the crude oil alone. Mixtures of the cationic with 473 l/ha of crude oil were not as effective as mixtures of the cationic with 1419 l/ha of crude oil in further decreasing evaporation. (Table A-2, Appendix)

To further delineate some of the differences between the treatments, the moisture content of the surface 15 cm layer and the volume

Table 2. Treatments evaluated in Greenhouse Experiment 2.

Treatment	Rate Per Hectare
A - Control	
B - Crude oil[1/]	473 l
C - Crude oil	1419 l
D - Anionic[2/]	90 kg
E - Crude oil + anionic	473 l + 90 kg
F - Crude oil + anionic	1419 l + 90 kg
G - Cationic[3/]	71 l
H - Crude oil + cationic	473 l + 71 l
I - Crude oil + cationic	1419 l + 71 l
J - Nonionic[4/]	71 l
K - Crude oil + nonionic	473 l + 71 l
L - Crude oil + nonionic	1419 l + 71 l

1/ Crude oil from the clear fork formation in the Anton-Irish oil field courtesy of Service Pipe Line Co., Lubbock, Texas.

2/ Petro® - S (alkylnapthalene sulfonate) manufactured by Petro Chemicals Co., 1825 East Spring Street, Long Beach, California.

3/ Hyamine 3500 (n-alkyl dimethyl benzyl ammonium chloride) manufactured by Rohm and Haas Company, Independence Mall West, Philadelphia, Pennsylvania.

4/ Tergitol Nonionic TMN (Trimethyl nonyl ether of polyethylene glycol) manufactured by Union Carbide Chemicals Co., New York, N. Y.

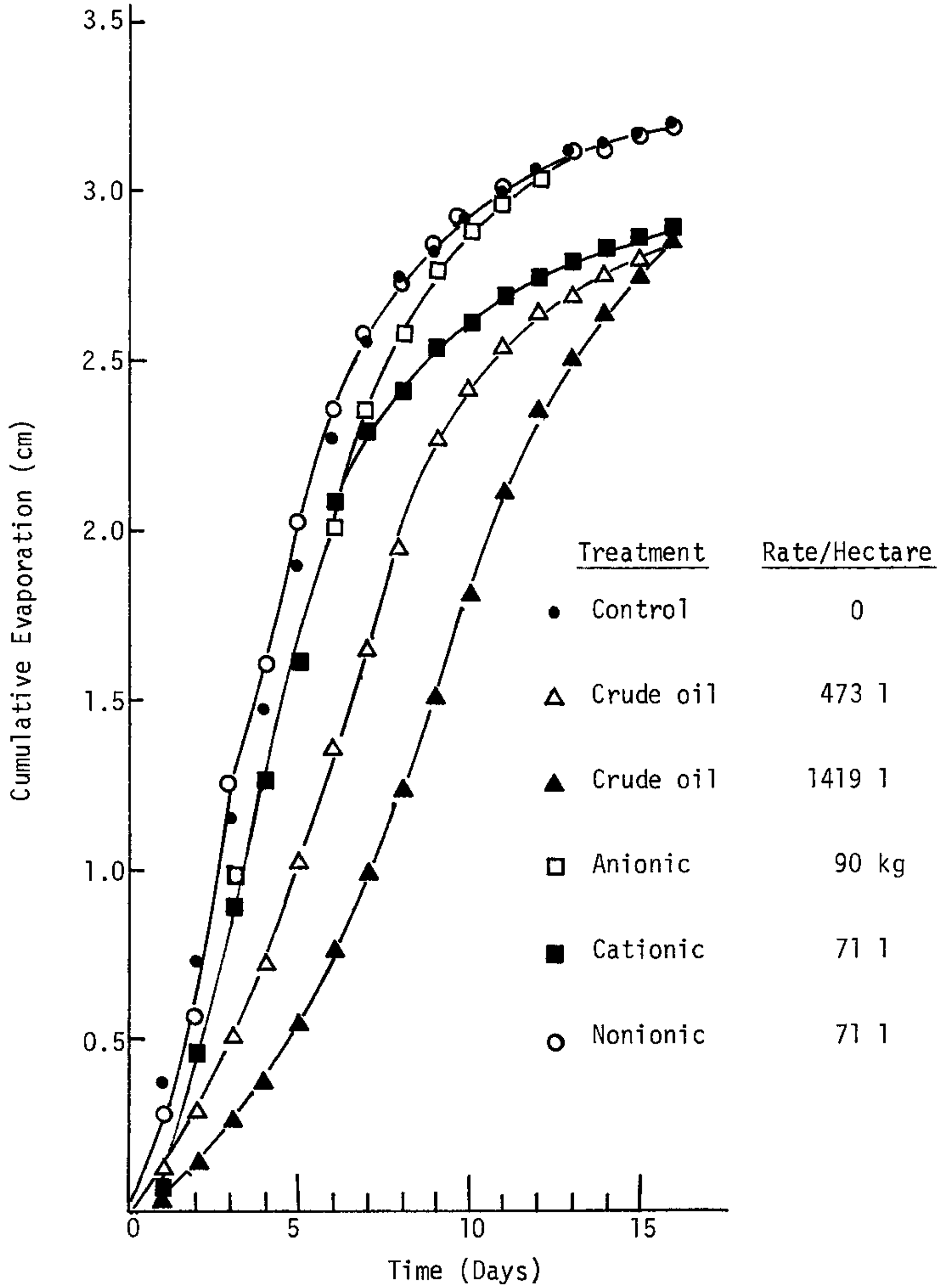

Figure 3. Cumulative evaporation from Olton loam soil treated with crude oil and surface active agents.

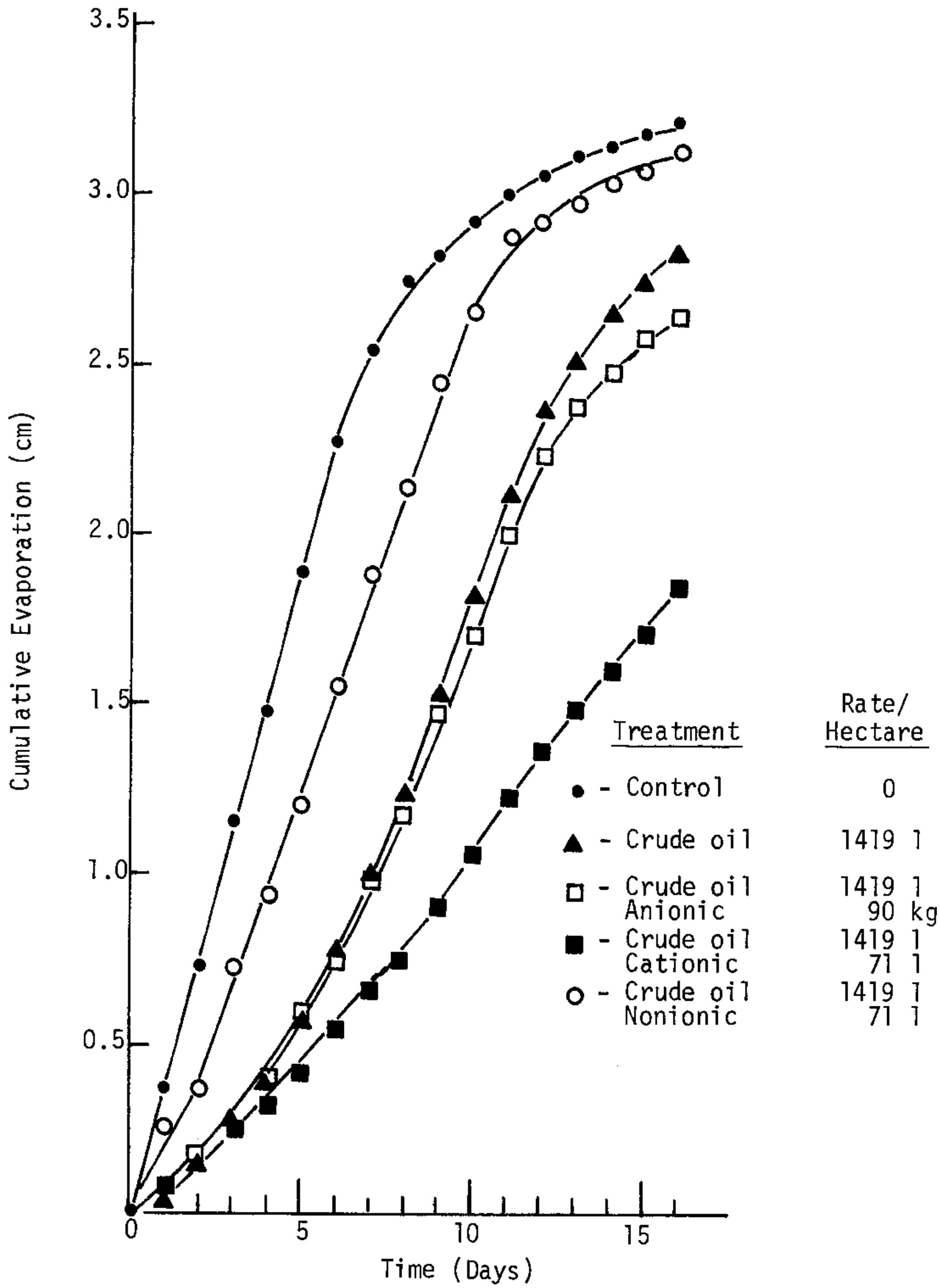

Figure 4. Cumulative evaporation from Olton loam soil treated with crude oil and mixtures of surface active chemicals and crude oil.

below the surface were determined. Estimates of the soil strength of the surface 15 cm were made by determining the amount of pressure required to push the penetrometer 15 cm into the surface of each pot in 3 locations. The data obtained from these experiments were rather erratic (Tables 3 and 4). There was a trend, however, for the containers which had the highest moisture contents and lowest penetrometer values to have low evaporation rates.

Table 3. Moisture content of the different soil layers from pots treated with various evaporation suppressants in Greenhouse Experiment 2.

Treatment Per Hectare	Percent Moisture Surface Layer	Percent Moisture Lower Layer
1419 l crude oil + 71 l cationic	25.37	23.65
1419 l crude oil + 18 kg anionic	16.13	16.69
1419 l crude oil + 14 l cationic	15.38	19.48
71 l nonionic	7.61	16.16
473 l crude oil + 90 kg anionic	7.40	18.11
473 l crude oil + 18 kg anionic	7.32	16.15
473 l crude oil + 14 l cationic	6.38	17.45
473 l crude oil + 71 l nonionic	5.51	16.45
473 l crude oil + 71 l cationic	5.32	15.01
71 l cationic	5.26	17.14
473 l crude oil + 71 l nonionic	5.22	17.15
473 l crude oil + 14 l nonionic	4.98	19.44
473 l crude oil	4.63	18.65
90 kg anionic	4.52	16.06
1419 l crude oil + 90 kg anionic	4.35	15.97
1419 l crude oil + 14 l nonionic	4.24	15.81
Control	4.10	16.31
473 l crude oil	DATA NOT AVAILABLE	

Table 4. Penetrometer readings of soils treated with various evaporation suppressants in Greenhouse Experiment 2.

Treatment Per Hectare	Average Penetrometer Reading* (g/cm^2)
1419 l crude oil + 71 l cationic	129
1419 l crude oil + 18 kg anionic	308
1419 l crude oil + 14 l cationic	392
71 l nonionic	545
473 l crude oil + 90 kg anionic	584
473 l crude oil + 18 kg anionic	640
473 l crude oil + 14 l cationic	674
1419 l crude oil + 71 l nonionic	697
473 l crude oil + 71 l cationic	715
71 l cationic	738
473 l crude oil + 71 l nonionic	750
473 l crude oil + 14 l nonionic	761
1419 l crude oil	794
90 kg anionic	844
1419 l crude oil + 90 kg anionic	1090
Control	1119
1419 l crude oil + 14 l nonionic	1190
473 l crude oil	DATA NOT AVAILABLE

* Each value is an average of 6 measurements.

Experiment 3 - Evaluation of Crude Oil and Crude Oil-Cationic Mixtures as Evaporation Suppressants.

From the previous 2 experiments it was found that crude oil was an effective evaporation suppressant. Further, in the second experiment a mixture of crude oil and a cationic was more effective than crude oil alone. Since there are a large number of different cationics manufactured by the different commercial firms, an experiment was undertaken to determine the effect of different crude oil-cationic mixtures on soil water evaporation.

Treatments used in the experiment are indicated in Table 5. Data for all treatments of this experiment are located in Table A-3, Appendix. There was some evaporation suppression in the treatments using cationics alone. (Figure 5). The suppression was much greater, however, when the cationics were mixed with crude oil. (Figure 6). The most effective evaporation suppression occurred in containers treated with a mixture of crude oil and Hyamine 3500. Mixtures of crude oil, plus Hyamine 1622, Hyamine X-400 and Hyamine 2389 were intermediate in effectiveness. A mixture of crude oil and Polymer X-150 was the least effective. Crude oil alone was not as effective in suppressing evaporation as it was in previous experiments. There was some difficulty in obtaining uniform surfaces in the crude oil treatments due to the heterogenity of the material. This may have decreased the effectiveness of these treatments compared to similar treatments in the previous 2 experiments.

The increased effectiveness of the cationic-crude oil mixture over crude oil alone was probably due to the chemical nature of the cationic. Cationics are surface active agents which have a structure

Table 5. Treatments evaluated in Greenhouse Experiment 3.

Treatment	Rate Per Hectare
A - Polymer X-150[1/][2/]	24 l
B - Polymer X-150 + crude oil[3/]	24 l and 2838 l
C - Hyamine 3500[4/]	47 l
D - Hyamine 3500 + crude oil	47 l and 2838 l
E - Hyamine 2389[4/]	47 l
F - Hyamine 2389 + crude oil	47 l and 2838 l
G - Hyamine 1622[4/]	47 l
H - Hyamine 1622 + crude oil	47 l and 2838 l
I - Hyamine X-400[4/]	47 l
J - Hyamine X-400 + crude oil	47 l and 2838 l
K - Crude oil	2838 l
L - Control	none

1/ Brand names are used for convenience and do not in any way indicate the endorsement of the products.

2/ Manufactured by Union Carbide Corp., New York, N. Y.

3/ Crude oil from the Anton-Irish field courtesy of Service Pipe Line Co., Lubbock, Texas.

4/ Manufactured by Rhom & Haas Co., Philadelphia, Pa.

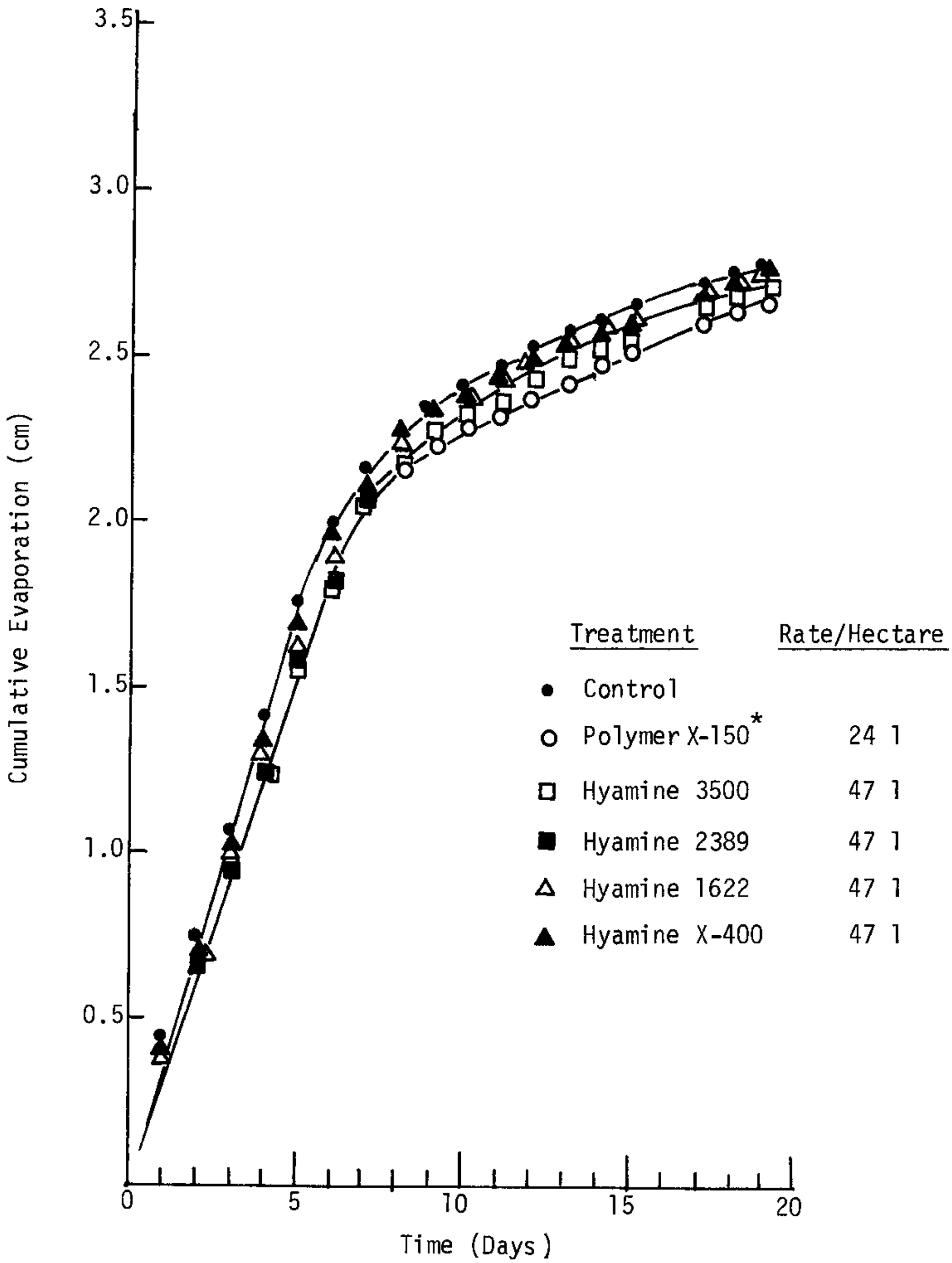

Figure 5. Cumulative evaporation from Olton loam soil treated with cationics.

* Brand names are used only for ease of identification and do not in any way indicate endorsement of products.

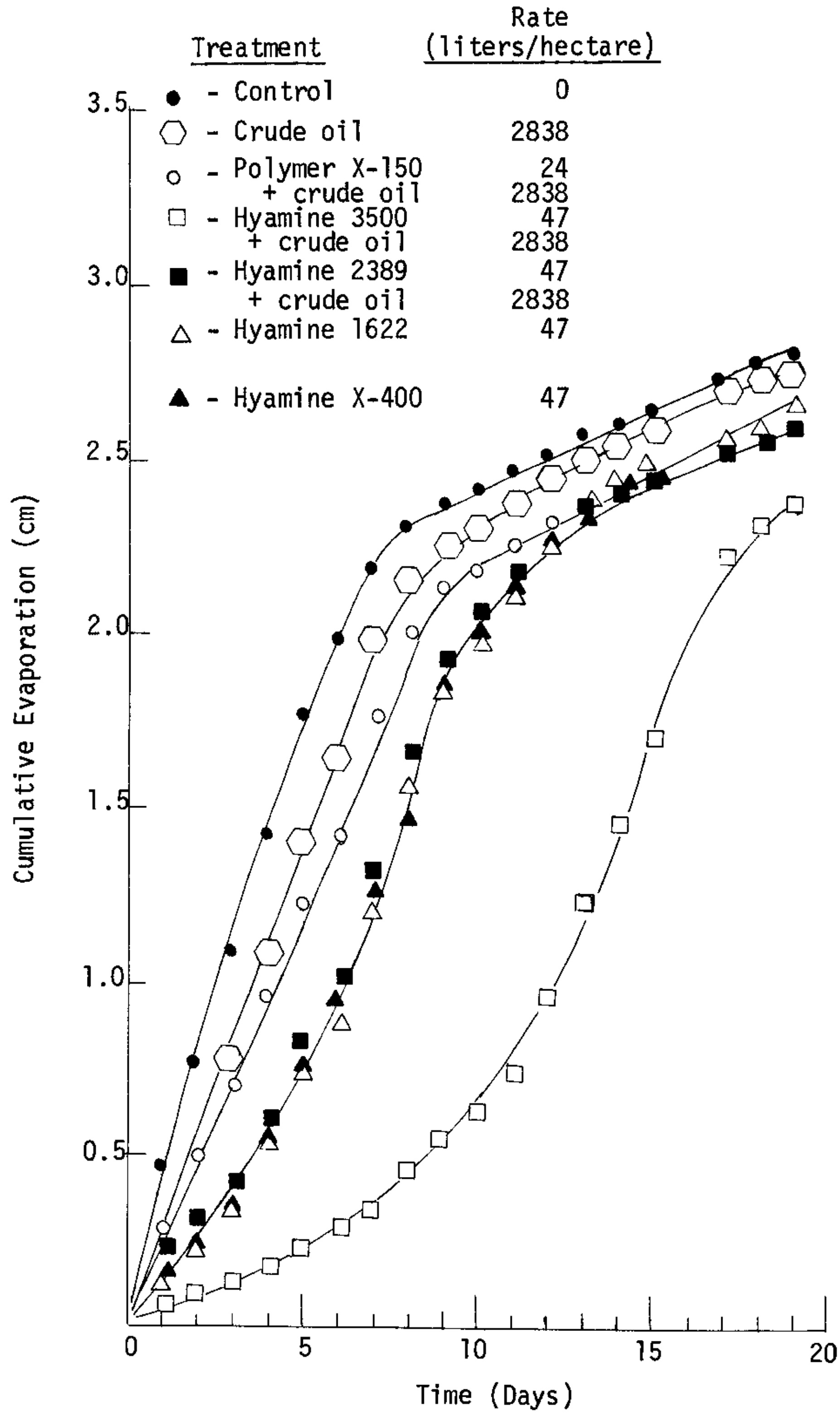

Figure 6. Cumulative evaporation from Olton loam soil treated with crude oil, cationics and mixtures of crude oil and cationics.

which is both hydrophobic and hydrophyllic in nature. The hydrophyllic "tail" has a positive charge while the hydrophobic "tail" is attracted to organic compounds. Cationics could thus serve to bond the crude oil to the soil in that the positive charge would be attracted to the cation exchange capacity of the soil and the hydrophyllic "tail" would be attracted to the crude oil by van der Waals' forces. Such a bond would cause crude oil to be more effective as an evaporation suppressant than crude oil alone.

Experiment 4 - A Comparison of Evaporation Suppression by Crude Oil-Cationic Mixtures and Fatty Alcohol.

Previous studies by Law (7) and Olsen (10) have shown that long chain fatty alcohols suppress soil water evaporation when mixed with the soil surface. No studies have been reported of the effects of a surface film of fatty alcohols on liquid or vapor transfer to the soil surface. An experiment was, therefore, conducted to see if such a film could be formed which could be compared with the suppression obtained when crude oil is applied to the smoothed soil surface.

Treatments used in the experiments are listed in Table 6. There was little suppression due to the application of the cationic, hexadecanol, or carbon tetrachloride, the solvent used for hexadecanol either alone or in mixtures except at the highest concentrations (Table A-4, Appendix). A comparison of the cumulative evaporation (Figure 7) curves shows that both the crude oil and crude oil-cationic mixtures were much more effective in suppressing soil water evaporation than the highest rate of hexadecanol used.

The mechanism of suppression by hexadecanol and crude oil apparently differ. Suppression by crude oil is highest during the first few days of evaporation and then decreases. Suppression by hexadecanol is rather constant throughout the drying cycle. This indicates that crude oil undergoes a chemical change during the evaporation cycle and a variation in the evaporation rate occurs. Suppression by hexadecanol is due to a change in the physical properties of the soil at the time of application and the evaporation rate is relatively constant throughout a particular drying cycle.

Table 6. Treatments evaluated in Greenhouse Experiment 4.

Treatment	Rate Per Hectare
A - Control	None
B - Control	None
C - Crude oil + Hyamine 3500[1/]	2838 l + 47 l
D - Crude oil + Hyamine 3500	2838 l + 47 l
E - Crude oil[2/]	2838 l
F - Hexadecanol + CCl_4	270 kg + 284 l
G - Hexadecanol + Hyamine 3500	270 kg + 47 l
H - CCl_4	284 l
I - CCl_4 + Hyamine 3500	284 l + 47 l
J - Hexadecanol + CCl_4	135 kg + 142 l
K - Hexadecanol + Hyamine 3500	135 kg + 24 l
L - Hexadecanol + CCl_4	540 kg + 568 l
M - Hexadecanol + CCl_4 + Hyamine 3500	540 kg + 568 l + 95 l
N - Hexadecanol + CCl_4	67 kg + 71 l
O - Hexadecanol + CCl_4 + Hyamine 3500	67 kg + 709 l + 12 l

1/ Manufactured by Rhom & Haas Co., Philadelphia, Pennsylvania.

2/ Crude oil from the Anton-Irish field courtesy of Service Pipe Line Co., Lubbock, Texas.

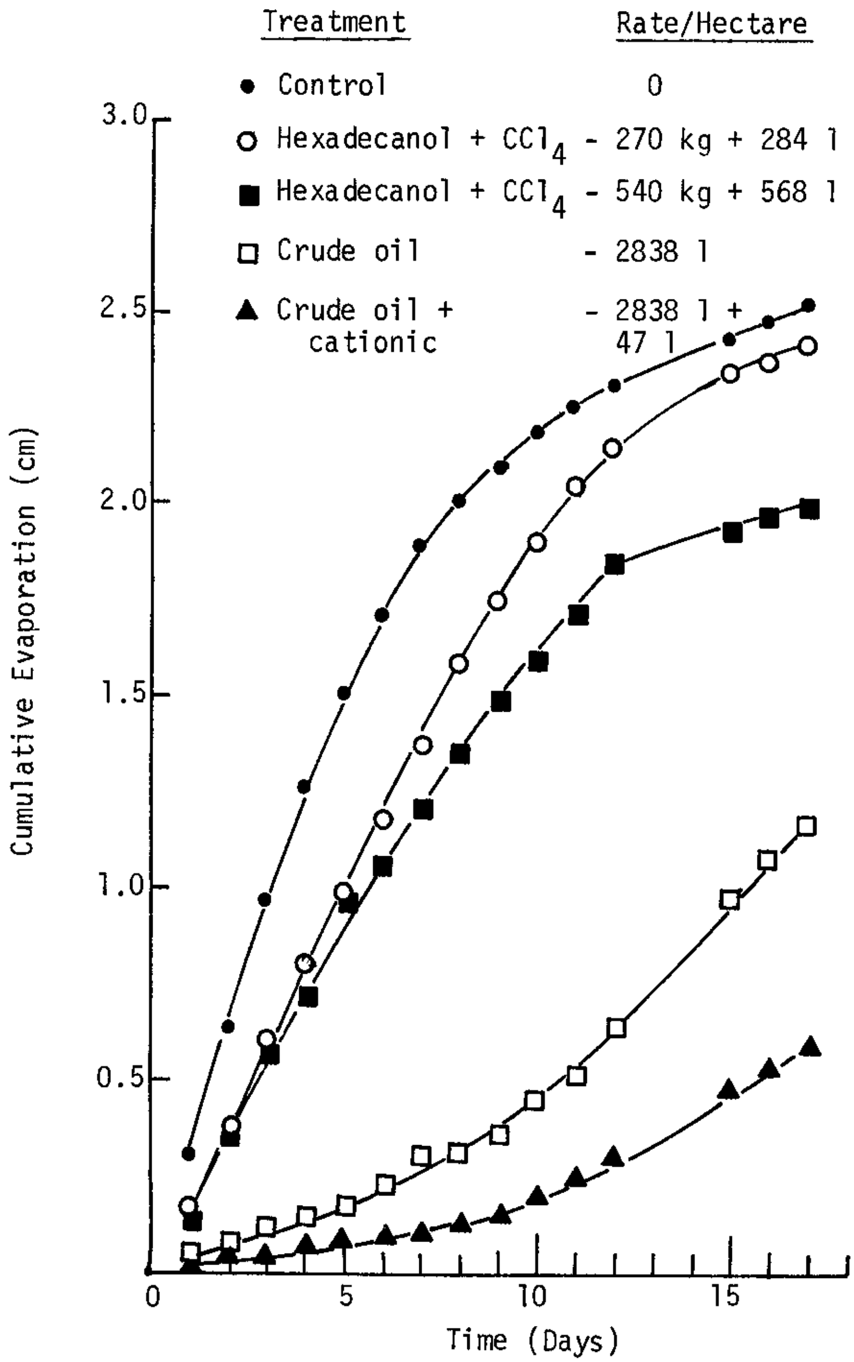

Figure 7. Cumulative evaporation from Olton loam soil treated with crude oil, hexadecanol and cationic.

