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A feasibility report based on laboratory measurements

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FOREWORD

This report summarizes the results of laboratory measurements of the infrared reflectance of selected living plants typical of the natural watersheds in northern Utah. Data indicate that the IR reflectance decreases as the moisture content of the soil decreases and the moisture tension in the soil increases. Additional data will be collected in the field to confirm the results and to further test the feasibility of using IR reflectance of vegetation as an indicator of soil moisture conditions on the watershed.

Mr. Briscoe, Research Physicist, has been responsible for the gathering of laboratory data and has written the manuscript for this report.

Frank W. Haws
Project Leader
CWRR-14 (a)

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Introduction

The continuing world-wide population explosion is placing an ever-increasing demand on present usable water supplies, and water shortages are becoming more severe. While scientists and engineers are working to produce additional fresh water by weather control or desalination, much can be done to alleviate water shortages by better management of our watershed areas.

In order to make optimum use of our watersheds, we must develop improved methods of determining the water conditions within them. An important contribution toward improved watershed management would be made if some method could be devised which would facilitate data acquisition of watershed parameters. The purpose of this study has been to investigate the feasibility of measuring these parameters by remote reconnaissance methods.

The remote sensing technique has been applied, to some extent, in the science of hydrology. Although some of the measurements taken have indicated that various hydrological factors influence the data received, comprehensive results are not available relating to quantitative measurements of water conditions. The procedure followed in this study was to conduct a literature survey of data available at all regions of the electromagnetic spectrum, and then to perform laboratory spectral measurements on certain areas which showed promise.

Basic Considerations in Remote Sensing

Any substance at a temperature above absolute zero radiates electromagnetic energy. The characteristics of this radiated energy are functions of the wavelength and the temperature. When an object is in equilibrium with its surroundings, the total energy radiated from it is equivalent to that which it receives or absorbs. If all the incident energy is absorbed and re-radiated, the object is termed a "blackbody" radiator. Some objects absorb and re-radiate nearly all of the incident radiation and thus approach the ideal blackbody radiator, while other objects absorb only a small portion and reflect the major portion of the incident radiation. Often the emissivity is a strong function of wavelength. This is particularly true at high temperatures and short wavelengths where electronic or molecular vibration causes emission or absorption to take place.

In order to obtain information concerning the type of emission or reflection and its spectral characteristics, there are three essentials which must be considered: First, there must be a source of energy.

Second, the intervening medium must not eliminate or absorb excessive amounts of the desired radiation. Third, there must be sensors available which are sensitive enough to measure the energy radiated by the source after any modifications by the intervening medium. Each of these three essentials is considered below.

Sources

For this study, our consideration of radiation sources has been limited to two sources which exist naturally; namely, the sun and the earth. While it may be possible to scan an area with a bright searchlight and measure the reflected energy, such a system was impractical for this study.

The sun radiates approximately as a blackbody at 6000° Kelvin. Figure 1 shows the radiation from the sun at the earth's surface. As indicated by this figure, the sun has its wavelength of maximum energy near the center of the visible spectrum, with a considerable amount of energy in the near infrared. Thus, the sun is an excellent source for experiments which measure reflection from soil or vegetation at wavelengths below 2.5 microns.

The earth has an average temperature of 300° K and radiates much like a blackbody with peak emission at 9.5 microns and with measurable energy from 5 to 25 microns. Although the energy emitted is low, there