Experiment 5 - Evaluation of Reflectance Material and Crude Oil-Cationic Mixtures as Evaporation Suppressants.

Gerard (4) reported that light colored reflectance materials which decrease the amount of radiation absorbed by the soil surface may also decrease evaporation. Since crude oil creates a black surface which absorbs a large amount of radiation, it was decided to undertake an experiment to see if decreasing the reflectance of the surface using kaolinite would affect the evaporation suppression of crude oil-treated surfaces.

Treatments used in the experiment are shown in Table 7. Kaolinite alone decreased the cumulative evaporation after the 4th day of the experiment (Figure 8). The crude oil and crude oil-cationic mixtures were both very effective in suppressing evaporation. When kaolinite was added to the crude oil-treated surface at a rate high enough to change the reflectance of the surface (20,400 kg/ha), the effectiveness of the crude oil-treated surface was decreased as indicated by the higher cumulative evaporation losses. This was probably due to the crude oil reacting with the kaolinite rather than the soil to form a barrier to decrease evaporation losses. Similar results were obtained when kaolinite was added to the surface treated with the crude oil-cationic mixture. (Table A-5, Appendix). As with previous experiments, only a small amount of suppression was obtained when the cationic alone was added to the soil surfaces.

Table 7. Treatments evaluated in Greenhouse Experiment 5.

Treatment	Rate Per Hectare
A - Control	
B - Crude oil	2838 l
C - Crude oil + cationic	2838 l + 47 l
D - Kaolinite	20,400 kg
E - Crude oil + kaolinite	2838 l + 20,400 kg
F - Crude oil + cationic + kaolinite	2838 l + 47 l + 20,400 kg
G - Kaolinite + cationic	20,400 kg + 47 l
H - Cationic	47 l

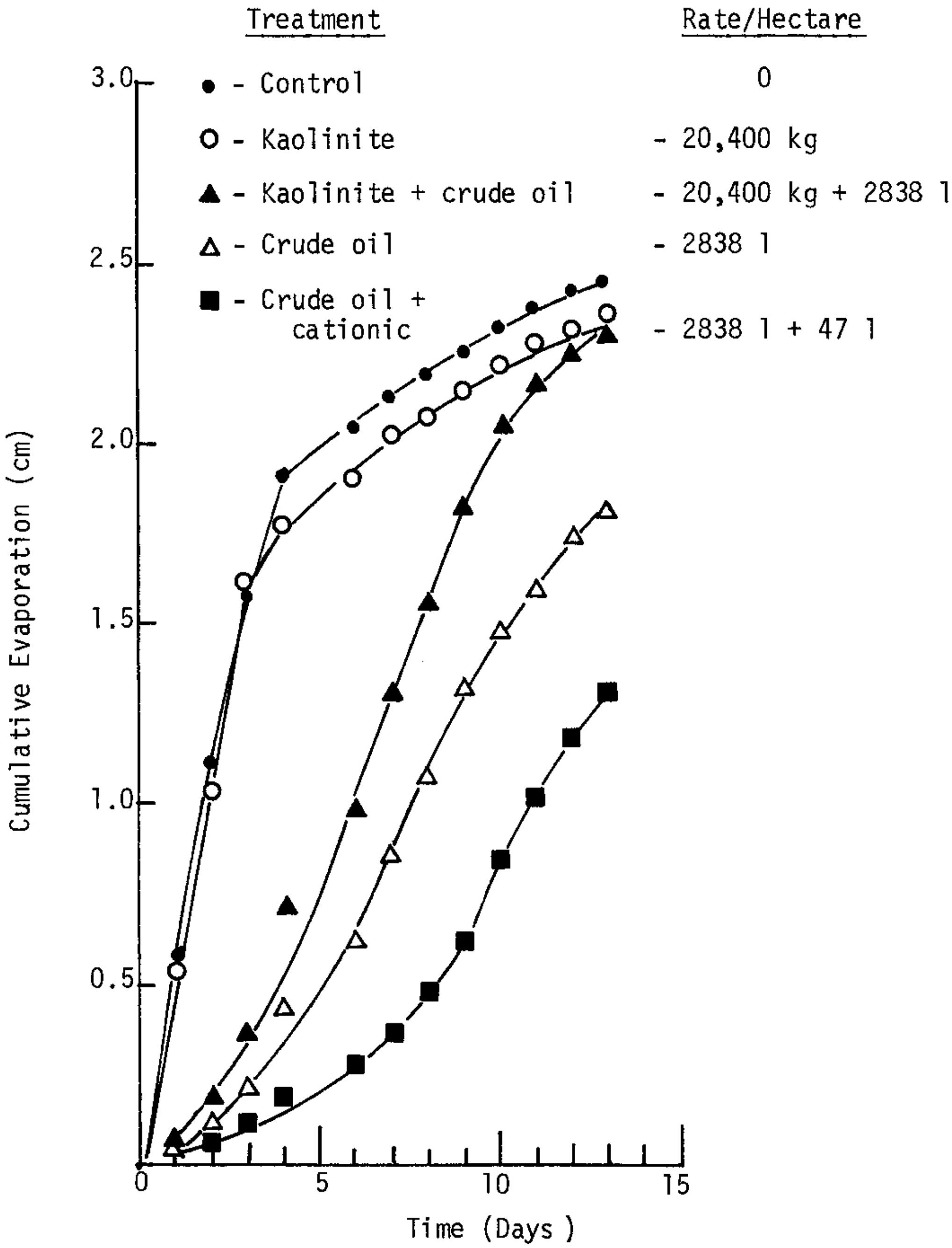

Figure 8. Cumulative evaporation from Olton loam soil treated with kaolinite, crude oil, and a cationic.

Experiment 6 - Influence of Crude Oil and Crude Oil-Surface Active Agent-Water Mixtures on Evaporation, Seedling Emergence and Soil Temperature.

In previous greenhouse experiments, containers treated with the various treatments were smoothed following water additions before treatments were applied. Under field conditions this may not be feasible. An experiment was conducted to determine if solutions containing crude oil plus surface-active agents added to the irrigation water would suppress evaporation. This technique could have important field application. The surface active agents were used primarily to make a solution of oil and water.

Also included in the same experiment were treatments which were seeded to various crops. The purposes of these treatments were to determine if (1) crude oil and crude oil-surface active agent mixtures would affect seedling emergence and (2) to evaluate the treatments'effectiveness in conserving soil water. These treatments were subirrigated by allowing the containers to stand in water and the treatments were applied after the containers became wet on the surface. Such conditions exist in the field when crops are furrow irrigated for seed germination and emergence. Soil temperature was measured at the 2.5 cm depth at 4 p.m. each day.

Crops and treatments of the experiment are shown in Table 8. There was some effect on evaporation due to adding crude oil plus cationic and nonionic with the water. (Figure 9). The containers with the crude oil plus cationic lost less due to evaporation during the first 10-11 days of the experiment while the containers with

Table 8. Treatments evaluated in Greenhouse Experiment 6.

Treatment	Rate Per Hectare
A - Control	
B - Control	
C - Watered with crude oil + anionic	2838 l + 18 kg
D - Watered with anionic	18 kg
E - Watered with crude oil + cationic	2838 l + 142 l
F - Watered with cationic	142 l
G - Watered with crude oil + nonionic	2838 l + 142 l
H - Watered with nonionic	142 l
I - Tomatoes planted 1/2" deep in smooth dry soil & subirrigated	
J - Tomatoes planted 1/2" deep in smooth dry soil & sprayed with	2838 l crude oil
K - Tomatoes planted & sprayed with water containing	2838 l crude oil + 142 l cationic
L - Tomatoes planted & sprayed with water containing	2838 l crude oil + 142 l cationic + 2838 l water
M - Onions planted and treated as Treatment J	
N - Onions planted and treated as Treatment K	
O - Onions planted and treated as Treatment L	
P - Onions planted and treated as Treatment M	
Q - Cucumbers planted and treated as Treatment J	

Continued

Table 8. (Continued)

Treatment	Rate Per Hectare
R - Cucumbers planted and treated as Treatment K	
S - Cucumbers planted and treated as Treatment L	
T - Cucumbers planted and treated as Treatment M	
U - Control until sprayed with crude oil on 8th day of study	2838 l
V - Control until 8th day of study when planted with cotton and sprayed with crude oil	2838 l
W - Control until 8th day of study when sprayed with crude oil and cationic	2838 l + 142 l
X - Control until 8th day of study when planted with cotton and sprayed with crude oil and cationic	2838 l + 142 l

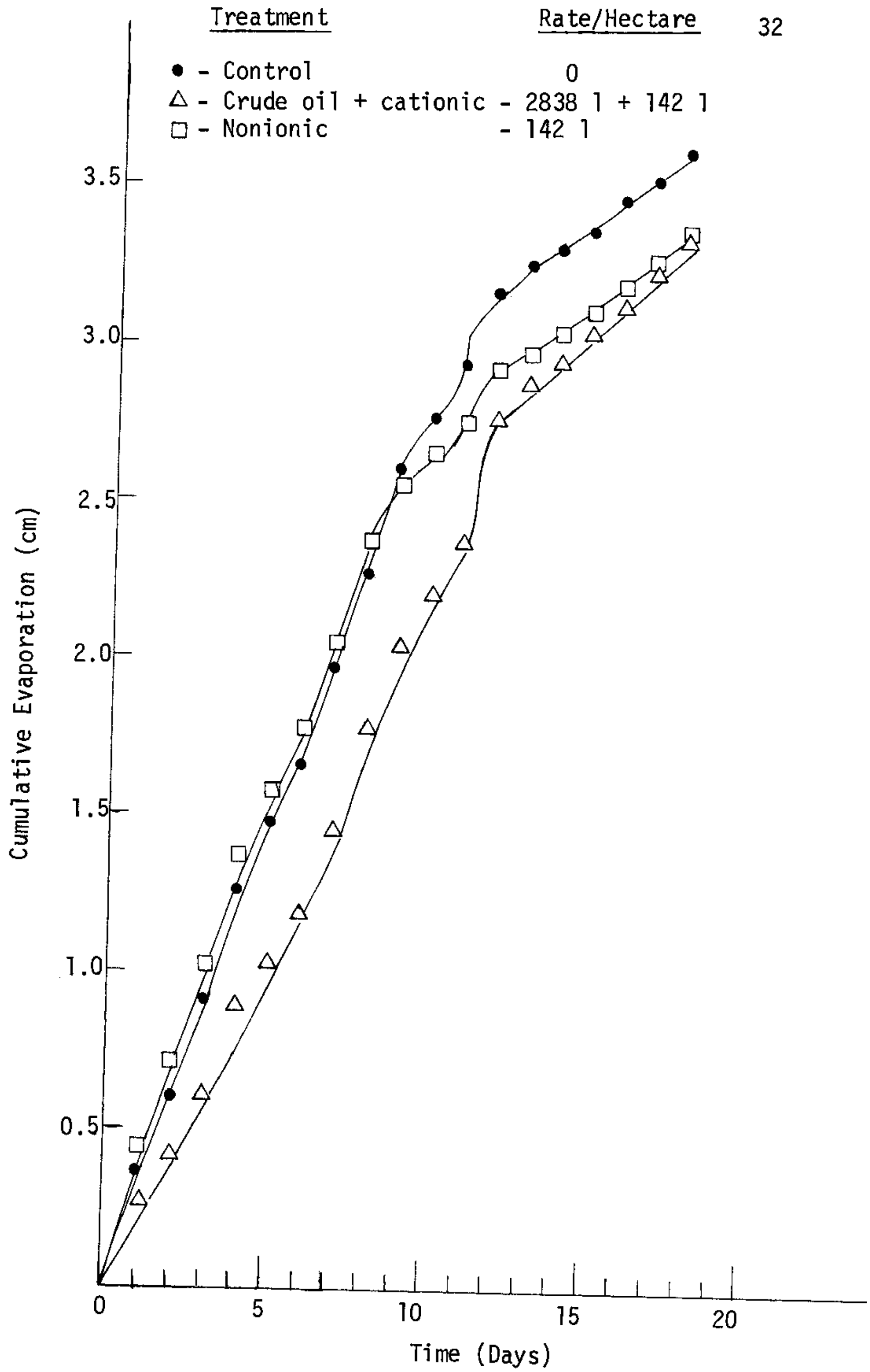

Figure 9. Cumulative evaporation from Olton loam soil treated with crude oil, cationic, and nonionic.

nonionic lost less after the first 12 days of the experiment. None of the other treatments affected evaporation to any extent. (Table A-6, Appendix).

There was less evaporation loss from some of the containers seeded to tomatoes, onions, and cucumbers that were treated with crude oil and mixtures of crude oil, cationic and water (Figures 10, 11, 12). Also, the average temperature prior to plant emergence of these crops was less. There was no increase in emergence due to these treatments. As a matter of fact, the treatment consisting of crude oil alone decreased the germination of the tomatoes and onions almost 50 percent. The treatment of crude oil plus cationic also decreased the germination of tomatoes over 50 percent. When water was added to the mixture, germination was not affected on any of the treatments. The germination of the cucumbers was the same regardless of treatment.

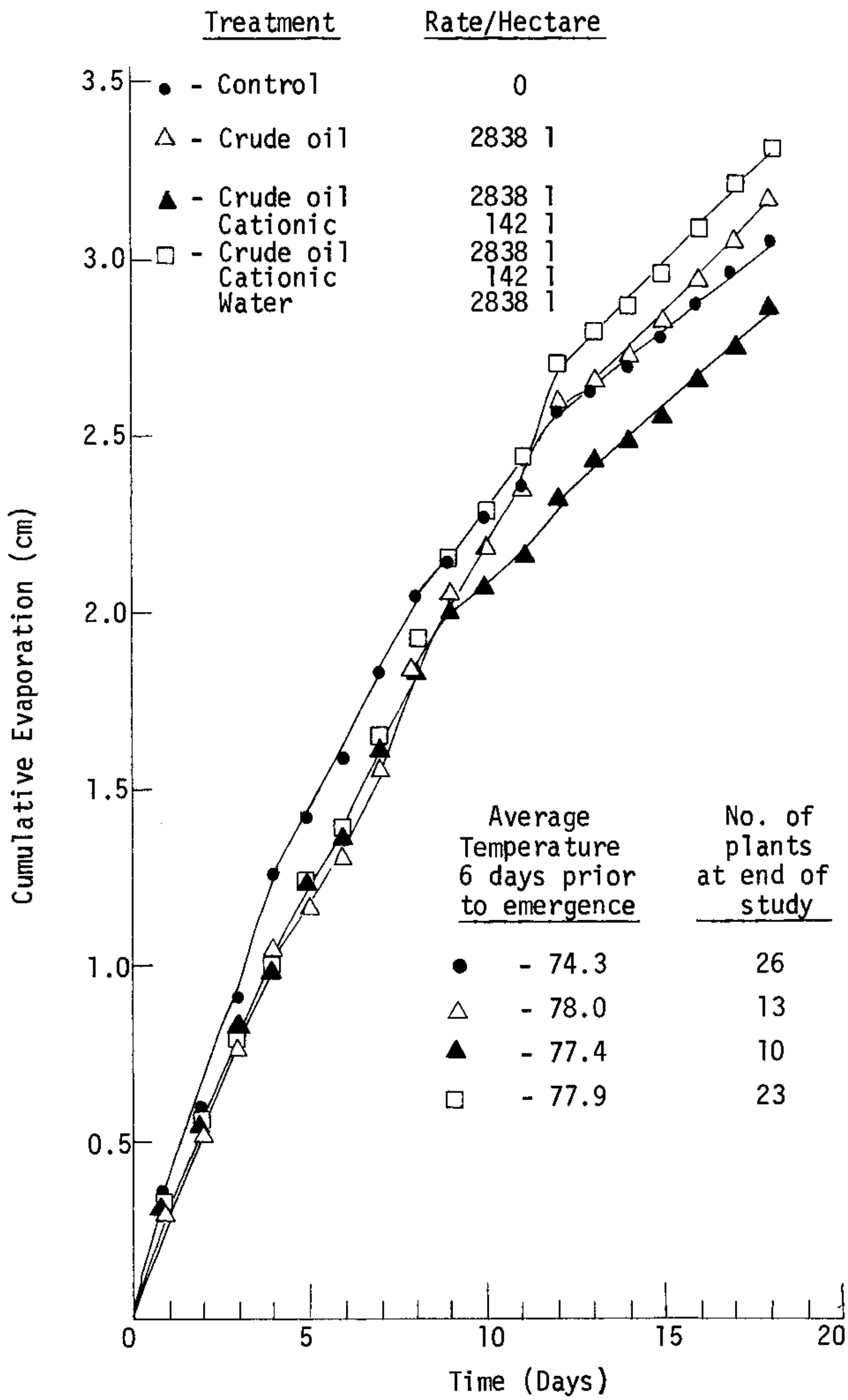

Figure 10. Cumulative evaporation and tomato emergence data from Olton loam soil sprayed with crude oil, crude oil-cationic mixtures.

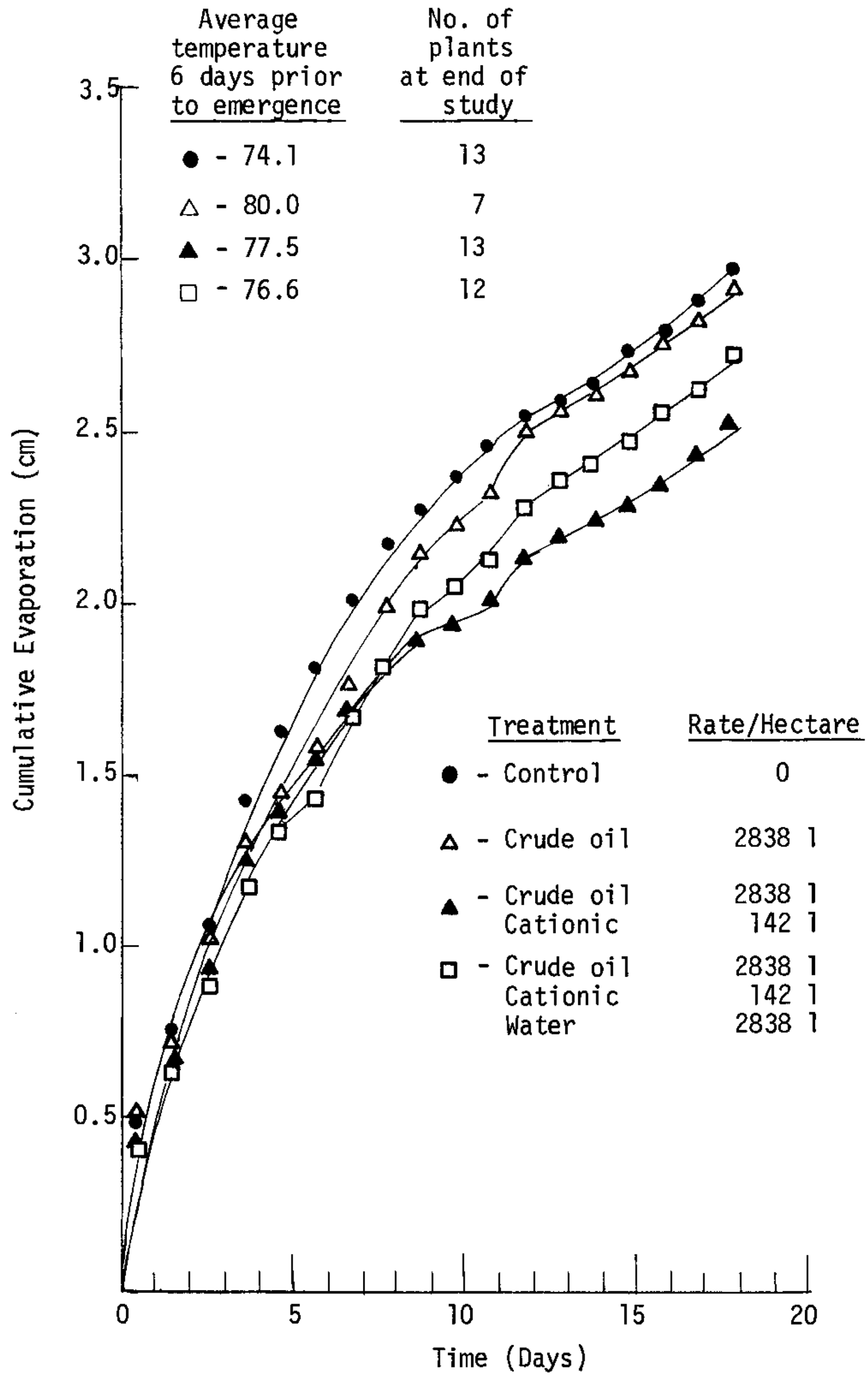

Figure 11. Cumulative evaporation and onion emergence data from Olton loam soil sprayed with crude oil and crude oil-cationic-water mixtures.

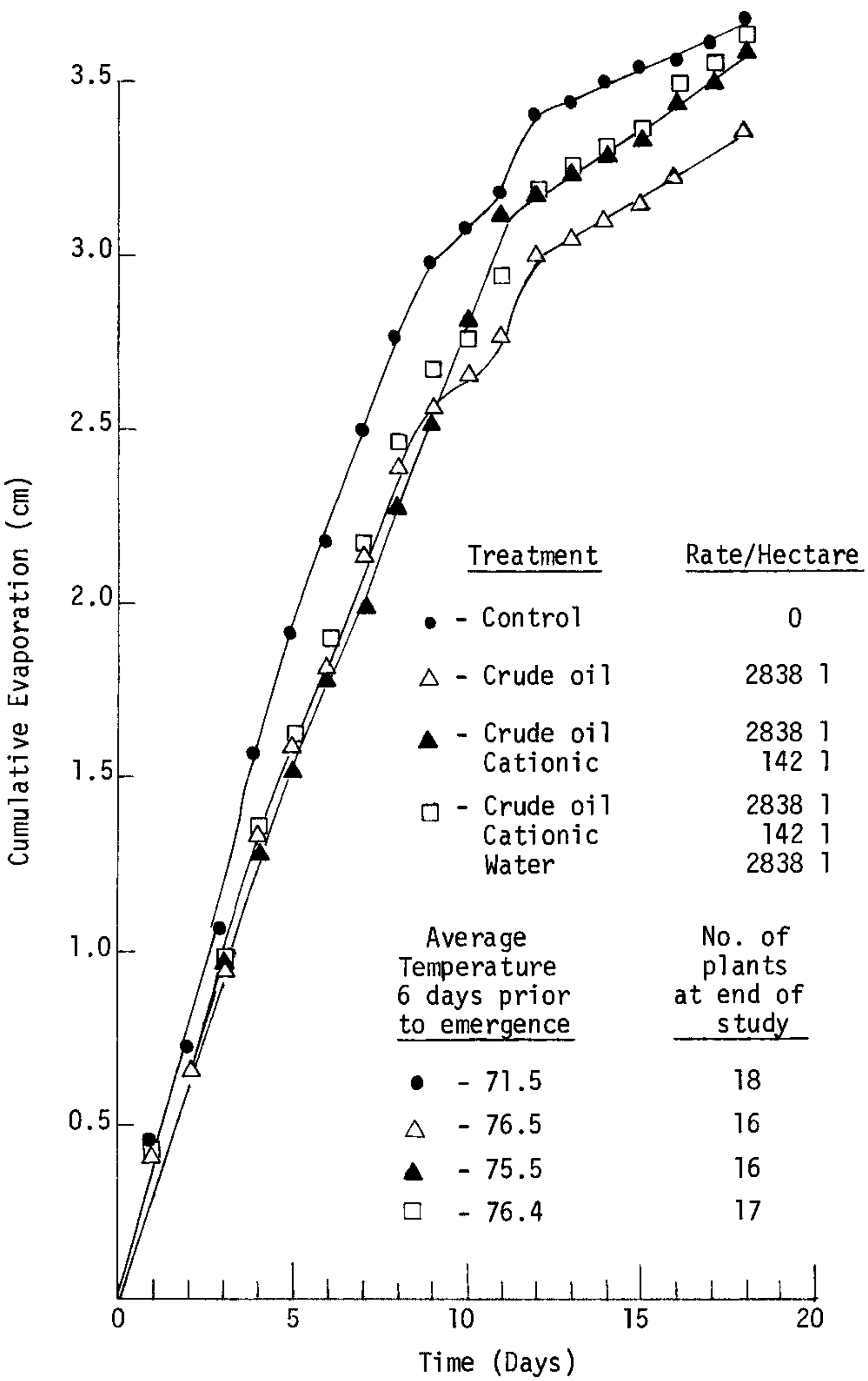

Figure 12. Cumulative evaporation and cucumber emergence data from Olton loam soil treated with crude oil and crude oil-cationic mixtures.

Experiment 7 - Influence of Crude Oil and Crude Oil-Carbon Black Mixtures on Evaporation, Seedling Emergence and Soil Temperature.

The results from Experiment 6 indicated that adding crude oil plus surface active chemicals and water had no major effect on soil water evaporation or seed germination. In Experiment 5, a reflectance material, kaolinite, also had little effect on soil water evaporation. Since neither oil in the water nor reflectance materials effected evaporation, it was decided to conduct an experiment to see if spraying crude oil and crude oil-cationic mixtures on a dry soil surface would influence soil water evaporation and seed germination.

This experiment differed from previous experiments. In previous experiments plastic containers were used and the surface of the treatments was 2.5 cm from the top of the containers. In these experiments the ceramic containers were filled to the surface and sub-irrigated to simulate a crop being irrigated for emergence. The evaporation data are thus higher, but relative differences between treatments were the same. Soil temperature was measured at 4 p.m. on selected days.

Treatment rates for Experiment 7 are shown in Table 9. Crude oil rates were not effective in suppressing evaporation below the concentration at the 4730 l/ha rate (Figure 13). As would be expected, the 9460 l/ha rate was more effective in suppressing evaporation than the 4730 l/ha rate. There was no definite relationship between treatment and plant emergence.

Table 9. Treatments evaluated in Greenhouse Experiment 7.

Treatment	Rate Per Hectare
A - Control	None
B - Carbon black	18 kg
C - Crude oil	946 l
D - Crude oil + carbon black	946 l + 18 kg
E - Crude oil	2838 l
F - Crude oil + carbon black	2838 l + 18 kg
G - Crude oil	4730 l
H - Crude oil + carbon black	4730 l + 18 kg
I - Crude oil	9460 l
J - Crude oil + carbon black	9460 l + 18 kg

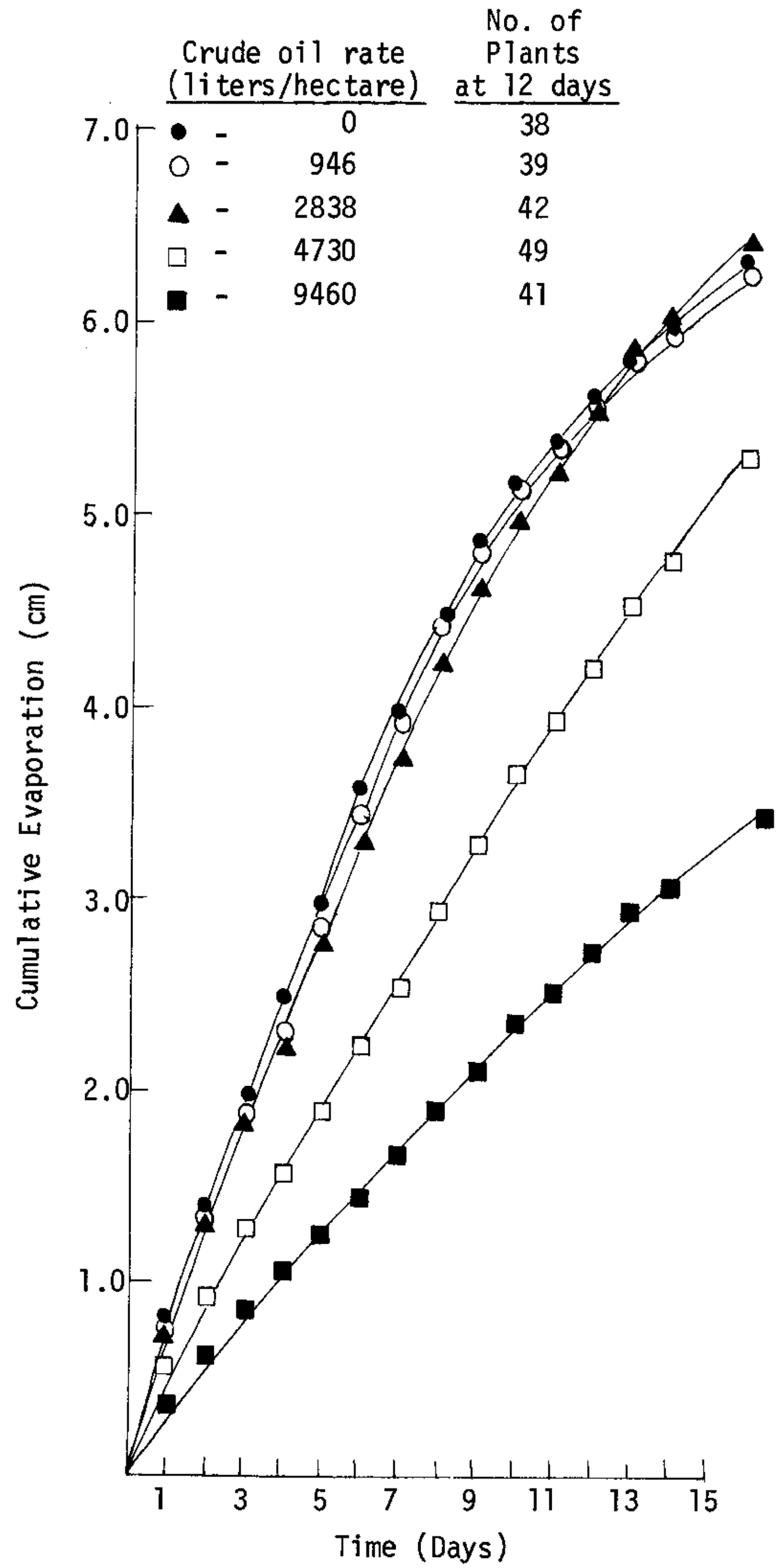

Figure 13. Cumulative evaporation and carrot emergence data from Olton loam soil treated with crude oil.

Carbon black alone decreased evaporation to a certain extent. (Figure 14). There was also a slight decrease in evaporation due to adding carbon black to crude oil.

In previous experiments, suppression was obtained with 2838 l/ha while 4730 l/ha were required in this experiment. This is probably due to the larger amount of surface area of the dry surface at the time of spraying in these experiments compared to smooth wet soil surfaces of Experiments 1-5.

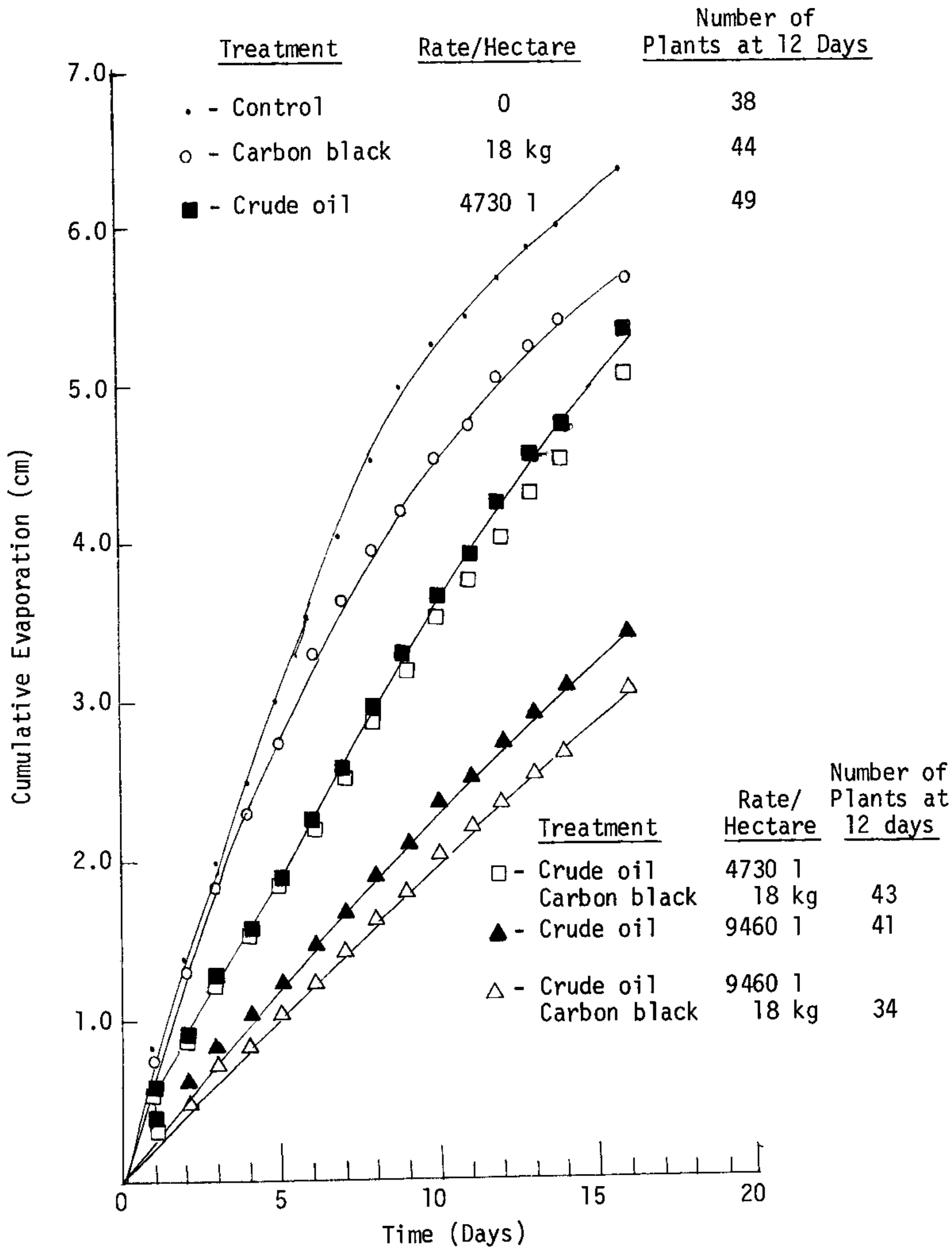

Figure 14. Cumulative evaporation and carrot emergence data from Olton loam soil treated with crude oil and crude oil-carbon black mixtures.

CHAPTER III

CONTROLLED ENVIRONMENT STUDIES

Results from greenhouse studies showed crude oil to be effective in suppressing soil water evaporation in every test. The tests, however, were exploratory in nature. Conditions were not controlled to the point that inferences could be made concerning the mechanisms of suppression or the soil and atmospheric conditions under which the crude oil would be most effective. With proper control of the environment, it is possible to delineate the separate influences of atmospheric conditions (light, temperature, wind and relative humidity) and soil conditions (temperature, crude oil treatments) on the evaporation of water from soils. It was, therefore, decided to further evaluate the most promising evaporation suppressant, crude oil, under more controlled conditions. In order to evaluate the most important parameters, it was necessary to use 2 sets of controlled environment facilities. One facility consisted of wind tunnels located in a controlled temperature room. The temperature was controlled to ±1.5° C. No attempt was made to control the humidity although it did not vary more than ±4% during the experiment.

The other facility was a custom built-controlled environment chamber. In this facility it was possible to control temperature, (soil and air) light intensity, and relative humidity. A description of the facilities is located in sections concerned with experiments in each of the 2 facilities.

The same soil and containers were used in all studies. The 0-15 cm layer of an Olton loam soil was sieved through a 2.00 mm screen and packed into containers, 25 cm tall x 15 cm wide x 20 cm long, to a bulk density of 1.4. Water was added to the containers so that the moisture content equaled the water content at -0.1 bar suction (35% by wt.). After a drying cycle, the soil was rewatered to the same moisture content. Also included in some of the experiments were containers filled with water. The temperature was 26 ±1° C. and the relative humidity was 30 ±5% to produce an average vapor pressure deficit of 22 mbs for all experiments in the controlled temperature room. Conditions were varied in the controlled environment chamber so as to evaluate the influence of the different parameters. Containers were weighed at the time of treatment and periodically thereafter until the end of the experiment to determine evaporation losses.

Controlled Temperature Room Studies

Many studies have shown that wind speed is one of the most important parameters influencing evapotranspiration and soil water evaporation in the Great Plains region (11) (12). Without considerable expense, it would not have been possible to incorporate facilities to determine the influences of different wind speeds on soil water evaporation in the same facilities for control of light intensity, air temperature and relative humidity, and soil temperature. It was, therefore, necessary to undertake these tests in separate facilities. A description of the facilities and the results obtained follow.

Methods and Materials

The wind tunnels were located in a controlled temperature room in which the temperature was controlled to ±1.5° C. A hygrothermograph was stationed in the room to monitor both temperature and relative humidity. Although the humidity was not controlled, it did not vary more than 4% during the experiments.

The wind tunnels were constructed of 2 blowers powered by a 1/2 hp. electric motor. (Figure 15). Each of the 2 blowers had 2 openings which were 9 1/2" x 10 1/2". Each opening was modified as indicated in Figure 15 to accomodate 2 containers. Since there was a total of 4 openings, a total of 8 containers could be studied at one time.

Different wind speeds were obtained by adjusting the amount of air entering the blowers. The tunnels were lined with Mylar to

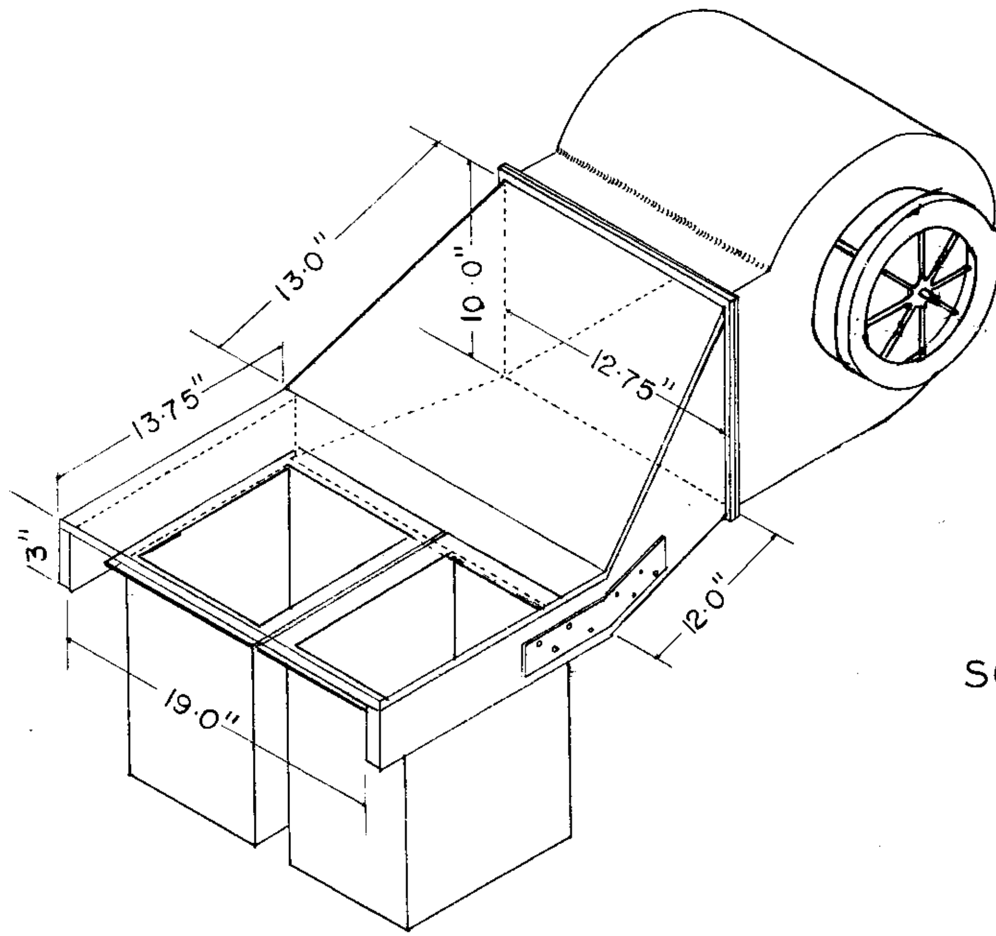

Figure 15. Wind tunnel used in controlled environment study of the influence of crude oil on soil water evaporation.

reduce friction. The wind speed was determined at various points with a hot wire anemometer within the tunnels to assure that only laminer flow was occurring.

The containers and soil used are described in the introduction. Three different experiments were conducted in the controlled temperature room. They were (1) a comparison of different surface treatments on evaporation, (2) the influence of wind speeds on evaporation and (3) the mechanisms of evaporation suppression by crude oil. The results from these experiments follow.

Results and Discussion

Experiment 1 - Influence of Different Soil Surface Treatments on Soil Water Evaporation.

In the first experiment the influence of different surface treatments on soil water evaporation was evaluated. Treatments applied in the experiment are listed in Table 10. A comparison of the untreated smooth wet soil surface and water (Figure 16) shows that the evaporation is equal from both surfaces for the first 12 days. Following this period, the evaporation loss from the water becomes greater. These curves are typical of those obtained by other workers (3) (7) (10).

The losses were approximately the same during the first 12 days from both the crude oil-treated water and soil surfaces. Following this period the evaporation from the soil surface became greater. These data indicate that after the 12-day period, the oil film was continuous and intact on the water surface causing the evaporation to remain low. The crude oil film, however, began to break down enabling an increase in evaporation to occur.

The data obtained give further evidence that the amount of surface area and the moisture content of the surface have a direct influence on the effectiveness of crude oil as an evaporation suppressant. The smooth wet soil surface had the least surface area and the highest moisture content and the crude oil was most effective on this surface. The subirrigated rough surface was intermediate in moisture content and surface area and the crude oil was intermediate in its effectiveness as an evaporation suppressant. The rough dry

Table 10. Treatments* evaluated in Controlled Temperature Room - Experiment 1.

Treatment Number	Treatments	Crude Oil Rate (liters/hectare)
1	Smoothed wet surface	
2	Smoothed wet surface + crude oil	4730
3	Subirrigated rough surface	
4	Subirrigated rough surface + crude oil	4730
5	Rough dry surface	
6	Rough dry surface + crude oil	4730
7	Water	
8	Water + crude oil	4730

* Data from treatments located in Table A-7, Appendix.

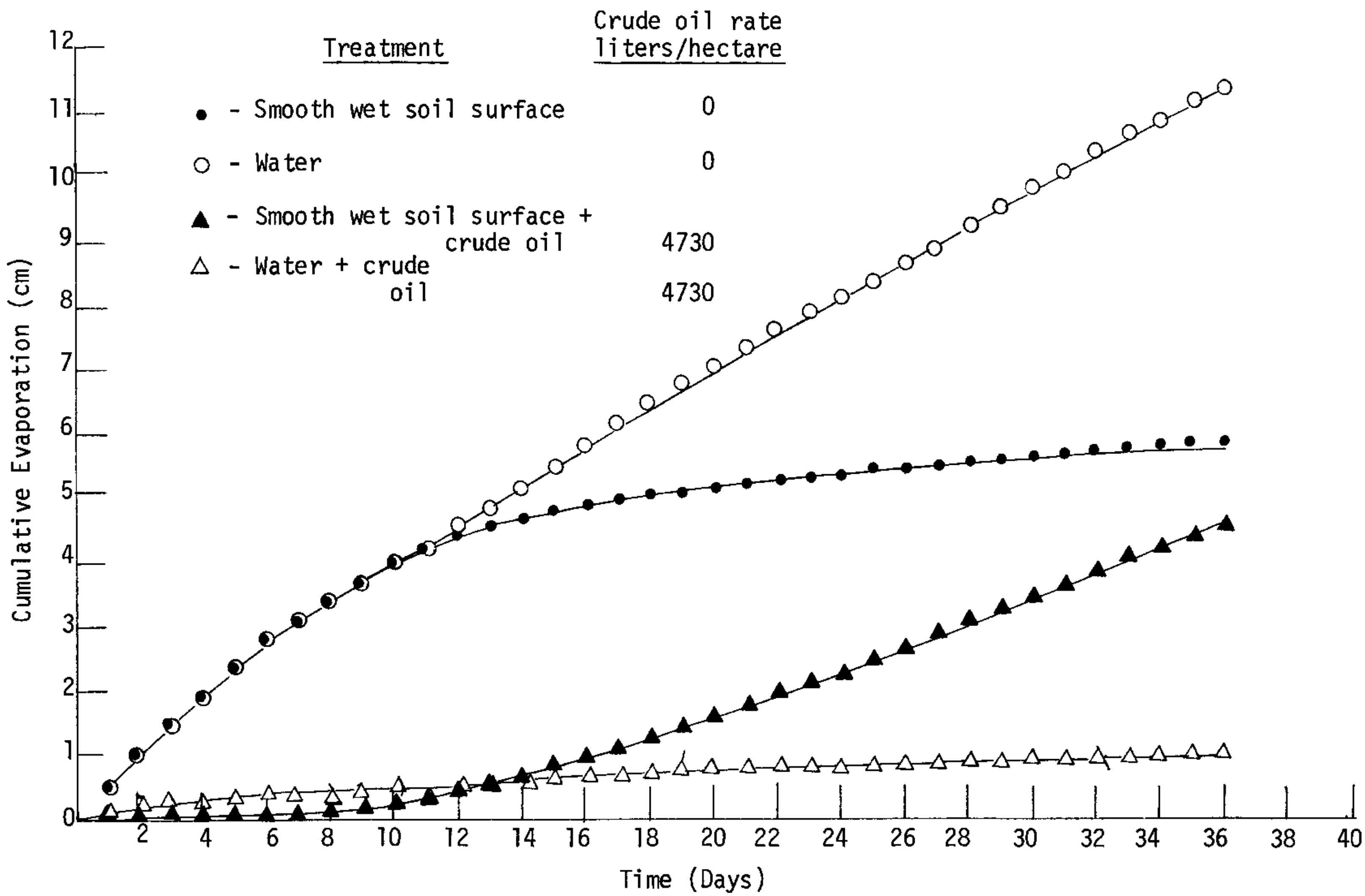

Figure 16. Cumulative evaporation of water and soil treated with crude oil.

surface had the least water and the most surface area and the crude oil was not effective as an evaporation suppressant. (Figure 17).

It should be noted that the evaporation loss after 22 days was greater from the crude oil-treated surface than from the rough dry soil surface. This shows the effectiveness of a rough dry soil surface as an evaporation suppressant. Although these surfaces are difficult to establish immediately following moisture additions, they can play a major role in conserving moisture over a long period because the moisture loss occurs only by vapor diffusion. These data suggest that the establishment of such a layer as soon as possible after moisture additions could aid in soil water conservation. However, such barriers could be a hazard in the Great Plains area due to the high wind velocities unless some crop residue is present to keep the barrier in place.

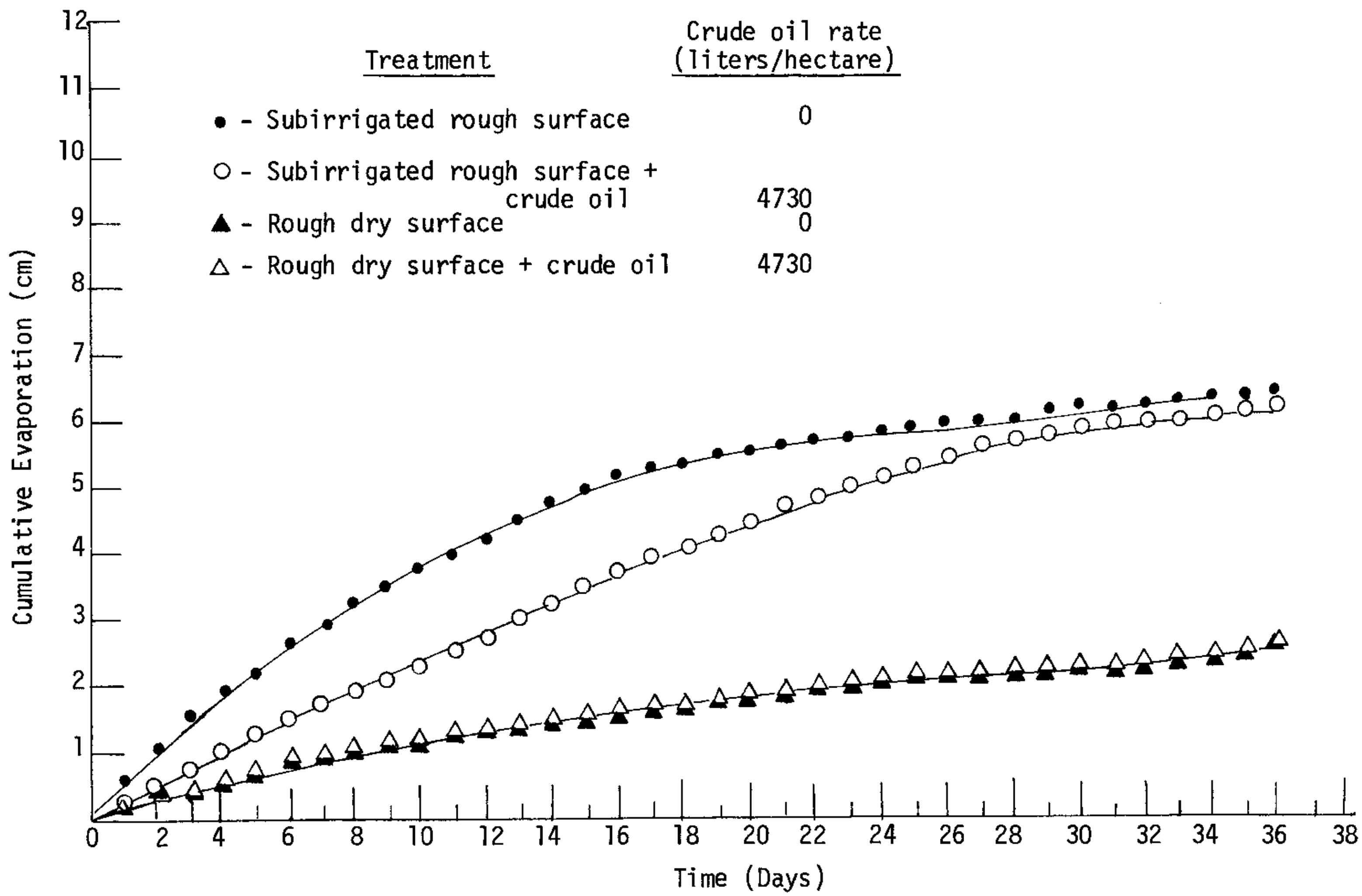

Figure 17. Cumulative evaporation of soil with different surface treatments receiving crude oil applications.

Experiment 2 - Influence of Wind on Evaporation from Crude Oil-Treated Surfaces.

In the previous experiments, the major suppression of soil water evaporation occurred from crude oil applications when they were applied to smooth wet surfaces. An experiment was undertaken to evauate the influence of wind speed on evaporation from surfaces receiving such treatments. Treatments evaluated included crude oil at rates of 0, 946, 2838, and 4730 l/ha at wind speeds of <0.4, 1.6, 3.3, and 6.5 m/sec.

The major increases in evaporation due to wind from the untreated containers occurred the first 3 days of the evaporation period (Figure 18). Over 50 percent of the water lost during the evaporation period from the containers receiving wind was lost during this period. Thirty-five percent of the water lost from containers receiving a wind speed of 6.5 m/sec was lost during the first day of the evaporation period. Less than 5 percent was lost during the same period from the containers receiving little or no wind.

Crude oil was very effective in suppressing evaporation during the first few days of the evaporation period (Figure 19). During the first 4 days less than 0.30 cm was lost regardless of wind speed or concentration. Following this period, however, the evaporation losses were related to wind speed and concentration. For instance, 4730 l/ha at 6.5 m/sec were required to get the evaporation suppression of 946 l/ha at the lowest wind speed for a 12 day-period (curves 4 and 6, Figure 19). The influence of crude oil concentration on evaporation suppression was much more pronounced at 6.5 m/sec (Figure 19)

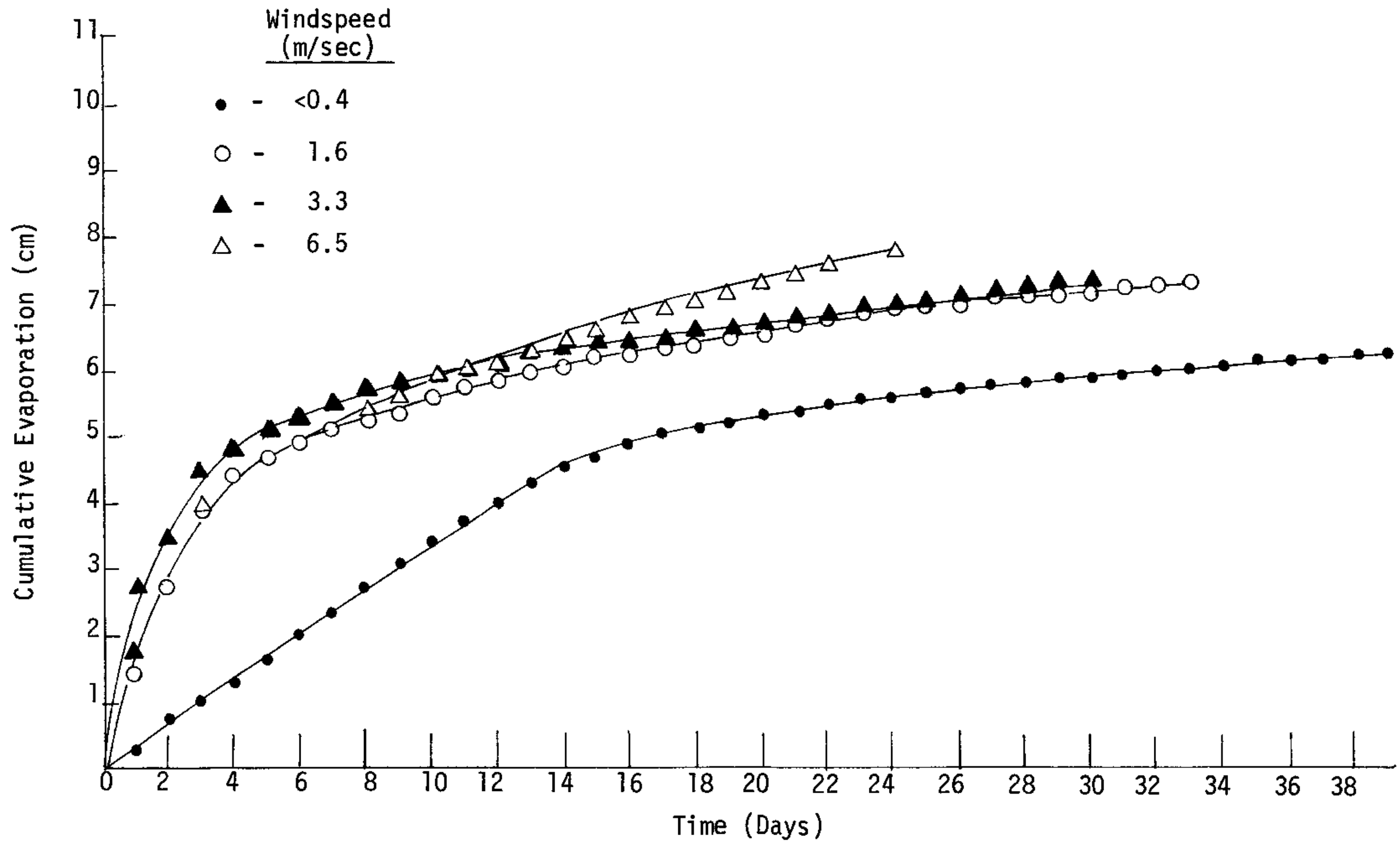

Figure 18. Cumulative evaporation of untreated Olton loam soil surfaces receiving different windspeeds.

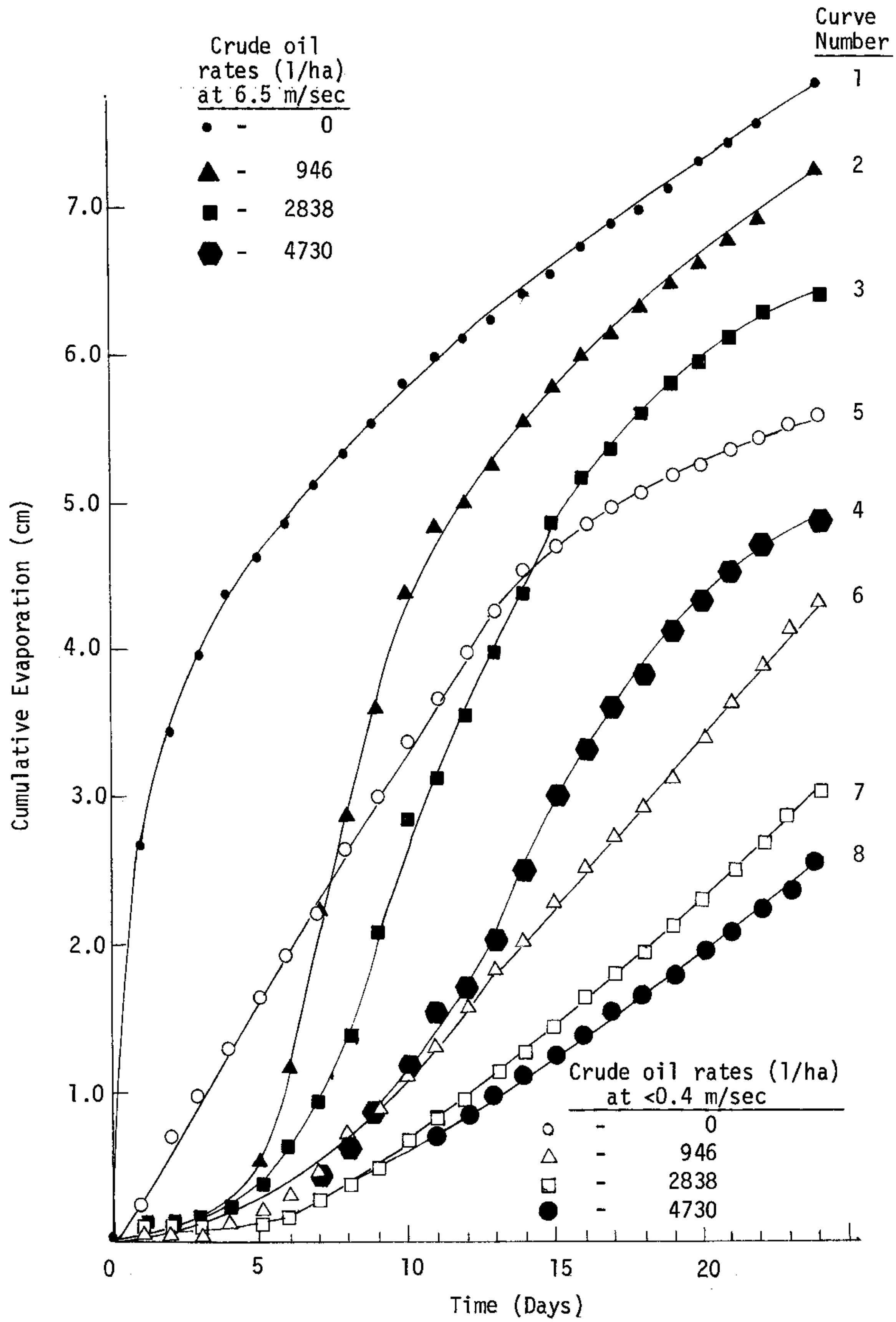

Figure 19. Cumulative evaporation of untreated and crude oil treated Olton loam soil surfaces receiving different windspeeds.

than at wind speeds <0.4 m/sec. The difference in evaporation between the 2838 and 4730 l/ha rate at wind speeds <0.4 m/sec (curves 7 and 8, Figure 19) is much less than the difference between the same rate at 6.5 m/sec (curves 3 and 4, Figure 19). Other data from the wind tunnel studies is located in Table A-8, Appendix.

These data indicate that only a small amount of wind is required to have a major effect on soil water evaporation (Figure 18), and that any modification which would keep wind speeds low immediately after rainfall or irrigations would have a major influence in decreasing soil water evaporation losses. Crude oil is effective during the 4-5 day period when most of these losses occur, but currently is impractical to apply. Plant residue management both when the crop is growing and during the period when the crop is not growing offer the best possibilities of decreasing evaporation losses due to wind removing the water vapor immediately after moisture additions.

Experiment 3 - Mechanisms of Evaporation Suppression from Applying Crude Oil to Smooth Wet Soil Surfaces.

To delineate the mechanisms of suppression due to the addition of crude oil to smooth wet soil surfaces, a separate experiment was undertaken using replicated treatments of crude oil rates of 0 and 2838 l/ha on both smooth wet soil surfaces and water surfaces. Bowers and Hanks (3) reported a decrease in evaporation with dioctadecyl-dimethyl-ammonium chloride (DDAC) but the compound also decreased infiltration. In view of these findings, an experiment was also conducted to see if the crude oil film influenced water movement into the soil. Soil was packed and treated as described above into polyvinylchloride (PVC) containers. The containers were constructed so that the water outflow could be determined from the central 7.5 cm diameter core of each container. The volume of outflow from the central core was determined at 1-hour intervals under a 1 cm constant head of water. After the outflow rate became constant, the columns were removed, drained and treated with crude oil at the rate of 2838 l/ha, and the outflow determined again at different evaporation rates.

Soil moisture retention data were obtained with a pressure plate on the soil and soil treated with crude oil at the rate of 5 percent by weight. This was the equivalent of treating a .375 cm surface layer of soil with 2838 l/ha of crude oil.

Crude oil used in the experiment was the same as that used in previous studies. It was from the Clear Fork formation of the Anton Irish oil field in Lubbock County, Texas. The oil is known as a "napthenic crude" and contains both paraffin and asphaltic compounds with usually more of the latter compound present. A typical fractionation of the crude is as shown in Table 11. The sample used in the experiment had a specific gravity of 0.86.

Typical cumulative evaporation curves, which were obtained from untreated soil and soil treated with crude oil, are indicated in Figure 20. Good repeatability was obtained between replications except with the oil-treated soil near the end of the experiment. The crude oil used in the experiment was not very homogeneous so there was probably some difference in the surfaces, which caused the difference between replications in the amount of water evaporated.

The data in the rate curves in Figure 21 are rather scattered. However, the different stages of drying in the treatments can be distinguished. The untreated soil was characterized by the 3 stages of drying described by Lemon (8): (1) the high-rate stage where the conduction of water to the soil surface is sufficient to maintain the surface in a wet condition, (2) the 1st falling-rate stage, which lasted only a short period, during which the resistance to movement of liquid water increased and (3) the 2nd falling-rate stage, which lasted for a long period of time at a low rate and was probably controlled by vapor diffusion.

The crude oil-treated soil was characterized by 5 stages of drying: (1) a short period, relatively constant low-rate stage, (2) a "rising" stage, which lasted for a short period, (3) a constant high-rate period of long duration, (4) a falling stage of very short duration followed by (5) a low-rate period.

Table 11. Typical fractionation of crude oil used in soil water evaporation suppression experiments.

Component	Percent
Gasoline	11.68
Gasoline + naptha	31.07
Kerosene	5.41
Gasoline + oil	19.11
Residium	31.73
Distillation loss	1.00

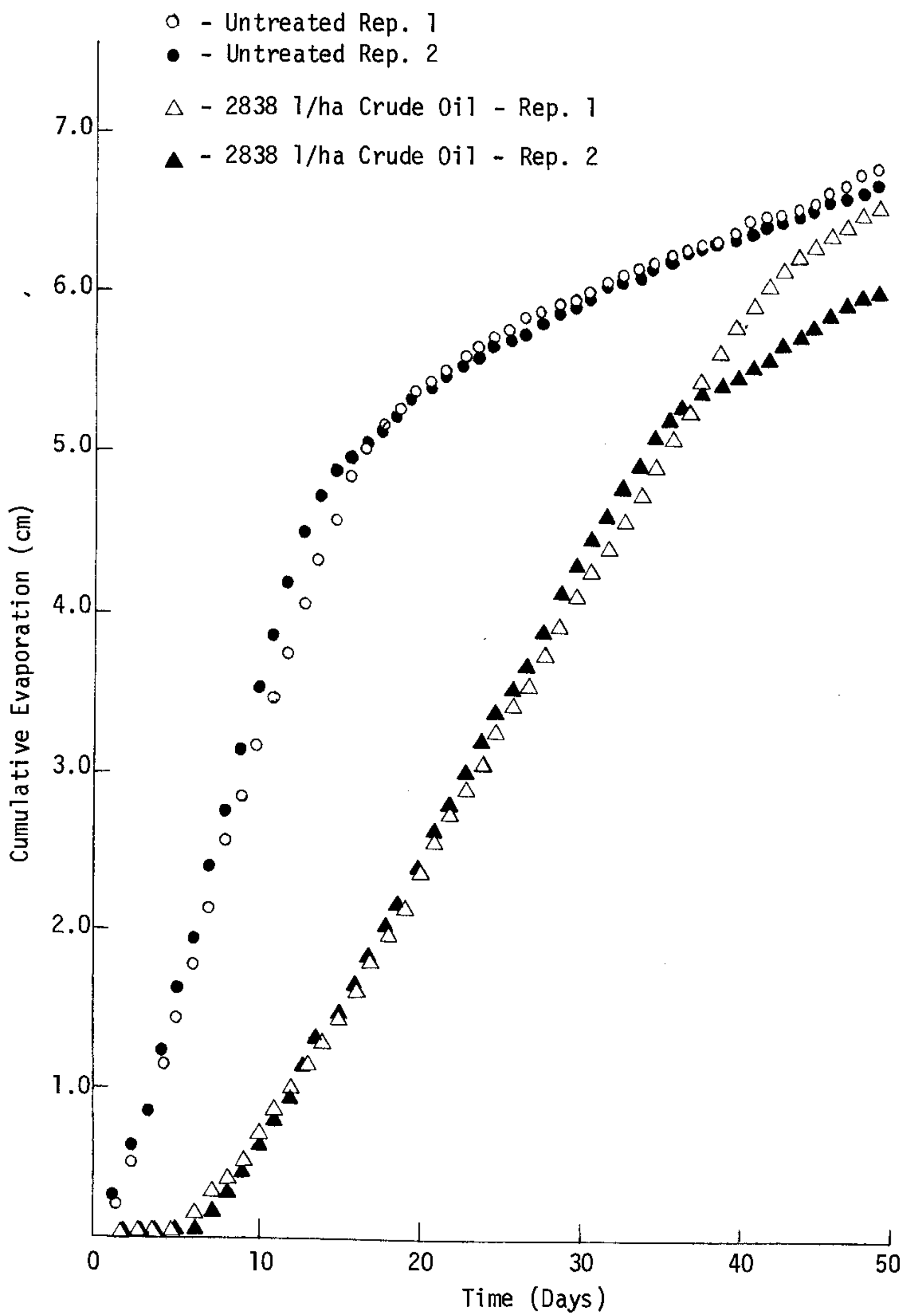

Figure 20. Cumulative evaporation by Olton loam soil as affected by crude oil.

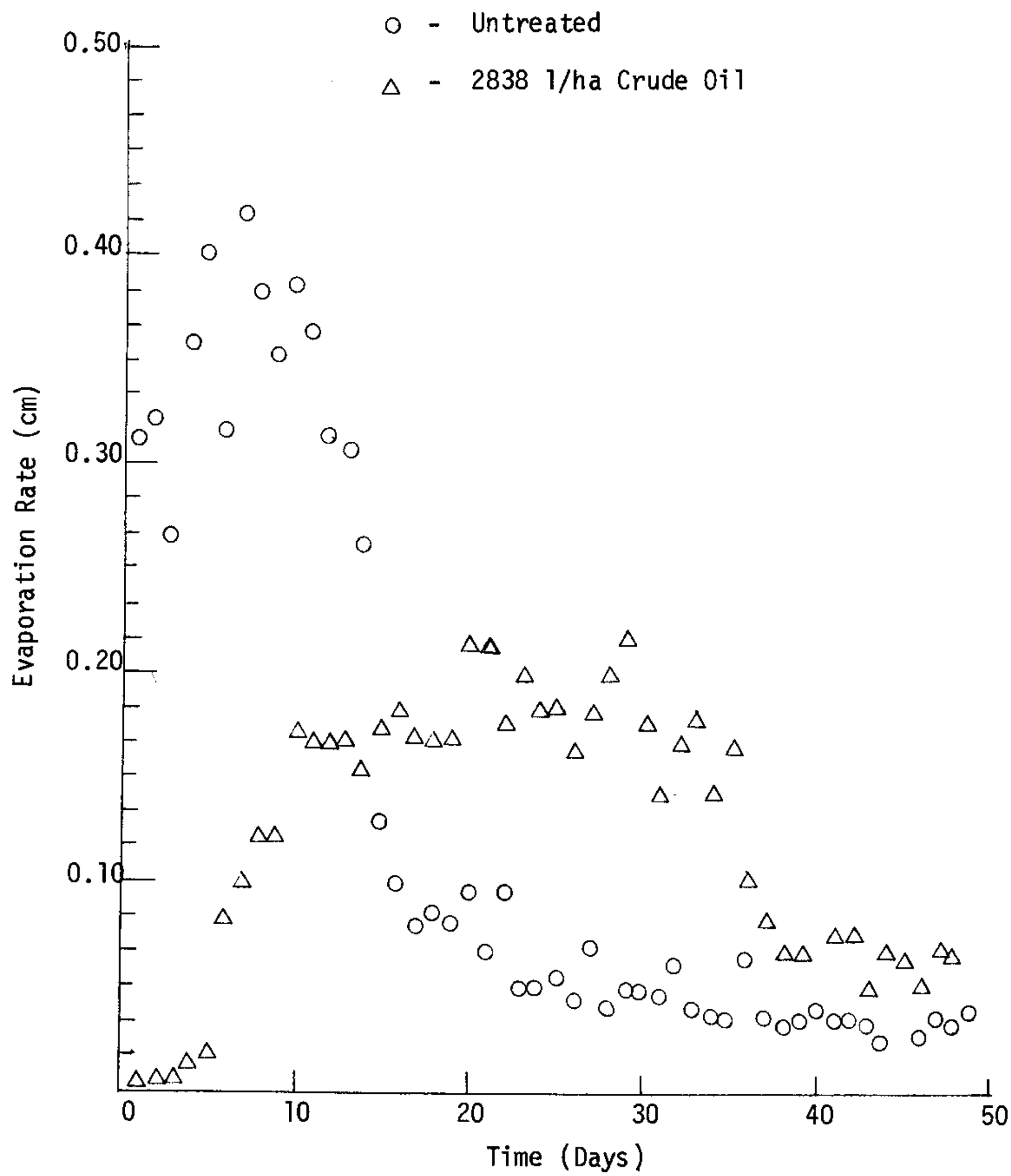

Figure 21. Evaporation rate of untreated and crude oil treated Olton loam soil.

The initial evaporation from the oil-treated surface was compared with the evaporation of a water surface with a continuous oil film (Figure 22). It appears that the suppression due to crude oil during the earlier stages of drying is the same type suppression that occurs when oil is spread on a free water surface and prevents vapor transfer from the water surface. During this period, the oil-treated soil surface was shiny in appearance indicating that a film of oil existed which had not reacted with the soil surface.

Following this constant stage of drying, the oil reacted with the soil surface and the surface appearance changed from shiny to dull. Area measurements were made of the amount of dull surface and a relationship was found to exist between the amount of dull surface and the cumulative evaporation during the rising stage of drying (Figure 23). As the dull surface area increased, soil water evaporation increased. Apparently as the surface dried, it became more porous, and the water that was under the oil surface was freer to evaporate. The evaporation rate increased until the surface was dry and the 2nd constant stage of drying from the oil-treated surface occurred.

A comparison of the cumulative evaporation of the 2nd constant stage of drying with the cumulative evaporation of the high-rate stage of drying from the untreated soil is given in Figure 24. The slopes of the regression equations approach 1 indicating that the accumulation is constant with respect to time. Therefore, the major difference between the two curves is the rate of accumulation. Evaporation from the crude oil-treated soil amounted to approximately

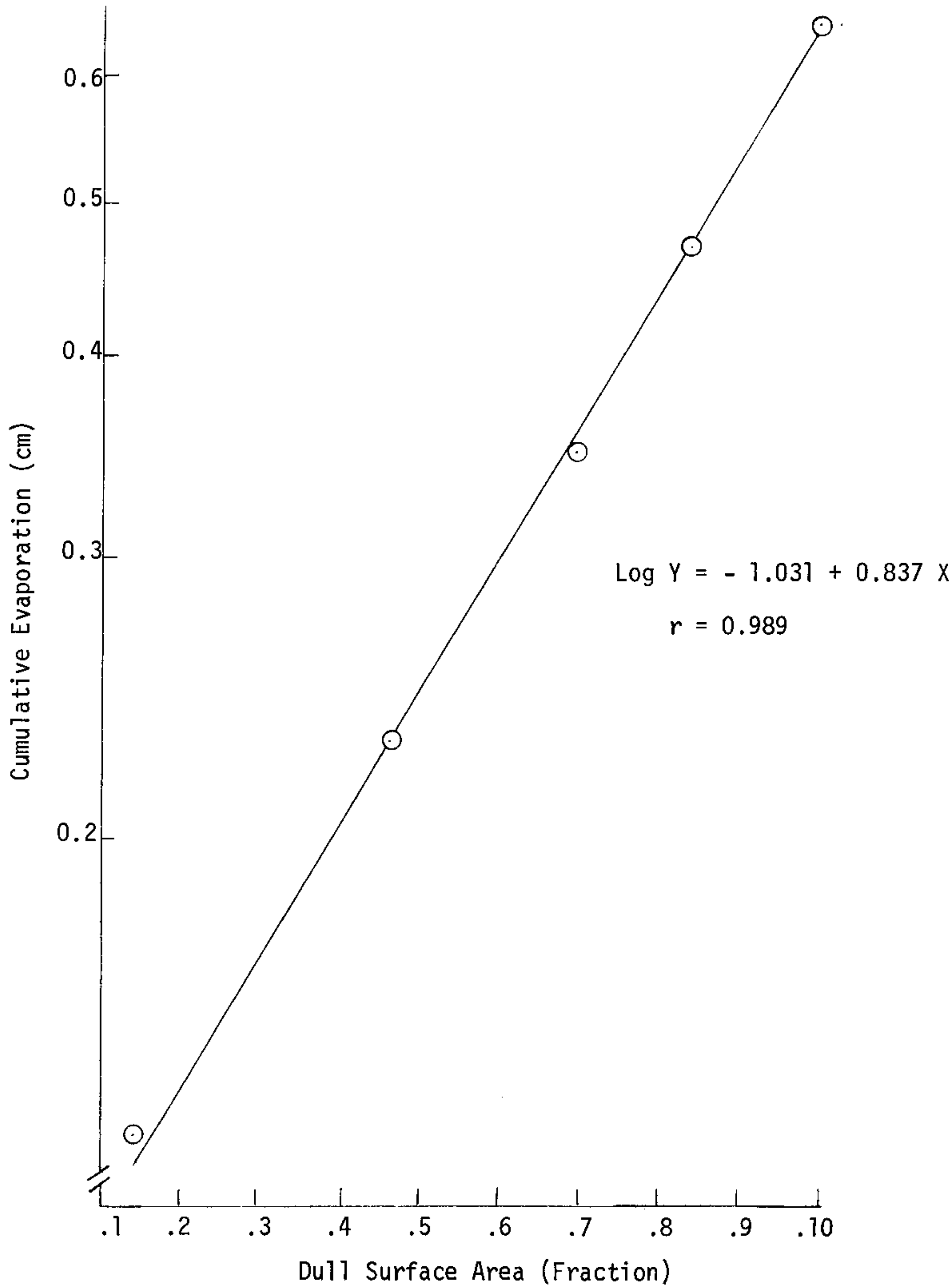

Figure 22. Relationship between the cumulative evaporation and the fraction of dull surface during the "rising" stage of drying.

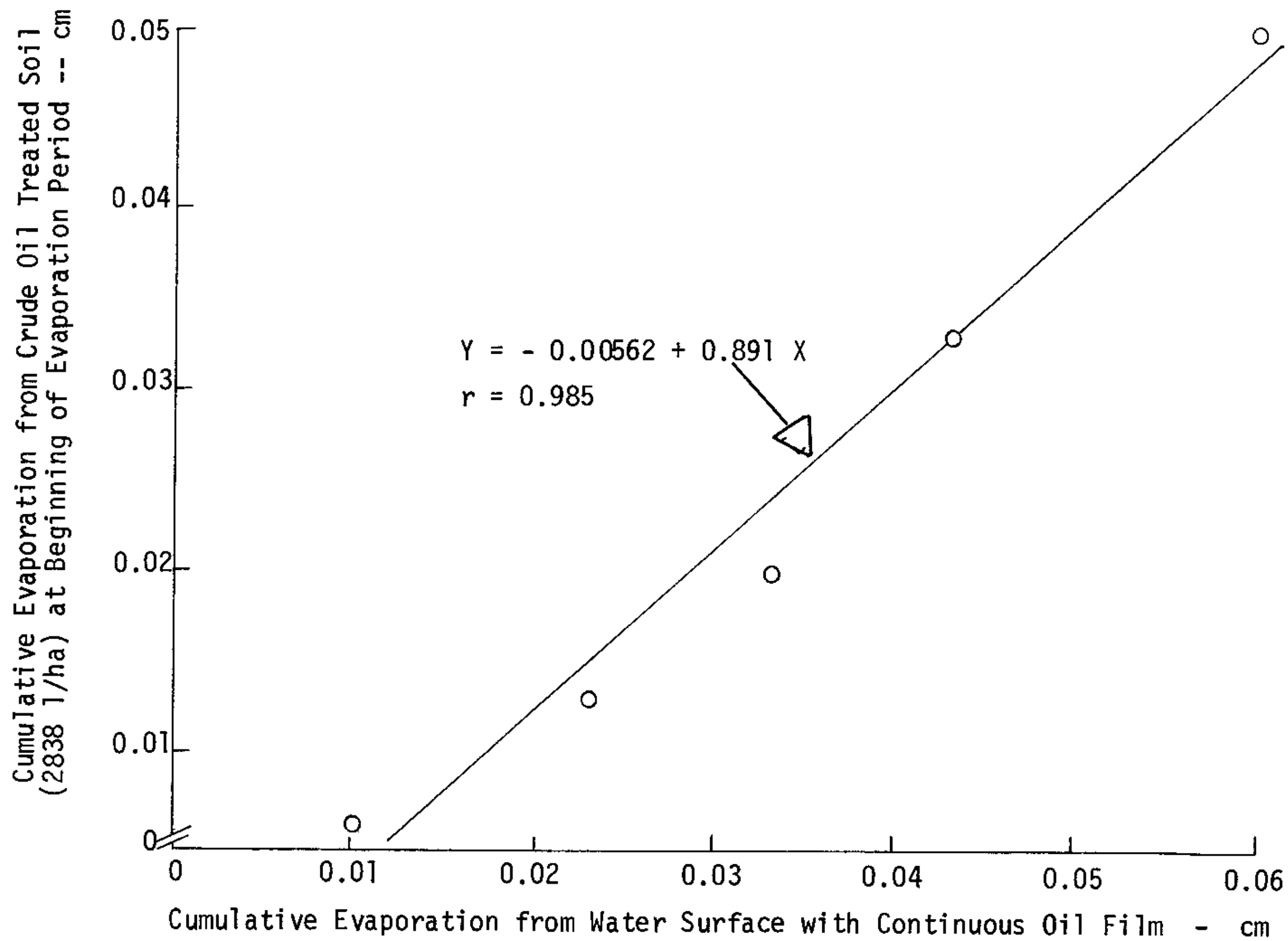

Figure 23. Relationship between the cumulative evaporation of a water surface with continuous crude oil film and the initial cumulative evaporation from an Olton loam soil sprayed with crude oil.

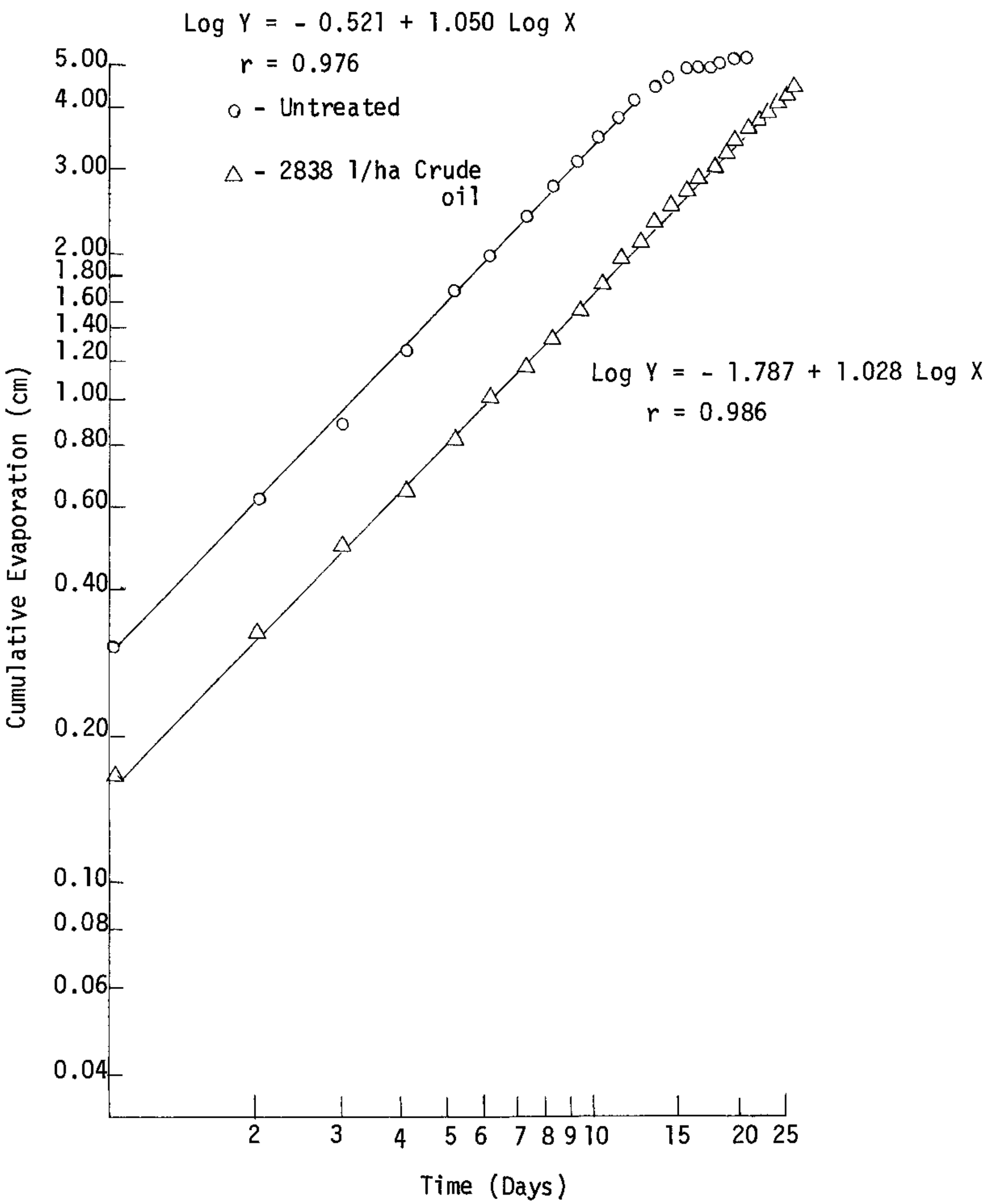

Figure 24. Cumulative evaporation during the high rate stage of drying of untreated and crude oil treated Olton loam soil.

0.16 cm/day while evaporation from the untreated soil amounted to about 0.31 cm/day during this stage. Approximately the same amount of water was lost from both the treated and untreated columns. Evaporation during this stage occurred for about 26 days from the oil-treated soil and for about 13 days from the untreated soil. During this period the rate of conduction of water to the soil surface was probably maintained at a constant rate in both cases. The rate of evaporation from the crude oil-treated surface, however, was only 43 percent of the rate from the untreated surface. This indicates that a barrier was formed when the crude oil reacted with the soil. This barrier, in turn, slowed down the rate of conduction of liquid water to the soil surface, and resulted in decreased evaporation.

The soil moisture retention data present further evidence for this thesis. Crude oil significantly influenced the amount of water retained at suctions less than 1 bar (Table 12). The data suggest that the reaction between crude oil and soil produced a barrier of low water retention which would slow down the rate of conduction of liquid to the soil surface. The data points lying on the upper right of the curves represent the falling stages of drying from the 2 treatments. As previously indicated from the rate curves, (Figure 21), these stages were only a few days in duration.

Following the short falling stages, the longer low-rate stages of evaporation occurred. Figure 25 shows the cumulative curves obtained during this period. The curve from the untreated soil has a slope of 0.804, which is less than one, implying that the rate is

Table 12. Moisture retention data of crude oil treated (5% by weight) and untreated Olton loam soil.

Pressure Applied (Bars)	% Moisture	
	Untreated	Crude Oil Treated
1/10	35.5	15.2
1/3	24.2	13.8
1	14.4	12.3
3	12.5	12.5
15	10.6	10.6

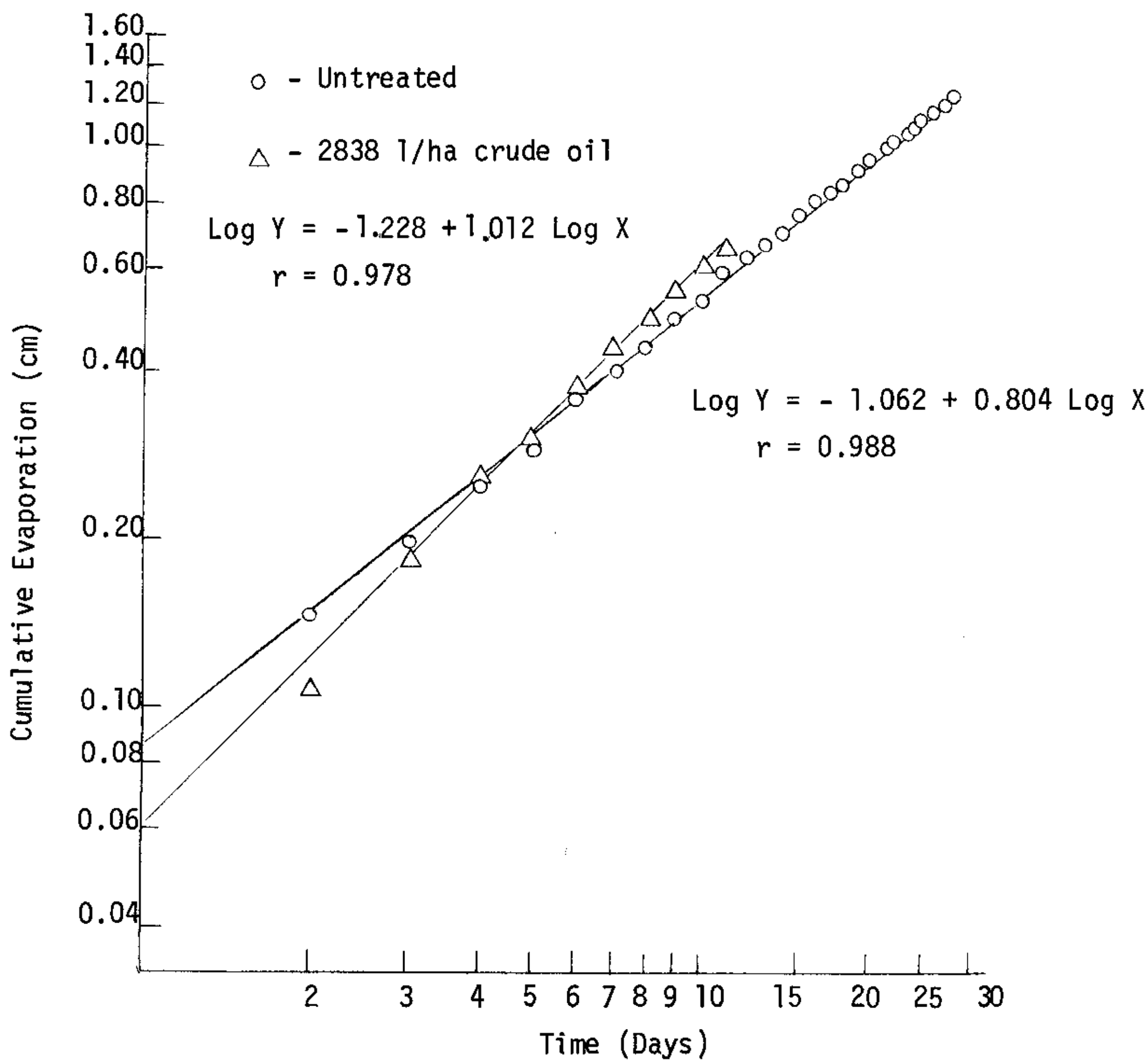

Figure 25. Cumulative evaporation during the last stage of drying of the untreated and crude oil treated Olton loam soil.

decreasing with time. During this stage of drying, evaporation losses occur by vapor diffusion. The slope of the curve from the crude oil treatment approaches one, implying that the rate is constant (0.06 cm/day) with respect to time. However, the curve is beginning to break at the upper end. If the experiment had been continued, the slope of the curve would probably have approached that of the untreated soil. It can be readily seen that the crude oil treatment had no major effect on evaporation during this stage of drying.

As previously indicated, Bowers and Hanks (3) found that the infiltration rate was decreased when DDAC was applied to the soil. The outflow data obtained under constant head of 1 cm before and after oil treatment are indicated in Table 13 for samples with different rates of drying. There was no major change in outflow rate due to the presence of the oil film. Thus, water movement through the oil film under a pressure head is not affected.

Both mechanisms of suppression discussed here have also been attributed to the fatty alcohols in previous studies. Law (7) postulated that the suppression due to fatty alcohols in sands was the same as that from a free water surface, while that from soil (Amarillo fine sandy loam) was due to changes in capillary conductivity. Olsen et al. (10) attributed the change in evaporation rate due to hexadecanol in a Weld loam soil to a change in capillary conductivity. In both cases, however, the material was mixed with the soil. In the present studies the material was sprayed only on the smoothed wet surface.

Table 13. Rate of outflow from columns of Olton loam soil before and after treatment with crude oil (2838 l/ha) at various evaporation rates.

Evaporation rate (cm/dy)	Outflow rate before treatment (cm/hr)	Outflow rate after treatment (cm/hr)	Outflow rate after crude oil layer removed (cm/hr)
0.03	1.35	1.22	1.48
0.11	1.25	1.15	1.25
0.16	1.18	1.17	1.18
0.19	1.21	1.18	1.24
0.24	1.33	1.27	1.29

Controlled Environment Chamber Studies

It was not possible to evaluate separately the influence of light intensity, air temperature and humidity, and soil temperature on soil water evaporation in the controlled temperature room. It was, therefore, necessary to obtain a controlled environment chamber modified with water baths to evaluate these parameters. A description of the facilities and results follow.

Methods and Materials

Surplus coolers were modified to contain 8 containers of soil as described in the wind tunnel studies. Each cooler could be varied from 4° - 38° $\pm 1^\circ$ C. by using chilled water and heaters.

These were located in a custom built controlled environment chamber (Series 5000) constructed by Scientific Systems, 9020 South Choctaw, Baton Rouge, La. 70815. The chamber had the ability to control the following parameters at the levels indicated.

Parameter	Level
Light Intensity	0 - 0.8 Langley/min ± 1%
Humidity	10 - 100% ± 3%
Temperature	4° - 38° $\pm 1^\circ$ C.

Initially, there was considerable trouble obtaining and maintaining the wide range of conditions in the chamber. It was a prototype and there were many factors the company failed to consider. Although the company personnel were most cooperative in modifying the chamber as needed, the initiation of the experiments was delayed about 18 months.

Results and Discussion

Experiment 1 - Influence of Soil Temperature on Evaporation

As soil temperature was increased from 10 - 38° C., the amount of water lost to evaporation from the untreated containers increased (Figure 26). This is not surprising as vapor pressure increases with temperature and more vapor transfer occurs.

The crude oil was much more effective as an evaporation suppressant at the lower temperatures (Figures 27 to 29). The amount of water lost after 28 days from the 10, 24, and 38° C. soil temperature levels was 0.60, 0.98, and 4.93 cm respectively from surfaces treated with 4730 l/ha of crude oil. Crude oil at the rate of 946 l/ha was more effective at 10° C. (Figure 27) than 2838 l/ha at 24° C. (Figure 28). At 24° C. (Figure 28) 946 l/ha of crude oil was almost as effective as 946 l/ha at 38° C. (Figure 29). These data are what would be expected in light of the previous experiment of the mechanisms of suppression due to crude oil. The crude oil layer does not impede vapor flow to the soil surface. Therefore, as vapor pressure increased with increasing soil temperature, more vapor moved from the soil to the surface through the crude oil layer and was lost to evaporation.

These data indicate that crude oil would be most effective in suppressing evaporation during the winter months when the soil temperature is low. However, water applications were not necessary during the winter months during the course of the experiment and the potential of the material as a suppressant could not be evaluated during this period. (All data in this experiment are located in Table A-9, Appendix)

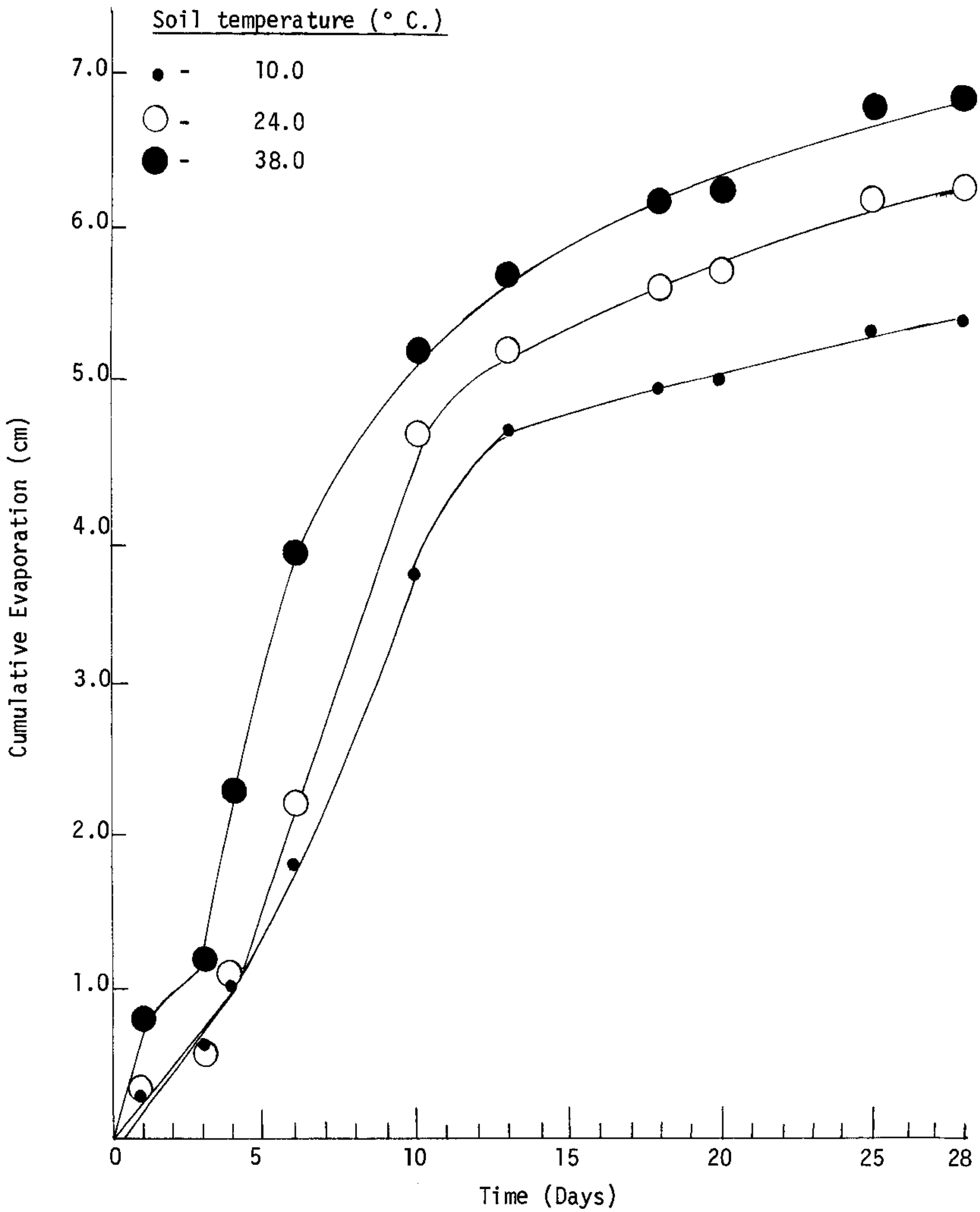

Figure 26. Cumulative evaporation from Olton loam soil at different soil temperatures. (Chamber temperature 24.0° C., relative humidity 50%)

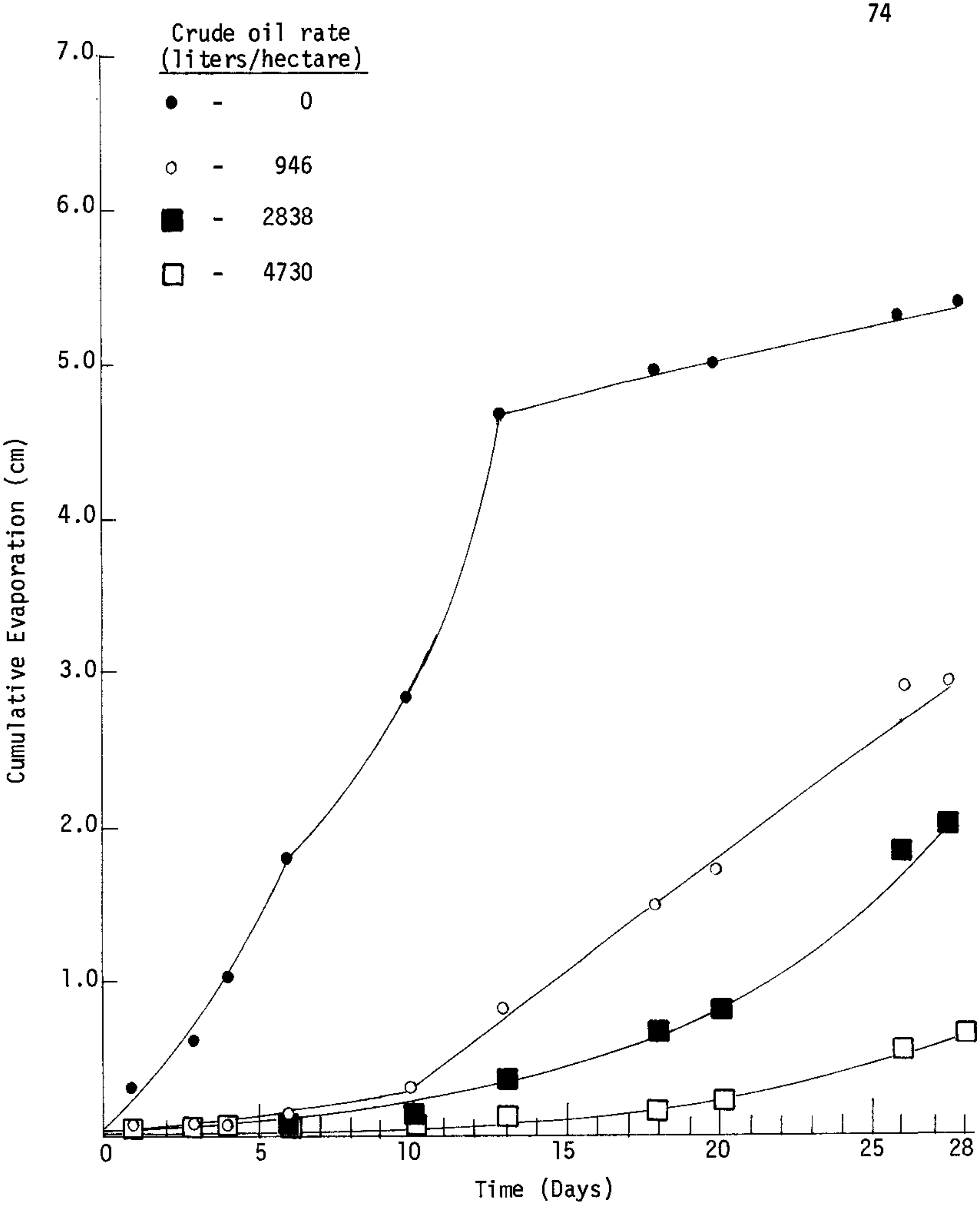

Figure 27. Cumulative evaporation from Olton loam soil at a temperature of 10.0° C. (Chamber temperature 24.0° C., relative humidity 50%)

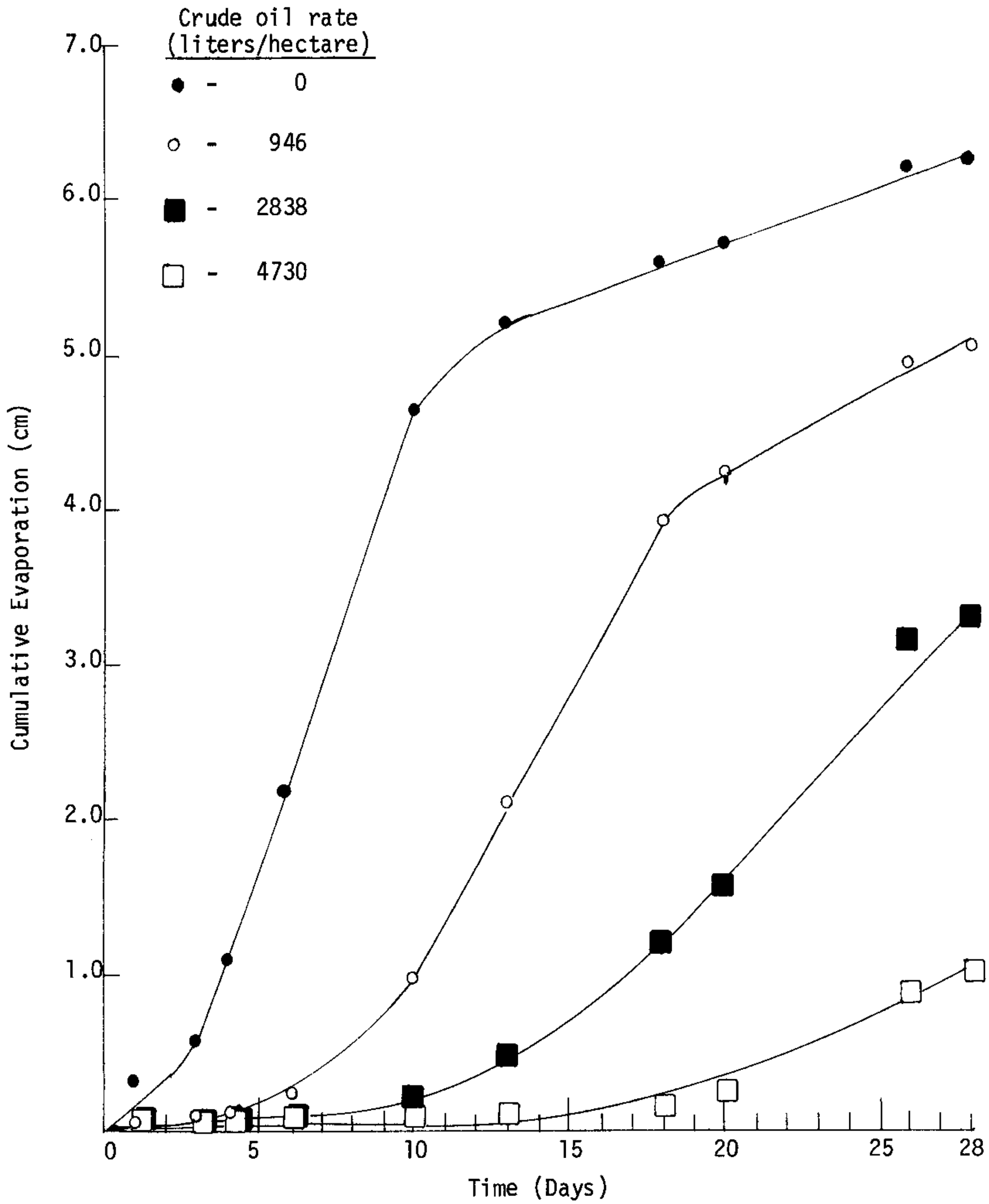

Figure 28. Cumulative evaporation from Olton loam soil at a temperature of 24.0° C. (Chamber temperature 24.0° C., relative humidity 50%)

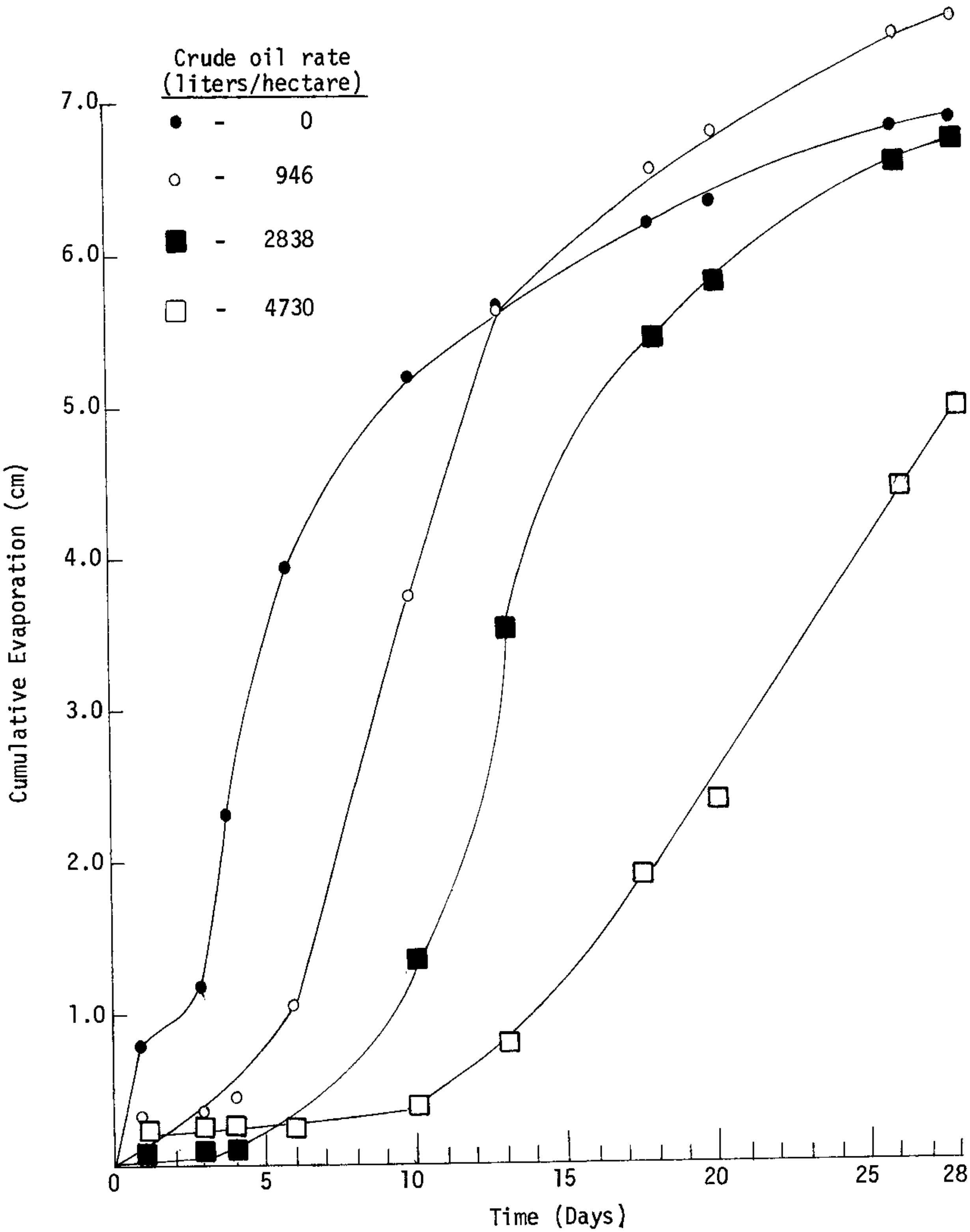

Figure 29. Cumulative evaporation from Olton loam soil at a temperature of 38.0° C. (Chamber temperature 24.0° C., relative humidity 50%)

Experiment 2 - Influence of Light Intensity on Evaporation.

Light intensity was evaluated at 2 different temperatures and relative humidities. It was first evaluated at an air temperature of 38° C. and relative humidity of 22%. Light levels of 0.15, 0.30, and 0.60 Langleys/min were used. The data obtained indicated an inverse relationship between the amount of light and total evaporation loss after 36 days (Figure 30).

It may have been possible that the high air temperature coupled with the high light intensity created a surface barrier very quickly through which only vapor movement occurred. Liquid movement may have occurred for a longer period of time in the light and heavy shade treatments contributing to a much larger evaporation loss.

The crude oil treatments were effective in reducing soil water evaporation for only a short period of time during the experiment. At the 946 l/ha rate of crude oil, suppression occurred for only 3 - 4 days (Table A-10, Appendix). At the end of the 36-day evaporation period, the evaporation loss was equal or greater than the untreated containers.

The 2838 l/ha rates of crude oil were effective 4 - 11 days. In general, the effectiveness increased with shading (Table A-10, Appendix). This further suggested that light intensity and surface temperature were related to evaporation losses from the crude oil-treated surfaces. As light intensity was decreased, the black surface may have absorbed less radiation and was, therefore, cooler, creating a lower vapor pressure in the soil profile resulting in less evaporation loss.

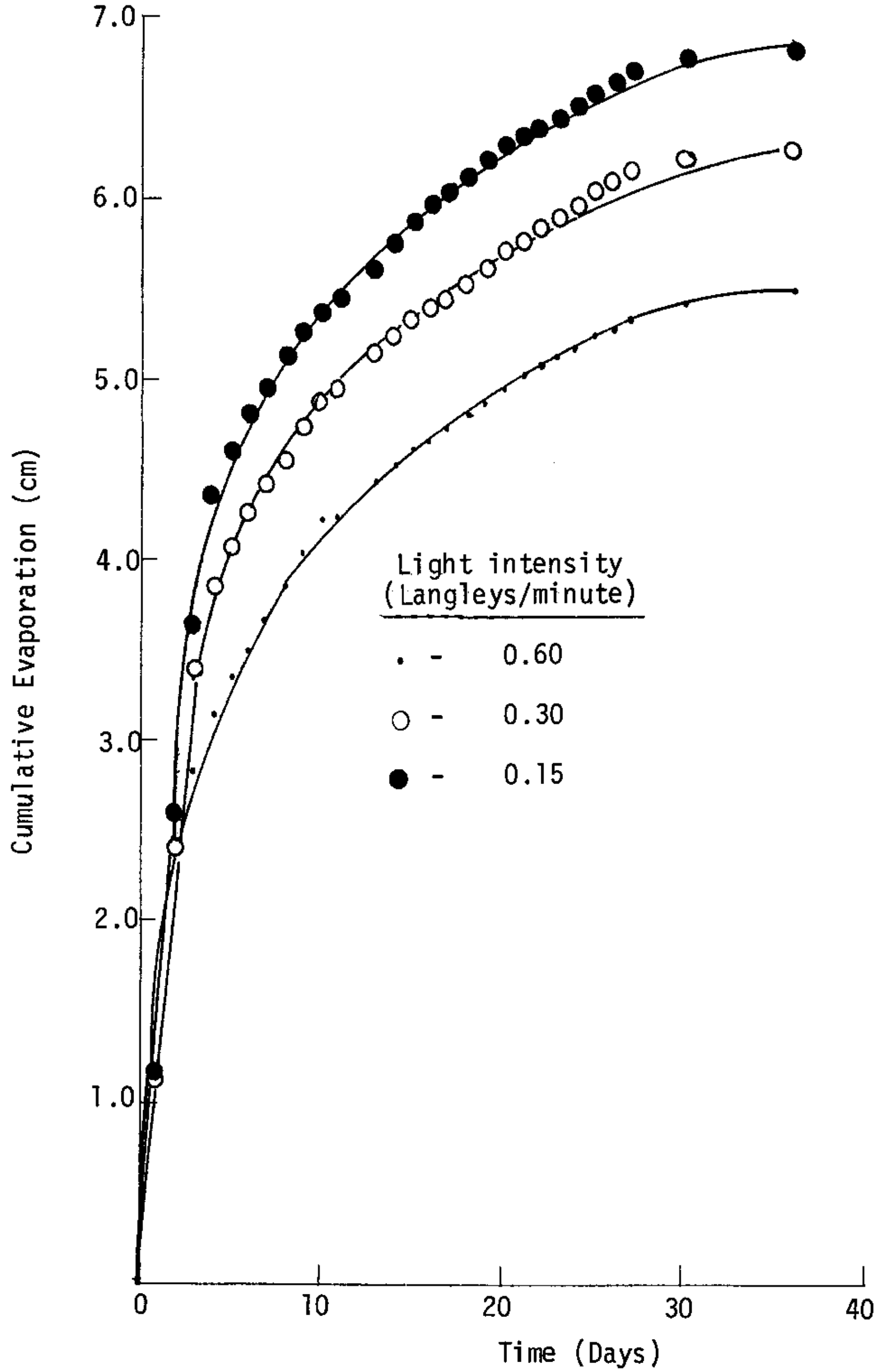

Figure 30. Cumulative evaporation from Olton loam soil receiving different light intensities. (Chamber temperature 38.0° C., relative humidity 22%)

The same trend did not hold, however, for the 4730 l/ha rate of crude oil (Figure 31). In general, there was less evaporation loss in the containers under the light shade. As mentioned in previous studies, the crude oil used in these studies was quite variable, and it may have been possible that some of the containers at the high rates received a larger portion of non-volatile materials which prevented a trend from being established between a parameter and the treated surfaces.

Since the data from the shading studies was quite variable when the study was conducted at 38° C., it was decided to conduct the same light intensity study at a lower temperature (10° C.) and a humidity of 50% so as to decrease temperature influences on the treatments. All the data obtained from this part of the experiment is located in Table A-11 of the Appendix.

At a lower air temperature, different light intensities did not influence the evaporation loss from a bare soil (Figure 32). It appears, therefore, that it is the net radiation resulting from light intensity that influences soil water evaporation--not solar radiation. This is not surprising when one considers that solar radiation is not a part of the energy balance equation (13).

Shading did, however, influence the amount of water lost to evaporation from the crude oil-treated containers. An inverse relationship existed between the amount of water lost to evaporation and the amount of light received (Figure 33). This relationship is similar to that obtained for untreated containers from the experiment

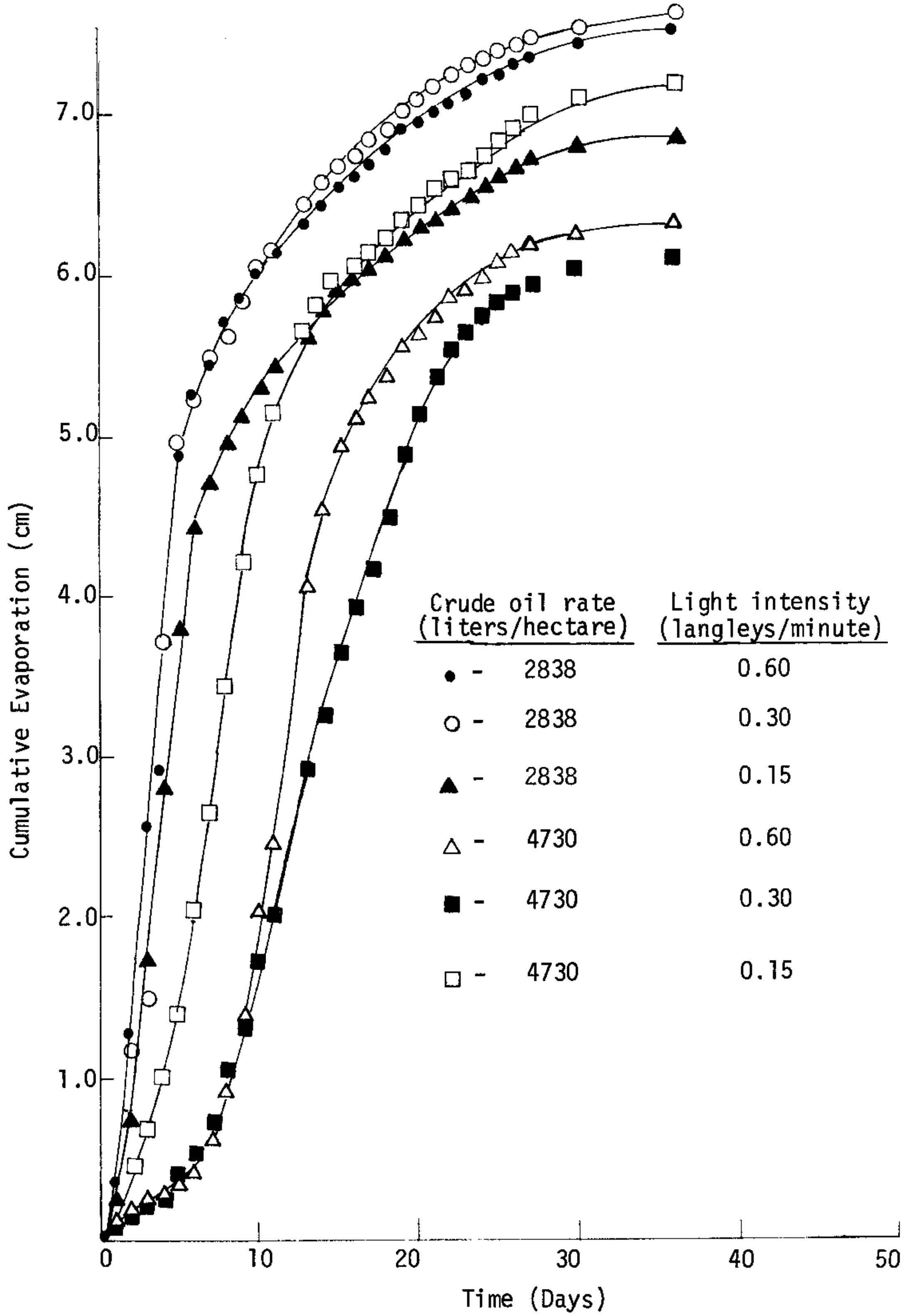

Figure 31. Cumulative evaporation from crude oil treated Olton loam soil receiving different light intensities. (Chamber temperature 38.0° C., relative humidity 22%)

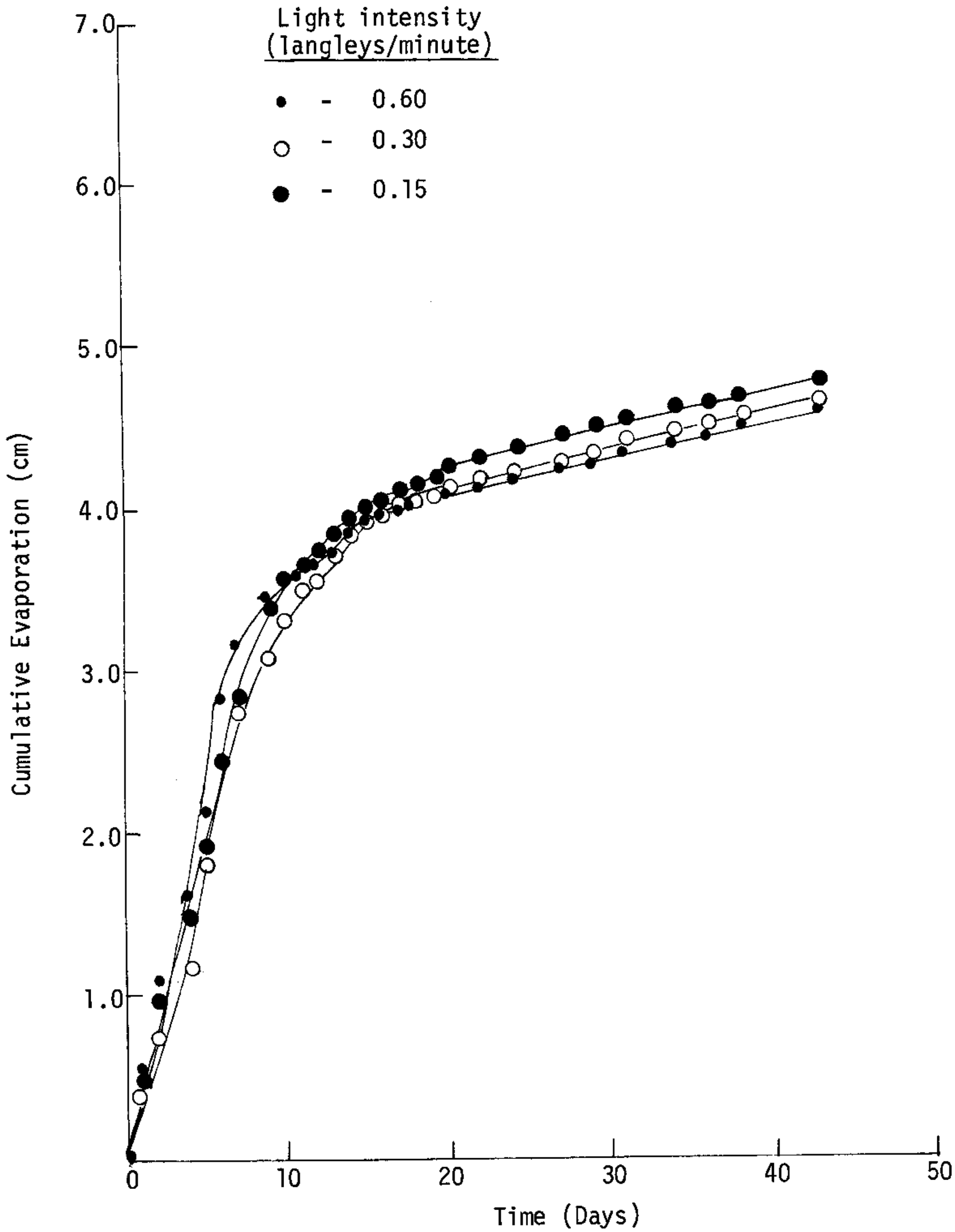

Figure 32. Cumulative evaporation from Olton loam soil receiving different light intensities. (Chamber temperature 10° C., relative humidity 50%)

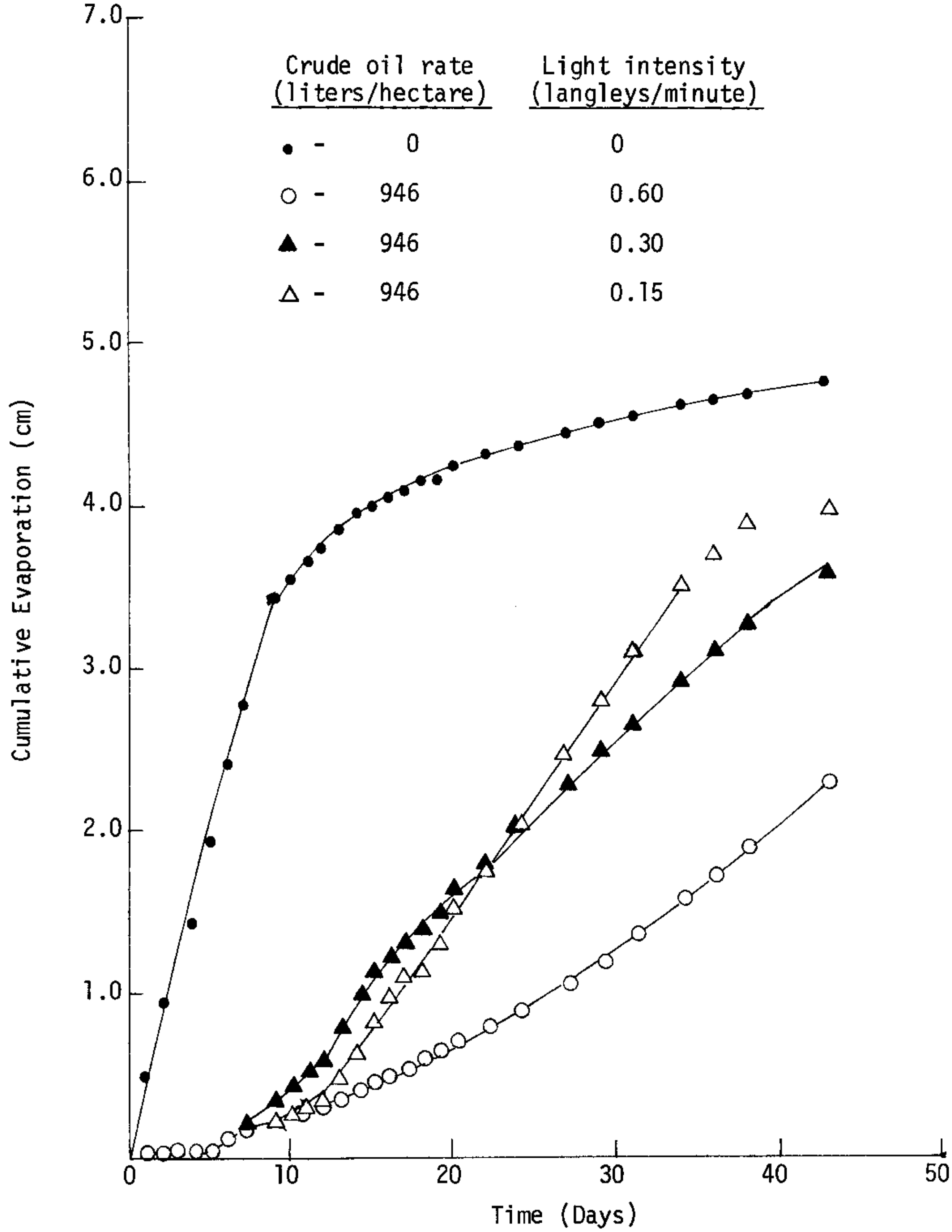

Figure 33. Cumulative evaporation from crude oil treated Olton loam soil receiving different light intensities. (Chamber temperature 10° C., relative humidity 50%)

conducted at 38° C. (Figure 30) This further suggests that incident radiation may contribute either to surface drying which would increase the amount of time that losses to vapor diffusion rather than liquid losses would occur. Also, wider temperature differentials between the surface and the soil below the surface could be created in the treatments with a high light intensity than with a low light intensity, which would decrease vapor losses.

The concentration influence of the various rates of crude oil are shown in Figure 34 for the heavy shade. As would be expected, evaporation decreased as concentration increased. Similar trends were observed for the other light intensities (Figure 31).

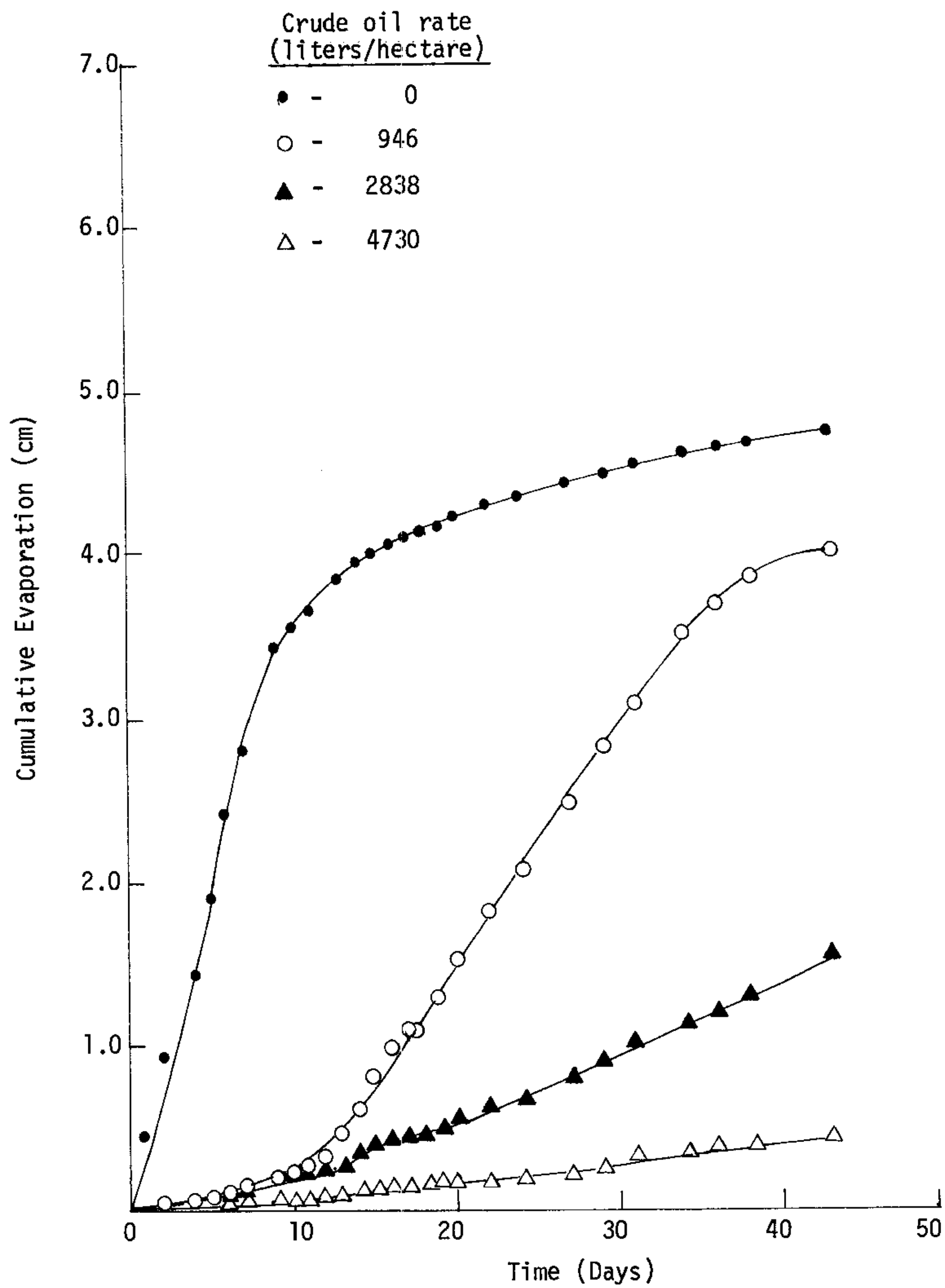

Figure 34. Cumulative evaporation from crude oil treated Olton loam soil at a light intensity of 0.15 langleys/minute. (Chamber temperature 10° C., relative humidity 50%)

Experiment 3 - Influence of Vapor Pressure Deficit on Evaporation.

The influence of vapor pressure deficits, a measure of the "dryness" of the atmosphere, on evaporation from treated and untreated containers was also evaluated. Vapor pressure deficits of 7.5, 13.5, and 22.1 mb were established in the controlled environment chamber at different times. At 22.1 mb, 4730 l/ha of crude oil was effective in suppressing evaporation for 5-6 days (Figure 35). At the end of the evaporation period, however, the crude oil-treated surface had lost more than the untreated surface. This was probably due to the combination of a dark surface on the crude oil-treated container which would cause a high surface temperature and a high chamber temperature. This would tend to cause a high vapor pressure in the water in the containers and high vapor diffusion.

At the lower vapor pressure deficits, the temperatures were lower and the crude oil surface was much more effective in suppressing evaporation. At a vapor pressure deficit of 13.5 mb, however, more water was evaporated from the untreated container than at either 7.5 or 22.1 mb. It may be possible that capillary continuity was maintained for a longer period than at 22.1 mb causing more water to be lost than at the higher vapor pressure deficit. On the other hand, less water was lost from the containers at 7.5 mb vapor pressure deficit due to the lower water vapor pressure although capillary continuity was maintained.

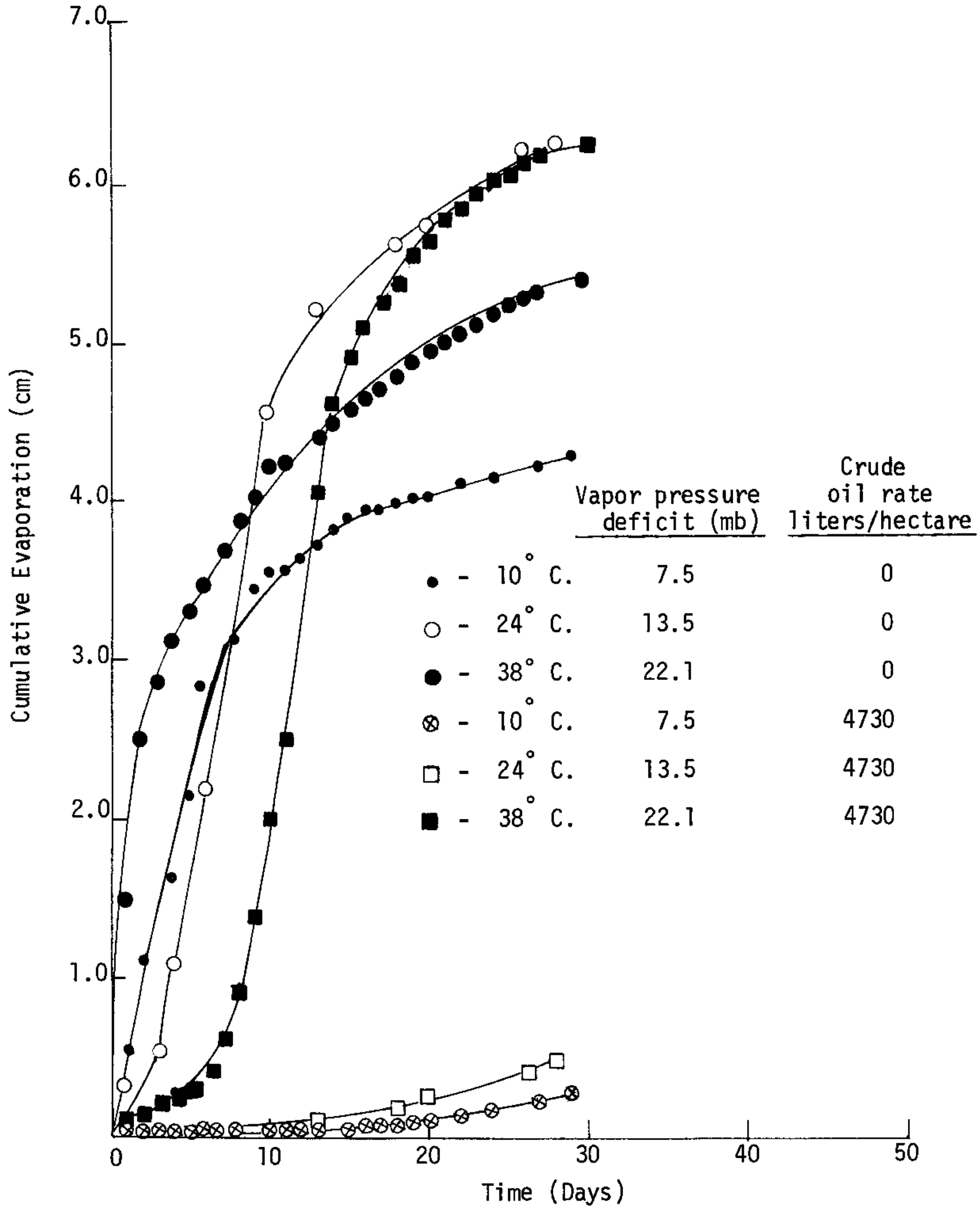

Figure 35. Cumulative evaporation from Olton loam soil - vapor pressure deficit studies. (Light intensity 0.60 Langleys/min)

CHAPTER IV

FIELD STUDIES

From the greenhouse and controlled environment studies, it appeared that crude oil was the only material which had potential as an evaporation suppressant. For the material to be an asset to the economy of the area, it would have to show crop yield increases with resultant increases in net income from the savings of soil moisture. Field studies were, therefore, conducted using cotton, the highest value crop planted on a large acreage in the area.

Methods and Materials

All of the experiments were conducted on an Olton loam on the Lubbock Station. The crude oil from the Anton-Irish oil field was used in all the experiments. Two different techniques of application were used: (1) The crude oil was sprayed on the soil surface with a hand sprayer following rains or irrigations and (2) the crude oil was floated on the surface of the irrigation water during irrigation. The rates, times, and methods of application during the 3-year period are shown in Table 14. Cotton was studied under dryland conditions in 1968 and under irrigation following the addition of 5.0-7.5 cm of irrigation water in 1969 and 1970. Moisture data was procured during the 1968 cropping season with the gamma attenuation probe. Temperature data were procured with a thermocouple recorder.

Results and Discussion

The yield data from the 3-year study is shown in Table 14. No increases in yield of cotton occurred from any of the sprayed treatments during the 3-year period. The data shown in Figures 36 and 37 show that increases in the maximum air and soil temperature occurred in the crude oil-treated plots. Soil moisture was also higher in the crude oil-treated plots (Figure 38). It was apparent that soil water extraction was reduced by the crude oil applications. Possible reasons for this are (1) the oil may have toxic material, (2) the oil may have produced a thermal regime less desirable for plant growth and (3) the oil may have produced a thermal regime which induced the water to be stored in the lower soil horizons.

The data from the controlled environment experiments indicated that crude oil was most effective in suppressing evaporation when the soil and air temperature was 24° C. and below. This suggests that it would be most effective in saving water during winter and spring irrigations. However, as previously mentioned, such irrigations have not been necessary at the Lubbock Station the past 3 years. It was therefore not possible to evaluate the potential of crude oil applications in suppressing evaporation during this period.

It was observed that water from rainfall failed to penetrate the crude oil-treated surfaces to any extent in sloping areas. This presented the possibility that crude oil could be an aid in harvesting water from soil surfaces. This potential is currently being investigated in another project.

Table 14. Yield data from Crude Oil Field Experiments.

Year	Method	Time	Rate l/ha	Cotton Yield kg/ha lint
1968	Sprayed on surface	July 14	2838	297
	Sprayed on surface	Aug. 2	2838	339
	Untreated			312
1969	Sprayed on surface	July 11	2838	598
	Untreated			568
	Floated	Aug. 15	473	560
	Untreated			457
1970	Sprayed on surface	Aug. 12	2838	363
	Untreated			402
	Floated	Aug. 5	1892	370
	Untreated			392

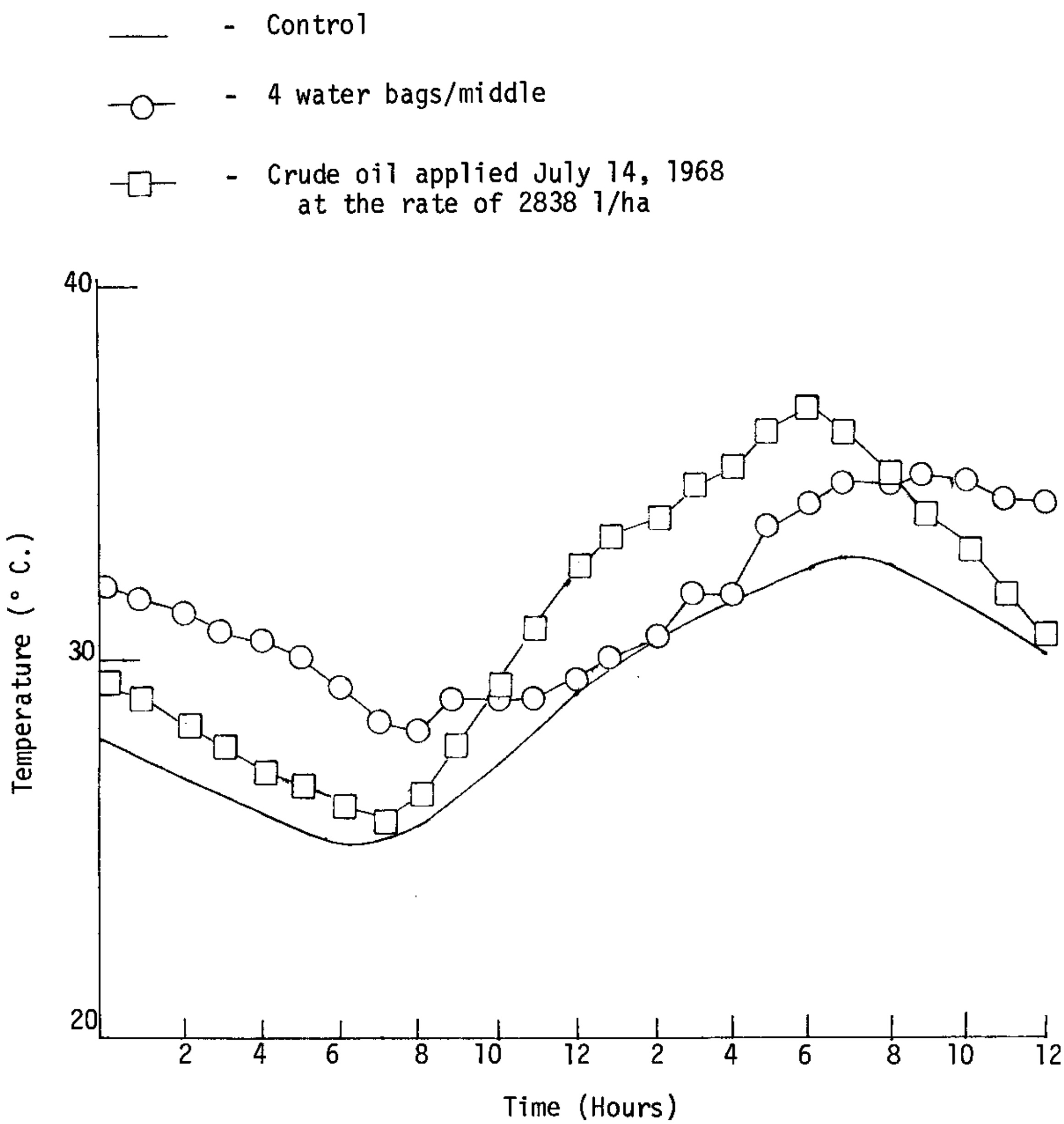

Figure 36. Temperature in mulch treatments at 10 cm below the soil surface of cotton.

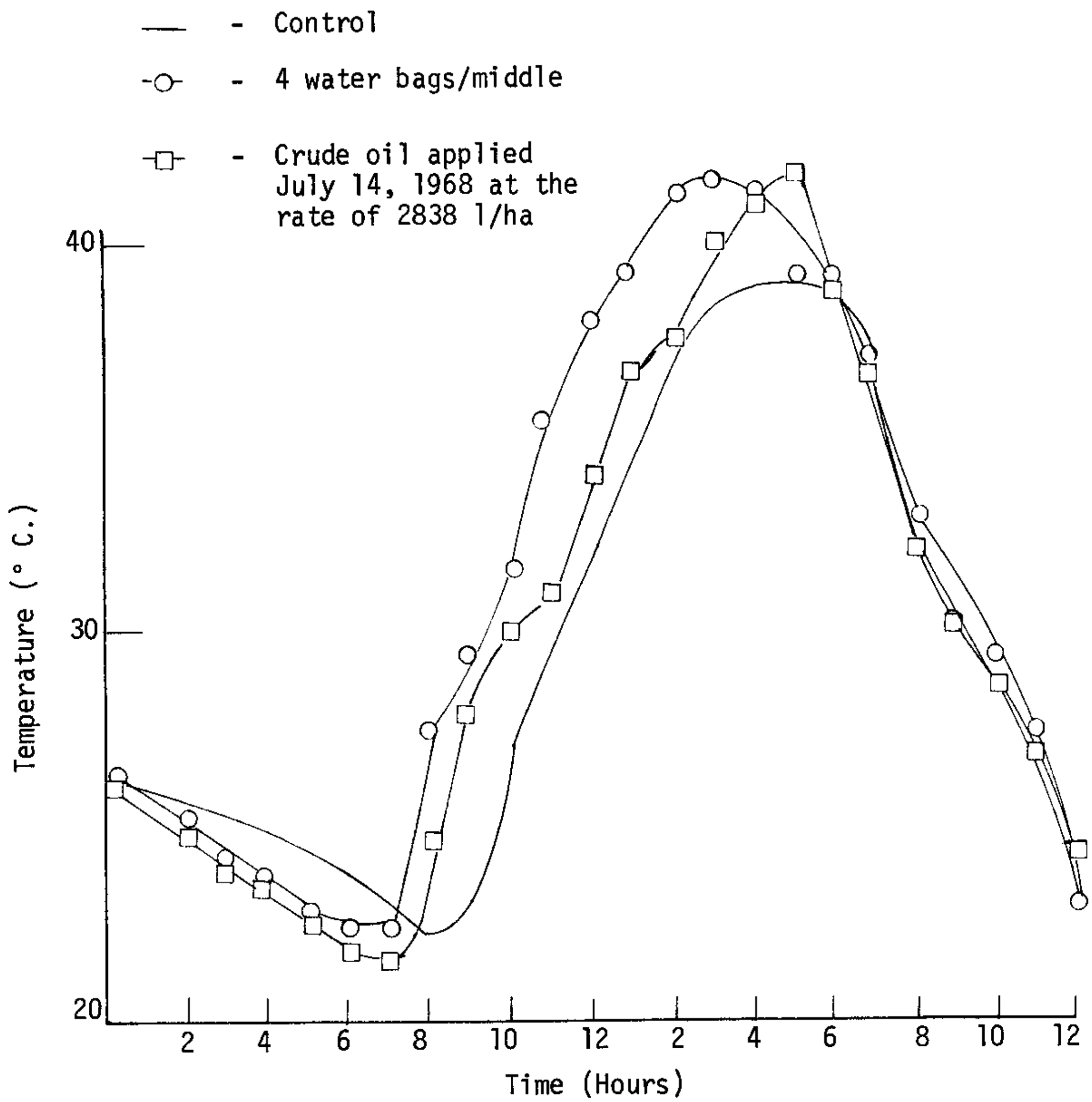

Figure 37. Temperature in mulch treatments at 10 cm above the soil surface of cotton.

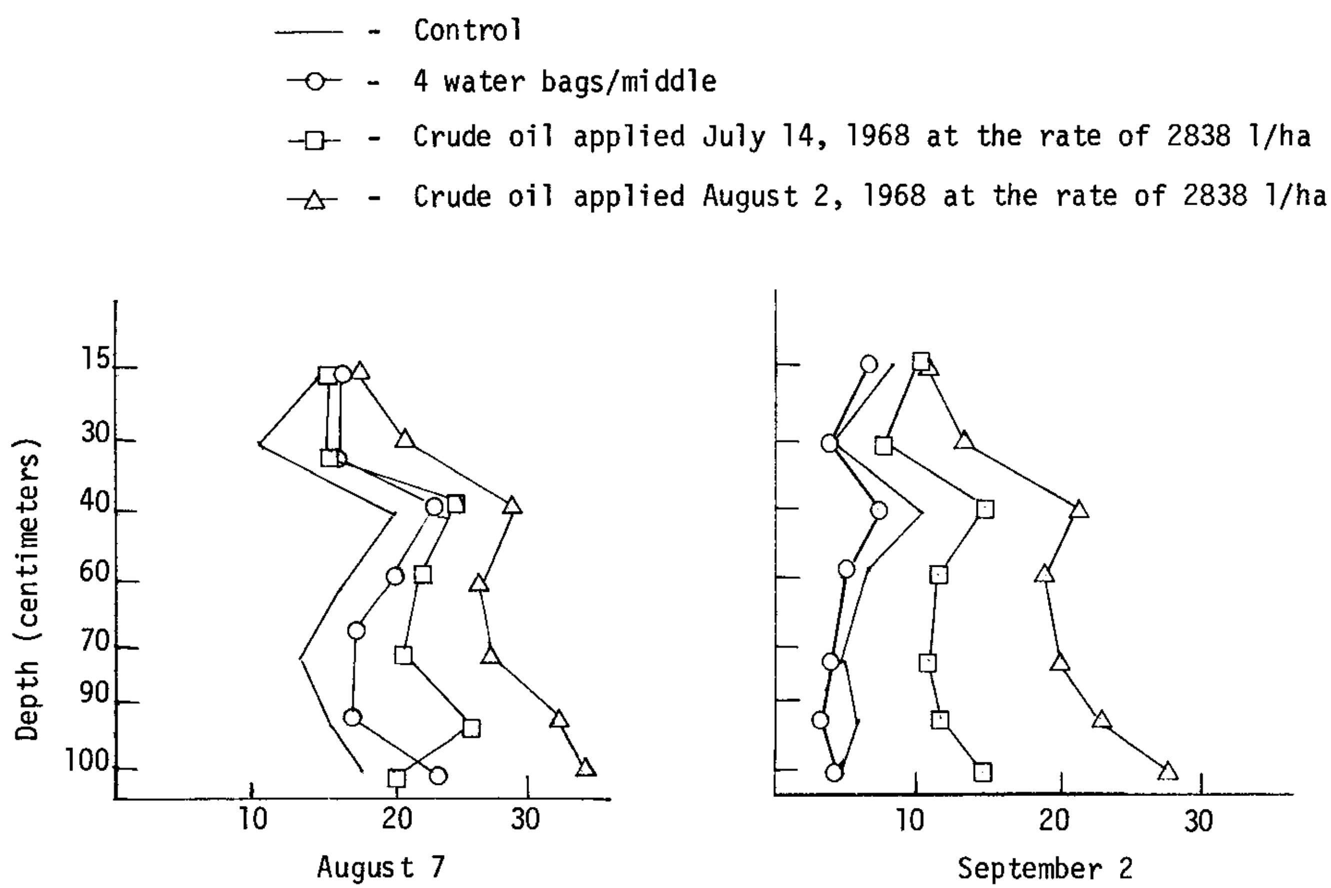

Figure 38. Moisture distribution in the soil profile of cotton treated with mulches.

CHAPTER V

SUMMARY AND CONCLUSIONS

Chemicals which will cause major decreases in soil water evaporation are not in widespread use because of expense and application problems. It was, therefore, deemed worthwhile to screen materials not previously studied for their potential as evaporation suppressants. Extensive greenhouse tests were conducted to screen, qualitatively, materials for their potential as evaporation suppressants. In the initial screening, crude oil, anionics, nonionics, silicones, polysaccharide-gum mixtures, oil-latex mixtures and fatty alcohols were applied to smooth wet Olton loam soil surfaces. Crude oil was effective up to 8 days at a rate of 1419 l/ha (150 gal/acre). The inclusion of an anionic at the rate of 90 kg/ha (100 lb/acre) further decreased evaporation when added to the above mentioned crude oil rate suggesting that surface active chemicals may be an aid in evaporation suppression by crude oil.

None of the other materials were effective in decreasing evaporation. Further studies were conducted with mixtures of surface active chemicals (anionics, cationics, nonionics) and crude oil showed that mixtures of crude oil at rates of 2838 l/ha (300 gal/acre) (5.0-12.5 percent by volume) and cationics were consistently more effective in suppressing evaporation than the same rate of crude oil alone. In a study involving different types of cationics (1.6 percent by volume) mixed with crude oil (2838 l/ha or 300 gal/acre), a difference was found to exist between cationics. The cationics which were quaternary ammonium compounds were the most effective in aiding crude oil to suppress evaporation. Cationics are compounds which are both hydrophobic and hydrophyllic in nature. The hydrophyllic portion of the compounds has a positive charge. It appears that the hydrophobic portion of the cationic compound is attracted to the crude oil and the hydrophyllic portion is attracted to the cation exchange capacity of the soil. Such a bond between the crude oil and the soil would make crude oil more effective as an evaporation suppressant.

The suppression by crude oil was compared to that of a film of hexadecanol. Differences in suppression between the materials was apparent. The crude oil was most effective early and decreased in effectiveness with time while hexadecanol was constant in its effectiveness throughout the evaporation period. This indicates that the suppression due to crude oil changes due to a change in the characteristics of the crude oil surface while the suppression due to hexadecanol is due to the change in soil characteristics at the time of application.

The addition of a reflectance material to the crude oil-treated surface decreased the effectiveness of the crude oil. The kaolinite used as reflectance material reacted with the crude oil and prevented the oil from reacting with the soil.

Under field conditions, it may be impractical to apply crude oil to smooth wet soil surfaces. Other approaches were therefore attempted to apply the crude oil. In one experiment, crude oil at a rate of 2838 l/ha (300 gal/acre) and surface active agent (5 percent by volume) were mixed with the water used to irrigate the containers seeded to cucumbers, tomatoes, and onions. This simulated irrigating to obtain emergence of the crops. There were no major decreases in evaporation losses or increases in seedling germination from such treatments. There was some decrease in the germination of the onions and tomatoes in containers treated with crude oil.

In another experiment, dry soil surfaces were sprayed and the containers were watered from the bottom to simulate irrigating rows of planted crops to obtain seedling emergence. At crude oil rates of 4730 l/ha (500 gal/acre) there was some evaporation suppression but no increases in seedling emergence.

The greenhouse studies showed that crude oil rates of 1419-2838 l/ha (150-300 gal/acre) were effective in suppressing evaporation when applied to smooth wet soil surfaces and at rates of 4730 l/ha (500 gal/acre) when applied to dry soil surfaces prior to adding water. However, the conditions were not controlled so that inferences could be made concerning the mechanisms of suppression or the influences of various atmospheric variables. Therefore, other investigations were made of different rates in controlled environment facilities. From these studies, further evidence of the importance of the smooth wet soil surface was obtained. The order of effectiveness of crude oil (4730 l/ha or 500 gal/acre) on the surfaces investigated was smooth wet soil surface > subirrigated wet surface > dry rough surface. Crude oil was effective during the first few days of the evaporation cycle as in previous experiments and decreased in effectiveness with time. The soil with the dry rough surface had the most water at the end of the 22-day drying cycle. However, such surfaces are difficult to obtain and maintain due to the high wind velocities of the Texas High Plains.

Since the crude oil applications applied to smooth wet soil surfaces were most effective in suppressing soil water evaporation, a detailed study of the mechanisms of suppression from such treatments was made. During the first few days of the drying cycle, the mechanism is the same that suppresses evaporation when an oil layer is spread on a water surface. Turbulent transfer of the vapor from the liquid at the soil surface to the atmosphere is affected. This is one of the major potentials presented by Lemon (8) to suppress evaporation. Following the first few days of the evaporation period, an increase in evaporation occurred until a constant evaporation rate was reached. However, the rate was not as high as that from an untreated soil. This indicates that a change in the soil surface occurred which decreased the capillary continuity.

The existence of two mechanisms of suppression by one material is a unique finding. Studies of mulches of gravel by Adams (1) and plant residue by Bond and Willis (2) show that such mulches decrease the rate of evaporation immediately after water additions in proportion to the amount present. Studies of various organics including dioctadecyl-dimethyl-ammonium chloride (DDAC) by Bowers and Hanks (3), tallow alcohols by Kolp et al. (6), and fatty alcohols by Olsen et al. (9) show that a diffusion barrier is produced when the materials are mixed with the soil surface. This barrier also decreases the rate of evaporation following water additions.

Both of the mechanisms of evaporation suppression described for crude oil have been attributed to fatty alcohols in previous studies by Law (7). He postulated that the suppression due to fatty alcohols in sands was the same as that from a free water surface while that from soil was due to a change in capillary conductivity. In both cases the material was mixed with the soil. In these studies crude oil was sprayed only on the smoothed wet soil surface.

The major parameters which were investigated as to their influence on evaporation from crude oil-treated surfaces were wind, soil temperature, light intensity and vapor pressure deficit.

Crude oil was very effective in suppressing evaporation the first 3-4 days of a drying cycle at rates as low as 946 l/ha (100 gal/acre) at wind velocities as high as 6.5 m/sec (15 mph). It was apparent that very little wind was required to cause major increases in evaporation following this period from the crude oil surface. From untreated surfaces receiving wind speeds >1.6 m/sec (4 mph), 50 percent of the water lost to evaporation during the 25-40 day drying cycles was lost during the first 3 days.

As soil temperature was increased from 10° to 34° C., soil water evaporation from untreated containers also increased due to an increase in vapor pressure of the soil water. Crude oil was also less effective in suppressing evaporation at the higher soil temperatures. This is due to the fact that the crude oil barrier does not impede vapor losses.

Different light intensities had no major effect on soil water evaporation. This is not surprising since it is the net radiation resulting from light intensity - not light intensity *per se* - that influences evaporation losses. Since the soil and air temperatures were controlled independent of light intensity, there was no effect from the net radiation which resulted from the different light intensities.

Varying the vapor pressure deficit affected evaporation as expected. As the deficit was increased the loss to evaporation also increased.

Field studies were undertaken to evaluate the practical potential of crude oil applications in crops. Crude oil was applied to the soil surface in cotton by spraying it on the soil surface at the rate of 2838 l/ha (300 gal/acre) following rainfall and irrigations. Although increases in soil moisture were observed in plots due to crude oil applications, no increases in cotton lint yield were observed. For some reason, the cotton was not able to use the water saved by the crude oil as an evaporation suppressant. When crude oil was floated on the water surface at the rate of 473 l/ha (50 gal/acre), an increase in yield was observed in 1969 but no yield increase was observed in 1970.

Results from the controlled environment studies indicate that crude oil may suppress evaporation best during the winter months. However, no water additions were necessary at Lubbock during the 3-year period of the study and this potential could not be evaluated.

It was observed that rainfall failed to penetrate crude oil-treated surfaces on sloping land. This finding is being investigated in another project on the use of crude oil as an aid in water harvesting.

Table A-1. Cumulative evaporation of treatments in Greenhouse Experiment 1 (cm.) (Letters refer to treatments on page 6)

	TREATMENTS												
Days	A	B	C	D	E	F	G	H	I	J	K	L	M
1	0.108	0.152	0.470	0.483	0.559	0.524	0.508	0.489	0.486	0.502	0.518	0.467	0.470
2	0.238	0.273	0.938	0.954	1.087	1.023	0.988	0.966	0.947	0.995	1.008	0.931	0.941
3	0.470	0.483	1.475	1.513	1.675	1.558	1.507	1.510	1.510	1.555	1.555	1.431	1.481
4	0.680	0.699	1.825	1.847	2.063	1.901	1.841	1.879	1.869	1.933	1.946	1.758	1.828
5	0.982	1.058	2.248	2.270	2.534	2.308	2.245	2.292	2.308	2.356	2.391	2.143	2.245
6	1.144	1.246	2.439	2.477	2.718	2.499	2.435	2.512	2.502	2.505	2.553	2.330	2.439
7	1.469	1.631	2.661	2.731	2.896	2.715	2.620	2.807	2.718	2.674	2.728	2.629	2.658
8	1.787	2.009	2.795	2.881	3.030	2.842	2.734	2.960	2.846	2.785	2.852	2.785	2.788
9	2.038	2.235	2.884	2.979	3.113	2.931	2.817	3.062	2.931	2.865	2.938	2.884	2.881
10	2.305	2.505	2.970	3.078	3.195	3.021	2.896	3.157	3.017	2.944	3.021	2.979	2.966
11	2.572	2.776	3.055	3.170	3.281	3.110	2.979	3.249	3.106	3.030	3.103	3.071	3.059
12	2.766	2.947	3.132	3.259	3.358	3.189	3.049	3.332	3.183	3.106	3.180	3.151	3.138
13	2.868	3.052	3.189	3.323	3.415	3.269	3.106	3.393	3.246	3.167	3.240	3.214	3.199
14	2.941	3.103	3.218	3.351	3.443	3.297	3.135	3.424	3.272	3.199	3.272	3.246	3.227
15	2.995	3.151	3.246	3.373	3.472	3.329	3.164	3.453	3.297	3.230	3.304	3.278	3.253
16	3.043	3.208	3.288	3.418	3.513	3.370	3.205	3.498	3.335	3.272	3.345	3.323	3.297
17	3.125	3.284	3.342	3.478	3.564	3.428	3.259	3.555	3.396	3.329	3.399	3.377	3.354

Table A-1 (Continued)

Days	TREATMENTS N	O	P	Q	R	S	T	U	V	W	X	Y
1	0.537	0.483	0.508	0.508	0.496	0.171	0.508	0.511	0.531	0.470	0.505	0.524
2	0.988	0.957	0.998	0.992	0.966	0.321	0.985	0.982	1.043	0.938	0.973	1.004
3	1.469	1.488	1.529	1.580	1.472	0.477	1.507	1.507	1.567	1.488	1.526	1.542
4	1.799	1.863	1.863	1.927	1.812	0.620	1.866	1.853	1.933	1.838	1.904	1.892
5	2.156	2.283	2.260	2.334	2.206	0.804	2.283	2.197	2.385	2.226	2.315	2.315
6	2.311	2.489	2.442	2.524	2.388	0.893	2.569	2.346	2.601	2.381	2.474	2.509
7	2.502	2.715	2.668	2.757	2.677	1.039	2.785	2.509	2.842	2.598	2.629	2.725
8	2.617	2.842	2.792	2.884	2.833	1.202	2.916	2.623	2.979	2.734	2.750	2.849
9	2.703	2.928	2.874	2.966	2.928	1.329	3.001	2.703	3.068	2.830	2.839	2.928
10	2.785	3.017	2.957	3.052	3.024	1.485	3.090	2.782	3.160	2.916	2.925	3.011
11	2.868	3.103	3.040	3.141	3.119	1.691	3.176	2.862	3.246	3.008	3.014	3.097
12	2.941	3.176	3.116	3.221	3.208	1.968	3.249	2.931	3.326	3.087	3.094	3.176
13	2.998	3.237	3.173	3.281	3.272	2.159	3.307	2.986	3.386	3.148	3.154	3.234
14	3.027	3.269	3.202	3.307	3.304	2.267	3.339	3.014	3.418	3.176	3.189	3.262
15	3.055	3.300	3.234	3.339	3.329	2.299	3.367	3.404	3.443	3.199	3.224	3.291
16	3.097	3.342	3.275	3.383	3.373	2.432	3.408	3.084	3.488	3.240	3.269	3.332
17	3.151	3.396	3.329	3.440	3.431	2.639	3.463	3.135	3.539	3.297	3.323	3.386

Table A-2. Cumulative evaporation of treatments in Greenhouse Experiment 2 (cm.) (Letters refer to treatments on page 12)

Days	TREATMENTS											
	A	B	C	D	E	F	G	H	I	J	K	L
1	0.365	0.133	0.034	0.254	0.143	0.082	0.066	0.127	0.076	0.276	0.340	0.248
2	0.734	0.292	0.146	0.578	0.232	0.178	0.457	0.298	0.155	0.591	0.636	0.365
3	1.154	0.515	0.270	0.982	0.378	0.257	0.903	0.454	0.251	0.969	0.995	0.725
4	1.478	0.747	0.384	1.272	0.496	0.356	1.265	0.747	0.318	1.252	1.278	0.941
5	1.892	1.017	0.553	1.628	0.651	0.508	1.659	1.046	0.407	1.605	1.631	1.208
6	2.280	1.364	0.775	2.022	0.874	0.740	2.095	1.418	0.540	2.035	2.079	1.564
7	2.550	1.650	0.995	2.372	1.062	0.960	2.295	1.726	0.655	2.346	2.410	1.885
8	2.753	1.946	1.237	2.642	1.265	1.189	2.429	2.044	0.750	2.578	2.607	2.146
9	2.811	2.270	1.526	2.785	1.504	1.465	2.540	2.413	0.915	2.734	2.737	2.467
10	2.925	2.410	1.815	2.890	1.749	1.704	2.620	2.655	1.055	2.833	2.836	2.668
11	3.005	2.544	2.117	2.982	2.016	2.003	2.696	2.798	1.227	2.925	2.925	2.836
12	3.068	2.636	2.372	3.052	2.245	2.248	2.757	2.916	1.376	3.011	2.992	2.931
13	3.106	2.696	2.502	3.100	2.394	2.385	2.798	2.960	1.481	3.040	3.040	2.992
14	3.145	2.750	2.645	3.145	2.537	2.489	2.839	3.014	1.602	3.078	3.081	3.046
15	3.183	2.798	2.753	3.189	2.664	2.572	2.874	3.068	1.723	3.122	3.119	3.094
16	3.214	2.846	2.842	3.230	2.782	2.645	2.912	3.100	1.853	3.160	3.157	3.141

Table A-3. Cumulative evaporation of treatments in Greenhouse Experiment 3 (cm.) (Letters refer to treatments on page 19)

	TREATMENTS											
Days	A	B	C	D	E	F	G	H	I	J	K	L
1	0.398	0.291	0.404	0.073	0.388	0.197	0.409	0.149	0.437	0.169	0.322	0.464
2	0.668	0.490	0.672	0.099	0.669	0.304	0.682	0.237	0.728	0.254	0.543	0.766
3	0.948	0.702	0.956	0.132	0.962	0.421	0.976	0.358	1.040	0.386	0.796	1.087
4	1.240	0.948	1.256	0.176	1.274	0.607	1.324	0.536	1.367	0.518	1.093	1.427
5	1.558	1.226	1.576	0.231	1.600	0.833	1.625	0.736	1.706	0.754	1.415	1.767
6	1.789	1.434	1.803	0.258	1.838	1.003	1.865	0.897	1.951	0.943	1.652	1.996
7	2.045	1.749	2.078	0.345	2.119	1.323	2.124	1.212	2.174	1.274	1.990	2.184
8	2.172	2.000	2.220	0.458	2.259	1.681	2.255	1.569	2.291	1.466	2.164	2.298
9	2.241	2.131	2.291	0.550	2.334	1.916	2.326	1.840	2.355	1.865	2.269	2.362
10	2.280	2.178	2.331	0.619	2.372	2.048	2.368	1.994	2.395	2.000	2.317	2.397
11	2.337	2.254	2.391	0.743	2.437	2.178	2.425	2.158	2.437	2.159	2.385	2.454
12	2.396	2.327	2.447	0.965	2.498	2.282	2.487	2.271	2.495	2.272	2.455	2.514
13	2.444	2.382	2.493	1.221	2.544	2.339	2.534	2.348	2.541	2.352	2.512	2.562
14	2.481	2.421	2.530	1.458	-	2.472	2.571	2.404	2.575	2.408	2.557	2.603
15	2.514	2.459	2.561	1.690	2.619	2.417	2.608	2.452	2.611	2.459	2.600	2.638
17	2.608	2.560	2.651	2.218	2.717	2.531	2.705	2.577	2.706	2.584	2.713	2.740
18	2.636	2.590	2.679	2.306	2.749	2.566	2.735	2.617	2.735	2.624	2.750	2.769
19	2.668	2.625	2.709	2.382	2.784	2.603	2.770	2.657	2.768	2.664	2.788	2.804

Table A-4. Cumulative evaporation of treatments in Greenhouse Experiment 4. (Letters refer to treatments on page 24) (cm.)

	TREATMENTS											
Days	A	B	C	D	E	F	G	H	I	J	K	L
1	0.308	0.300	0.020	0.014	0.042	0.162	0.263	0.243	0.294	0.252	0.262	0.147
2	0.623	0.634	0.047	0.030	0.079	0.374	0.537	0.545	0.610	0.526	0.564	0.341
3	0.944	0.966	0.089	0.047	0.117	0.595	0.814	0.847	0.938	0.795	0.872	0.545
4	1.208	1.251	0.149	0.057	0.141	0.792	1.057	1.093	1.206	1.017	1.135	0.720
5	1.448	1.497	0.200	0.068	0.171	0.981	1.294	1.330	1.467	1.224	1.389	0.884
6	1.642	1.714	0.262	0.084	0.217	1.181	1.545	1.543	1.706	1.416	1.647	1.052
7	1.812	1.885	0.329	0.108	0.259	1.380	1.771	1.717	1.884	1.532	1.885	1.214
8	1.944	2.004	0.402	0.127	0.313	1.574	1.952	1.876	2.008	1.612	2.055	1.361
9	2.028	2.084	0.478	0.152	0.367	1.754	2.089	1.995	2.090	1.679	2.160	1.480
10	2.103	2.187	0.561	0.192	0.440	1.898	2.192	2.079	2.165	1.747	2.248	1.593
11	2.170	2.256	0.663	0.235	0.527	2.056	2.280	2.157	2.240	1.809	2.330	1.723
12	2.227	2.310	0.780	0.287	0.626	2.158	2.354	2.226	2.302	1.866	2.400	1.842
15	2.354	2.443	1.038	0.477	0.981	2.339	2.513	2.369	2.453	2.006	2.561	1.925
16	2.383	2.472	1.087	0.524	1.071	2.377	2.547	2.399	2.485	2.035	2.596	1.965
17	2.424	2.515	1.151	0.602	1.225	2.426	2.593	2.443	2.528	2.079	2.640	2.017

Table A-4. (Continued)

Days	TREATMENTS		
	M	N	O
1	0.230	0.244	0.251
2	0.504	0.534	0.583
3	0.775	0.814	0.907
4	1.014	1.041	1.194
5	1.232	1.249	1.437
6	1.451	1.464	1.690
7	1.663	1.626	1.935
8	1.847	1.729	2.111
9	1.920	1.803	2.218
10	2.063	1.871	2.295
11	2.143	1.938	2.377
12	2.213	2.001	2.447
15	2.361	2.133	2.586
16	2.391	2.163	2.620
17	2.437	2.206	2.666

Table A-5. Cumulative evaporation of treatments in Greenhouse Experiment 5. (Letters refer to treatments on page 27) (cm.)

	TREATMENTS							
Days	A	B	C	D	E	F	G	H
1	0.589	0.058	0.042	0.537	0.093	0.063	0.511	0.559
2	1.111	0.116	0.077	1.033	0.205	0.147	0.936	1.081
3	1.570	0.213	0.116	1.513	0.372	0.329	1.337	1.383
4	1.931	0.438	0.197	1.796	0.710	0.720	1.842	1.791
6	2.043	0.632	0.278	1.922	0.988	1.020	1.987	1.920
7	2.133	0.858	0.360	2.012	1.305	1.357	2.087	2.022
8	2.197	1.071	0.467	2.084	1.555	1.661	2.165	2.100
9	2.264	1.318	0.615	2.154	1.825	1.900	2.238	2.167
10	2.342	1.470	0.841	2.230	2.067	2.070	2.326	2.251
11	2.385	1.582	1.011	2.281	2.171	2.163	2.383	2.299
12	2.429	1.747	1.198	2.330	2.257	2.203	2.435	2.345
13	2.454	1.809	1.300	2.359	2.300	2.245	2.458	2.367

Table A-6. Cumulative evaporation (cm.) of treatments in Greenhouse Experiment 6. (Letters refer to treatments on page 30)

	TREATMENTS							
Days	A	B	C	D	E	F	G	H
1	0.376	0.399	0.305	0.417	0.281	0.401	0.355	0.440
2	0.622	0.666	0.518	0.719	0.440	0.674	0.604	0.720
3	0.924	0.936	0.766	1.013	0.620	0.954	0.859	1.026
4	1.280	1.286	1.094	1.410	0.902	1.331	1.192	1.398
5	1.473	1.455	1.286	1.673	1.041	1.538	1.358	1.584
6	1.673	1.644	1.480	1.883	1.200	1.741	1.545	1.782
7	1.985	1.930	1.771	2.188	1.482	2.054	1.844	2.064
8	2.349	2.259	2.116	2.517	1.790	2.404	2.170	2.396
9	2.623	2.538	2.396	2.768	2.059	2.668	2.418	2.569
10	2.777	2.674	2.544	2.891	2.213	2.800	2.539	2.651
11	2.942	2.848	2.718	2.997	2.385	2.918	2.666	2.740
12	3.182	3.156	3.037	3.169	2.779	3.118	2.951	2.934
13	3.252	3.236	3.131	3.223	2.878	3.178	3.026	2.989
14	3.309	3.291	3.177	3.272	2.957	3.239	3.075	3.042
15	3.384	3.377	3.259	3.339	3.050	3.307	3.158	3.113
16	3.471	3.469	3.353	3.414	3.148	3.384	3.253	3.196
17	3.545	3.550	3.433	3.484	3.248	3.460	3.341	3.275
18	3.631	3.647	3.523	3.562	3.349	3.541	3.441	3.368

Table A-6. (Continued)

Days	TREATMENTS I			J			K			L		
		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)
1	0.347		25.2	0.318		27.2	0.310		27.7	0.311		27.2
2	0.591		24.2	0.546		26.1	0.558		26.4	0.551		26.6
3	0.917		28.5	0.777		31.3	0.825		30.5	0.802		33.0
4	1.261		21.1	1.025		24.2	1.095		23.0	1.095		23.3
5	1.431		20.0	1.167		20.2	1.248		21.1	1.254		20.2
6	1.601		23.5	1.324		25.5	1.389		25.2	1.399		25.3
7	1.835	22	32.7	1.553	10	33.3	1.613	7	36.1	1.648	20	34.1
8	2.059	23	36.1	1.84	13	32.5	1.836	8	38.0	1.933	22	36.6
9	2.156	26	18.8	2.05	13	18.3	1.993	9	18.6	2.149	24	21.6
10	2.271	26	25.0	2.19	13	25.0	2.079	9	25.5	2.280	23	22.6
11	2.361	28		2.345	14		2.173	10		2.442	23	
12	2.582	26		2.594	14		2.380	10		2.710	22	
13	2.641	28		2.664	14		2.443	12		2.792	20	
14	2.700	26		2.731	14		2.494	9		2.866	23	
15	2.786	26		2.830	14		2.567	9		2.968	23	
16	2.886	27		2.957	14		2.669	9		3.110	23	
17	2.978	27		3.063	14		2.744	10		3.234	23	
18	3.077	26		3.191	13		2.834	10		3.364	23	

Table A-6. (Continued)

	TREATMENTS											
	M			N			O			P		
Days		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)
1	0.453		26.1	0.473		29.4	0.384		28.8	0.381		28.3
2	0.721		23.8	0.710		26.1	0.631		25.8	0.613		25.2
3	1.025		30.3	0.993		34.1	0.893		28.0	0.855		30.0
4	1.396		20.2	1.276		25.0	1.197		23.3	1.162		22.6
5	1.599		18.8	1.411		21.6	1.365		21.1	1.306		20.2
6	1.783		23.4	1.547		26.6	1.504		25.2	1.456		24.7
7	1.990	13	35.3	1.747	6	37.7	1.652	12	40.5	1.674	9	33.4
8	2.144	13	40.5	1.965	7	38.0	1.774	13	42.5	1.796	10	38.0
9	2.246	13	18.6	2.124	8	19.1	1.860	13	20.0	1.950	10	18.6
10	2.299	13		2.206	8	23.8	1.906	13		2.017	11	
11	2.377	13		2.295	8		1.968	12		2.097	11	
12	2.544	13		2.491	8		2.130	12		2.286	12	
13	2.598	13		2.545	8		2.178	13		2.340	11	
14	2.647	13		2.598	7		2.221	12		2.388	12	
15	2.720	13		2.669	7		2.260	12		2.461	12	
16	2.790	13		2.752	7		2.345	13		2.544	12	
17	2.882	13		2.834	8		2.421	13		2.623	12	
18	2.974	13		2.925	7		2.510	13		2.720	12	

Table A-6. (Continued)

	TREATMENTS											
	Q			R			S			T		
Days		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)
1	0.461		26.6	0.399		30.3	0.402		28.5	0.426		29.1
2	0.731		24.4	0.651		25.5	0.636		26.6	0.698		25.8
3	1.082		27.5	0.957		35.5	0.922		29.4	0.966		29.1
4	1.569		18.3	1.359		20.2	1.287		18.8	1.361		19.4
5	1.906		15.5	1.578		20.2	1.524		20.0	1.623		21.6
6	2.181		21.9	1.812		24.7	1.725		24.2	1.903		24.5
7	2.504	18	31.6	2.135	16	35.0	1.995	16	30.8	2.184	17	30.5
8	2.780	18	36.1	2.392	16	36.6	2.288	16	31.3	2.472	18	37.2
9	2.978	18	19.7	2.564	16	18.6	2.523	16	18.3	2.688	18	18.3
10	3.084	18		2.671	16	25.5	2.841	16	25.5	2.817	16	26.6
11	3.195	17		2.782	16		3.113	16		2.944	17	
12	3.413	18		3.005	16		3.180	16		3.186	17	
13	3.459	18		3.057	16		3.245	16		3.248	17	
14	3.502	18		3.102	16		3.296	16		3.297	17	
15	3.560	18		3.162	16		3.351	16		3.362	17	
16	3.626	18		3.232	16		3.451	16		3.497	17	
17	3.685	18		3.296	16		3.523	16		3.571	17	
18	3.755	18		3.366	16		3.594	16		3.644	17	

Table A-6. (Continued)

	TREATMENTS											
	U			V			W			X		
Days		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)		No. Plants	Temp (° C.)
1	0.438			0.432			0.427			0.413		
2	0.721			0.704			0.694			0.677		
3	0.984			0.982			0.979			0.968		
4	1.322			1.262			1.308			1.322		
5	1.526			1.438			1.494			1.502		
6	1.737			1.626			1.706			1.700		
7	2.047			1.908			2.012			2.016		
8	2.415			2.450			2.652			2.380		
9	2.699			2.618			2.784			2.535		
10	2.871			2.806			2.936			2.668		
11	3.046			3.075			3.172			2.813		
12	3.294			3.156			3.273			3.067		
13	3.367			3.229	7		3.327			3.147	3	
14	3.428			3.340	7		3.397			3.218	4	
15	3.502			3.472	7		3.482			3.312	4	
16	3.587			3.602	7		3.537			3.427	4	
17	3.664			3.734	7		3.625			3.535	4	
18	3.760			3.893	7		3.712			3.672	4	

Table A-7. Cumulative evaporation (cm.) From Controlled Temperature Experiment 1.

	WIND SPEED - <0.4 m/sec							
	TREATMENTS							
Days	1	2	3	4	5	6	7	8
1	0.57	0.02	0.63	0.32	0.24	0.23	0.57	0.13
2	1.05	0.01	1.11	0.55	0.37	0.37	1.05	0.22
3	1.49	0.01	1.55	0.80	0.49	0.50	1.45	0.26
4	1.92	0.03	1.95	1.09	0.59	0.61	1.89	0.32
5	2.38	0.03	2.32	1.29	0.70	0.70	2.35	0.34
6	2.81	0.03	2.69	1.54	0.77	0.80	2.80	0.37
7	3.09	0.08	2.98	1.72	0.85	0.88	3.08	0.41
8	3.40	0.12	3.26	1.90	0.92	0.96	3.40	0.43
9	3.65	0.15	3.48	2.09	0.97	1.05	3.66	0.45
10	3.96	0.23	3.74	2.30	1.05	1.11	3.98	0.48
11	4.20	0.30	3.96	2.49	1.12	1.17	4.25	0.49
12	4.45	0.41	4.23	2.74	1.20	1.24	4.60	0.53
13	4.59	0.50	4.57	3.04	1.27	1.32	4.84	0.55
14	4.71	0.65	4.81	3.26	1.37	1.41	5.17	0.58
15	4.82	0.81	5.03	3.49	1.44	1.49	5.53	0.61
16	4.91	0.94	5.19	3.73	1.52	1.56	5.87	0.64
17	4.98	1.11	5.30	3.93	1.60	1.63	6.17	0.68
18	5.05	1.28	5.40	4.13	1.64	1.67	6.49	0.69
19	5.11	1.43	5.48	4.30	1.71	1.73	6.80	0.73
20	5.18	1.60	5.56	4.48	1.77	1.77	7.05	0.74
21	5.23	1.77	5.64	4.69	1.80	1.82	7.33	0.75
22	5.29	1.97	5.70	4.85	1.88	1.88	7.65	0.77
23	5.33	2.14	5.77	5.02	1.92	1.90	7.91	0.78
24	5.38	2.28	5.82	5.16	1.97	1.95	8.17	0.79
25	5.44	2.48	5.87	5.30	2.03	2.00	8.42	0.80

Continued

Table A-7. (Continued)

	WIND SPEED - <0.4 m/sec							
	TREATMENTS							
Days	1	2	3	4	5	6	7	8
26	5.48	2.68	5.95	5.44	2.08	2.04	8.70	0.83
27	5.52	2.86	6.00	5.60	2.13	2.10	8.92	0.85
28	5.57	3.08	6.06	5.67	2.18	2.14	9.28	0.88
29	5.61	3.25	6.09	5.76	2.22	2.19	9.55	0.89
30	5.66	3.46	6.14	5.83	2.26	2.22	9.83	0.91
31	5.70	3.65	6.18	5.89	2.30	2.26	10.09	0.92
32	5.75	3.84	6.23	5.95	2.36	2.31	10.39	0.93
33	5.78	4.03	6.28	6.02	2.40	2.34	10.66	0.95
34	5.82	4.21	6.30	6.07	2.43	2.37	10.90	0.96
35	5.86	4.38	6.35	6.12	2.47	2.57	11.21	0.97
36	5.90	4.53	6.38	6.19	2.51	2.61	11.44	0.98
37	5.94	4.65						
38	5.97	4.70						
39	6.00	4.80						
40	6.04	4.89						
41	6.08	4.99						
42	6.12	5.04						
43	6.15	5.10						

Table A-8. Cumulative evaporation (cm.) from Controlled Temperature Room Experiment 2.

	WIND SPEED - <0.4 m/sec			
	Crude Oil Rate (l/ha)			
Days	946	2838	4730	0
1	0.04	0.02	0.02	0.29
2	0.04	0.02	0.04	0.72
3	0.08	0.04	0.08	1.01
4	0.15	0.08	0.13	1.33
5	0.23	0.12	0.16	1.67
6	0.36	0.19	0.23	1.97
7	0.52	0.30	0.33	2.34
8	0.72	0.40	0.42	2.68
9	0.92	0.52	0.52	3.03
10	1.13	0.68	0.65	3.37
11	1.34	0.82	0.76	3.69
12	1.60	0.97	0.89	3.99
13	1.84	1.15	1.02	4.27
14	2.07	1.29	1.14	4.53
15	2.31	1.46	1.27	4.71
16	2.56	1.64	1.39	4.88
17	2.76	1.80	1.53	5.01
18	2.98	1.96	1.64	5.11
19	3.19	2.13	1.79	5.21
20	3.42	2.32	1.94	5.29
21	3.67	2.52	2.10	5.36
22	3.90	2.69	2.24	5.45
23	4.17	2.87	2.39	5.57
24	4.31	3.04	2.53	5.61
25	4.48	3.18	2.65	5.68
26	4.62	3.35	2.77	5.72
27	4.77	3.53	2.93	5.77
28	4.94	3.73	3.07	5.81
29	5.06	3.90	3.21	5.85
30	5.17	4.04	3.33	5.89
31	5.28	4.20	3.44	5.94
32	5.37	4.36	3.56	5.98
33	5.44	4.50	3.63	6.00
34	5.52	4.68	3.74	6.05
35	5.61	4.81	3.83	6.09

Continued

Table A-8. (Continued)

	WIND SPEED - <0.4 m/sec			
	Crude Oil Rate (l/ha)			
Days	946	2838	4730	0
36	5.67	4.95	3.90	6.13
37	5.72	5.06	3.99	6.16
38	5.79	5.18	4.06	6.20
39	5.84	5.27	4.14	6.23
41	5.93	5.37	4.29	6.27
43	6.02	5.44	4.44	6.30
44	6.07	5.50	4.50	6.34
45	6.12	5.57	4.60	6.39
46	6.17	5.62	4.68	6.42
47	6.22	5.69	4.76	6.47
48	6.27	5.76	4.84	6.51
49	6.29	5.79	4.90	6.54

Table A-8. (Continued)

	WIND SPEED -- 1.6 m/sec			
	Crude Oil Rate (l/ha)			
Days	946	2838	4730	0
1	0.03	0.06	0.04	1.42
2	0.12	0.16	0.07	2.69
3	0.26	0.33	0.23	3.87
4	0.48	0.59	0.41	4.42
5	0.76	0.93	0.65	4.73
6	1.10	1.32	0.94	4.95
7	1.51	1.77	1.33	5.13
8	2.03	2.30	1.78	5.32
9	2.43	2.84	2.34	5.45
10	3.09	3.30	2.92	5.62
11	3.77	3.64	3.13	5.74
12	4.23	3.98	3.42	5.84
13	4.70	4.33	3.83	5.97
14	4.94	4.69	4.22	6.06
15	5.13	5.05	4.62	6.18
16	5.28	5.26	5.04	6.25
17	5.38	5.39	5.25	6.32
18	5.50	5.53	5.44	6.40
19	5.64	5.65	5.59	6.48
20	5.71	5.75	5.74	6.56
21	5.81	5.86	5.83	6.62
22	5.90	5.93	5.92	6.69
23	5.99	6.02	6.00	6.73
24	6.06	6.08	6.09	6.80
25	6.14	6.16	6.18	6.88
26	6.24	6.24	6.26	6.93
27	6.30	6.44	6.31	6.99
28	6.39	6.52	6.40	7.06
29	6.47	6.60	6.49	7.13
30	6.54	6.66	6.56	7.18
31	6.60	6.72	6.61	7.23
32	6.68	6.78	6.69	7.28
33	6.72	6.82	6.73	7.32

Table A-8. (Continued)

	WIND SPEED -- 3.3 m/sec			
	Crude Oil Rate (l/ha)			
Days	946	2838	4730	0
1	0.07	0.07	0.03	1.83
2	0.18	0.17	0.12	3.50
3	0.32	0.28	0.18	4.39
4	0.50	0.46	0.34	4.84
5	0.70	0.68	0.51	5.10
6	0.91	0.95	0.72	5.32
7	1.17	1.29	0.99	5.51
8	1.52	1.70	1.33	5.68
9	1.90	2.16	1.70	5.80
10	2.32	2.67	2.15	5.92
11	2.72	3.19	2.59	6.01
12	3.14	3.76	3.11	6.08
13	3.65	4.40	3.74	6.19
14	4.21	4.91	4.38	6.29
15	4.68	5.21	4.86	6.37
16	5.10	5.41	5.30	6.43
17	5.45	5.59	5.57	6.50
18	5.77	5.73	5.77	6.59
19	5.94	5.88	5.97	6.66
20	6.10	6.01	6.15	6.73
21	6.22	6.10	6.29	6.81
22	6.34	6.19	6.39	6.86
23	6.44	6.27	6.45	6.91
24	6.54	6.38	6.58	7.00
25	6.63	6.44	6.66	7.05
26	6.71	6.53	6.74	7.12
27	6.79	6.59	6.80	7.17
28	6.90	6.69	6.89	7.25
29	6.99	6.76	6.96	7.30
30	7.03	6.80	7.00	7.34

Table A-8. (Continued)

Days	WIND SPEED -- 6.5 m/sec Crude Oil Rate (l/ha) 946	2838	4730	0
1	0.03	0.06	0.04	2.71
2	0.05	0.07	0.05	3.45
3	0.10	0.17	0.07	3.98
4	0.28	0.26	0.15	4.40
5	0.55	0.40	0.22	4.64
6	1.19	0.65	0.33	4.88
7	2.24	0.96	0.47	5.15
8	2.91	1.40	0.62	5.37
9	3.63	2.09	0.82	5.56
10	4.43	2.84	1.18	5.83
11	4.85	3.13	1.59	6.02
12	5.02	3.57	1.72	6.11
13	5.31	3.99	2.07	6.27
14	5.57	4.40	2.55	6.43
15	5.79	4.85	3.05	6.57
16	6.00	5.17	3.39	6.74
17	6.17	5.38	3.62	6.90
18	6.33	5.59	3.87	7.02
19	6.50	5.78	4.13	7.15
20	6.66	5.94	4.32	7.31
21	6.80	6.11	4.53	7.46
22	6.95	6.28	4.73	7.59
23	7.10	6.41	4.87	7.75

Table A-9. Cumulative evaporation (cm.) from Controlled Environmental Chamber Experiment 1.

	TREATMENTS											
Days	A	B	C	D	E	F	G	H	I	J	K	L
1	0.30	0.02	0	0	0.32	0.03	0.03	0	0.79	0.34	0.04	0.22
3	0.62	0.05	0.01	0	0.57	0.05	0.03	0	1.18	0.36	0.06	0.25
4	1.02	0.05	0.04	0	1.10	0.09	0.03	0.01	2.32	0.46	0.08	0.25
6	1.80	0.13	0.05	0.02	2.19	0.22	0.07	0.03	3.98	1.08	-	0.25
10	3.82	0.32	0.14	0.05	4.65	0.97	0.21	0.06	5.21	3.75	1.35	0.36
13	4.68	0.83	0.38	0.11	5.21	2.10	0.47	0.09	5.68	5.64	3.54	0.79
18	4.95	1.46	0.65	0.17	5.61	3.96	1.21	0.18	6.17	6.55	5.39	1.88
20	5.00	1.73	0.77	0.18	5.72	4.26	1.60	0.25	6.33	6.78	5.79	2.38
26	5.33	2.89	1.84	0.53	6.21	4.97	3.20	0.88	6.82	7.44	6.65	4.44
28	5.38	2.91	2.00	0.60	6.25	5.04	3.31	0.98	6.85	7.52	6.72	4.93

Table A-10. Cumulative evaporation (cm.) from Controlled Environment Chamber Experiment 2**

	No Shade (0.60 ly)				Light Shade (0.30 ly)				Heavy Shade (0.15 ly)			
Days	0	946*	2838*	4730*	0	946*	2838*	4730*	0	946*	2838*	4730*
1	1.51	0.70	0.35	0.12	1.17	0.35	0.30	0.04	1.18	0.43	0.25	0.21
2	2.51	2.26	1.27	0.18	2.42	1.40	1.20	0.11	2.59	1.77	0.75	0.47
3	2.86	3.73	2.58	0.22	3.44	2.66	2.49	0.14	3.65	3.05	1.75	0.69
4	3.12	4.41	3.92	0.26	3.86	3.70	3.77	0.23	4.35	4.07	2.80	1.02
5	3.33	4.68	4.90	0.32	4.09	4.09	4.92	0.34	4.60	4.45	3.87	1.40
6	3.50	4.89	5.25	0.42	4.28	4.29	5.23	0.50	4.80	4.65	4.44	2.06
7	3.68	5.09	5.48	0.63	4.43	4.49	5.50	0.73	4.97	4.83	4.72	2.66
8	3.87	5.29	5.71	0.92	4.57	4.67	5.66	1.04	5.13	5.02	4.94	3.44
9	4.07	5.43	5.88	1.38	4.73	4.87	5.85	1.34	5.28	5.19	5.13	4.20
10	4.22	5.56	6.03	2.02	4.89	5.05	6.03	1.72	5.38	5.32	5.29	4.75
11	4.23	5.67	6.15	2.46	4.96	5.13	6.13	2.03	5.45	5.42	5.42	5.13
12	4.40	5.81	6.31	3.84	5.12	5.32	6.44	2.78	5.58	5.57	5.60	5.42
13	4.41	5.83	6.33	4.07	5.13	5.34	6.45	2.96	5.62	5.60	5.63	5.63
14	4.51	5.93	6.45	4.62	5.23	5.45	6.57	3.28	5.77	5.79	5.79	5.79
15	4.60	6.05	6.55	4.93	5.35	5.56	6.68	3.67	5.89	5.93	5.93	5.92
16	4.66	6.15	6.62	5.11	5.40	5.64	6.75	3.94	5.96	6.00	5.97	6.03
17	4.71	6.23	6.69	5.25	5.46	5.70	6.84	4.19	6.02	6.05	6.03	6.11
18	4.80	6.32	6.81	5.38	5.53	5.80	6.93	4.50	6.12	6.12	6.13	6.23
19	4.88	6.43	6.94	5.56	5.64	5.91	7.04	4.89	6.23	6.20	6.24	6.35
20	4.95	6.52	6.97	5.66	5.71	5.97	7.10	5.14	6.29	6.29	6.30	6.45
21	5.02	6.61	7.02	5.74	5.78	6.05	7.18	5.37	6.34	6.37	6.36	6.54
22	5.08	6.65	7.08	5.84	5.85	6.12	7.25	5.52	6.40	6.44	6.42	6.62
23	5.11	6.69	7.13	5.92	5.90	6.16	7.30	5.64	6.45	6.47	6.48	6.67
24	5.18	6.75	7.22	5.99	5.98	6.25	7.36	5.78	6.53	6.54	6.56	6.75
25	5.24	6.82	7.27	6.07	6.04	6.31	7.42	5.84	6.59	6.59	6.63	6.85

Continued

Table A-10. (Continued)

	No Shade (0.60 ly)				Light Shade (0.30 ly)				Heavy Shade (0.15 ly)			
Days	0	946*	2838*	4730*	0	946*	2838*	4730*	0	946*	2838*	4730*
26	5.29	6.89	7.34	6.14	6.10	6.37	7.46	5.90	6.65	6.64	6.69	6.93
27	5.34	6.91	7.40	6.19	6.15	6.42	7.51	5.95	6.71	6.70	6.73	7.01
30	5.42	6.97	7.46	6.26	6.22	6.48	7.57	6.04	6.77	6.76	6.80	7.12
36	5.50	7.08	7.57	6.32	6.29	6.55	7.63	6.11	6.83	6.84	6.86	7.21

* Crude oil rates (liters/hectare).

** Chamber temperature 38° C., relative humidity 22%.

Table A-11. Cumulative evaporation (cm.) from Controlled Environment Chamber Experiment 2**

	No Shade (0.60 ly)				Light Shade (0.30 ly)				Heavy Shade (0.15 ly)			
Days	0	946*	2838*	4730*	0	946*	2838*	4730*	0	946*	2838*	4730*
1	0.56	-0-	-0-	-0-	0.38	-0-	-0-	-0-	0.48	-0-	-0-	-0-
2	1.10	0.01	-0-	-0-	0.75	0.01	-0-	-0-	0.94	0.04	0.03	0.04
4	1.65	0.02	0.02	-0-	1.17	0.02	0.01	-0-	1.44	0.05	0.04	0.04
5	2.14	0.06	0.06	0.02	1.82	0.04	0.02	0.03	1.93	0.06	0.08	0.06
6	2.87	0.12	0.11	0.03	2.47	0.12	0.02	0.04	2.42	0.09	0.13	0.07
7	3.16	0.15	0.13	0.03	2.76	0.18	0.03	0.04	2.80	0.12	0.14	0.07
9	3.46	0.22	0.17	0.03	3.09	0.35	0.05	0.07	3.43	0.21	0.20	0.08
10	3.54	0.27	0.20	0.03	3.30	0.46	0.07	0.09	3.57	0.25	0.21	0.08
11	3.59	0.28	0.23	0.03	3.48	0.52	0.08	0.10	3.66	0.30	0.22	0.08
12	3.63	0.31	0.26	0.04	3.64	0.60	0.10	0.12	3.74	0.33	0.23	0.09
13	3.74	0.37	0.30	0.05	3.72	0.81	0.10	0.12	3.86	0.48	0.29	0.10
14	3.86	0.42	0.37	0.07	3.83	0.99	0.12	0.13	3.95	0.63	0.35	0.12
15	3.91	0.46	0.40	0.08	3.90	1.16	0.13	0.13	4.00	0.83	0.40	0.13
16	3.94	0.51	0.44	0.09	3.93	1.23	0.16	0.14	4.06	0.99	0.43	0.13
17	3.97	0.54	0.47	0.09	4.01	1.31	0.16	0.15	4.10	1.10	0.45	0.15
18	4.00	0.60	0.55	0.10	4.02	1.39	0.17	0.15	4.16	1.11	0.47	0.16
19	4.03	0.65	0.63	0.11	4.08	1.49	0.19	0.16	4.18	1.30	0.51	0.17
20	4.06	0.73	0.72	0.11	4.13	1.67	0.21	0.18	4.26	1.53	0.58	0.17
22	4.12	0.81	0.81	0.13	4.18	1.84	0.25	0.18	4.31	1.81	0.61	0.17
24	4.16	0.93	0.93	0.17	4.23	2.01	0.28	0.20	4.36	2.08	0.69	0.19
28	4.21	1.08	1.05	0.21	4.29	2.29	0.31	0.23	4.44	2.48	0.81	0.22
29	4.28	1.23	1.17	0.25	4.38	2.50	0.36	0.25	4.51	2.82	0.90	0.26
31	4.35	1.37	1.27	0.27	4.42	2.66	0.40	0.28	4.55	3.12	0.99	0.28
34	4.40	1.59	1.44	0.33	4.49	2.92	0.45	0.31	4.61	3.50	1.12	0.32

Continued

Table A-11. (Continued)

	No Shade (0.60 ly)				Light Shade (0.30 ly)				Heavy Shade (0.15 ly)			
Days	0	946*	2838*	4730*	0	946*	2838*	4730*	0	946*	2838*	4730*
36	4.44	1.73	1.54	0.37	4.52	3.11	0.51	0.35	4.64	3.70	1.20	0.34
38	4.50	1.88	1.67	0.43	4.57	3.28	0.55	0.36	4.69	3.87	1.32	0.39
43	4.59	2.31	1.85	0.53	4.64	3.59	0.71	0.43	4.77	4.02	1.55	0.42

* Crude oil rates (liters/hectare).

** Chamber temperature 10° C., relative humidity 50%.

REFERENCES

1. Adams, J. E. 1966. Influences of mulches on runoff, erosion, and soil moisture depletion. Soil Sci. Soc. Amer. Proc. 30:110-114.

2. Bond, J. J. and W. O. Willis. 1969. Soil water evaporation: Surface residue rate and placement effects. Soil Sci. Soc. Amer. Proc. 33:445-448.

3. Bowers, S. A. and R. J. Hanks. 1961. Effects of DDAC on evaporation and infiltration of soil moisture. Soil Sci. 92:340-346.

4. Gerard, C. J. and G. Chambers. 1967. Effect of reflective coatings on soil temperatures, soil moisture, and the establishment of fall bell peppers. Agron. Jour. 59:293-296.

5. Haas, H. J. and W. O. Willis. 1962. Moisture storage and use by dryland spring wheat cropping systems. Soil Sci. Soc. Amer. Proc. 26:506-509.

6. Kolp, D. G., F. P. Drause and W. Lange. 1966. Effect of tallow alcohol added to soil on the tension, flow and evaporation of soil water. Water Resources Res. 2:213-222.

7. Law, J. P. 1964. The effect of fatty alcohol and a nonionic surfactant on soil moisture evaporation in a controlled environment. Soil Sci. Soc. Amer. Proc. 28:695-699.

8. Lemon, E. R. 1956. The potentialities for decreasing soil moisture evaporation loss. Soil Sci. Soc. Amer. Proc. 24:414-418.

9. Myers, Lloyd E. May 1966. Director, U.S. Water Conservation Laboratory, Phoenix, Arizona. Personal communication.

10. Olsen, S. R., F. S. Watanake, F. E. Clark and W. D. Kemper. 1964. Effect of hexadecanol on evaporation of water from soil. Soil Sci. 97:13-18.

11. Rosenberg, N. J. 1969. Advective contribution of energy utilized in evapotranspiration by alfalfa in the East Central Great Plains. Agr. Meteorol. 6:179-184.

12. Skidmore, E. L., H. S. Jacobs and W. L. Powers. 1969. Potential evapotranspiration as influenced by wind. Agron. J. 61: 543-546.

13. van Bavel, C. H. M. 1966. Potential Evaporation:The combination concept and its experimental verification. Water Resources Res. 2:455-467.