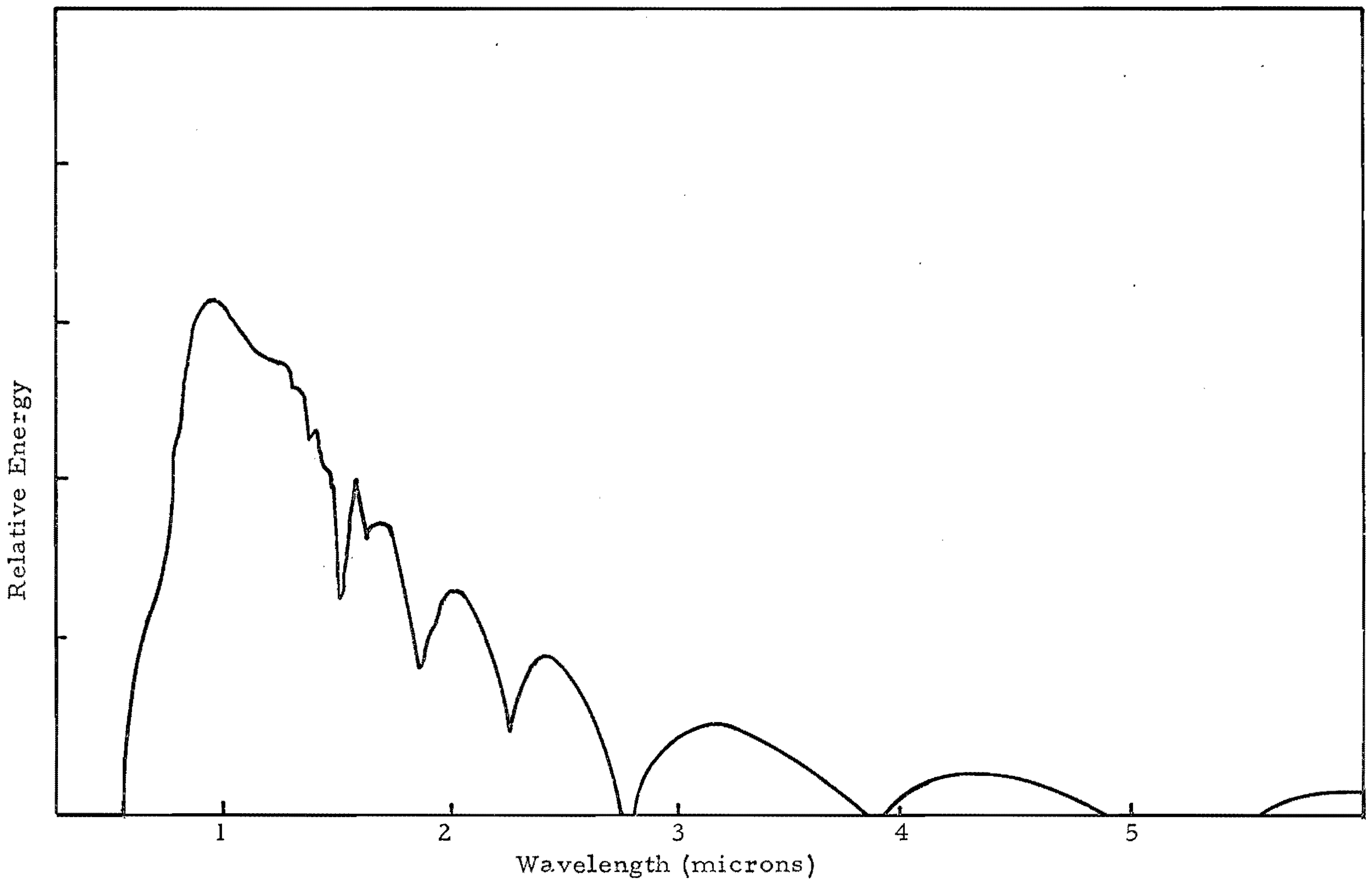

Figure 1. Radiation from the sun at the surface of the earth.

are detectors available which will respond to small changes in this low-intensity emission throughout the wavelength region of interest.

Atmospheric transmission

There are four main wavelength regions where the atmosphere is sufficiently transparent to permit useful remote measurement of the radiated energy. These regions are from 0.3 to 0.7 μ (visible), 0.7 to 2.5 μ (near IR), 3 to 6 μ (near IR), and 8 to 14 μ (intermediate IR).

Sensors

Photographic film can be used to graphically display the reflected energy from the surface being investigated. Film is available which will respond to radiation beyond the visible, but it is limited to wavelengths below 1.2 μ. There are a variety of thermal, photoconductive, and photovoltaic detectors available; thus a detector can be selected which will yield the desired sensitivity throughout any of the atmospheric windows which may be used.

Possible Applications of Remote Sensing to the Determination of Water Conditions

Vegetation and soils emit very nearly like a blackbody at infrared wavelengths beyond 5 μ. Therefore, a variation in the amount of energy radiated indicates a variation in temperature. Since the temperature variations are related to the water content, an accurate determination of these variations would be valuable in determining water conditions. A portion of the sunlight incident upon vegetation or soil is reflected, and the characteristics of this reflected light may reveal a great deal about the nature of the object from which it is reflected.

Radiation from plants and soils

The temperature of vegetation is regulated to some degree by evapo-transpiration, and the evapo-transpiration rate is, in turn, inversely proportional to the water content of the vegetation. It is therefore quite probable that a system which could produce a temperature profile map would give indications of water stress in vegetation. Since various other factors such as wind and shade from clouds can also lower the temperature of the vegetation, some knowledge of these factors would be necessary to make the temperature profile map useful.

The soil is heated by radiant energy from the sun, and this heat is dissipated primarily through conduction or re-radiation. The heat conductivity of soils varies directly with the water content; thus the presence of moisture in the soil tends to moderate the surface temperature. Other factors excluded, moist soils therefore tend to have lower daytime surface temperatures and higher nighttime surface temperatures than do dry soils. This leads one to conclude that thermal profiles of the soil taken at intervals throughout the day would give a strong indication of the water content.

Reflection from plants and soils

Most green plants exhibit a strong absorption at 4300 and 6500 Å. These absorptions are due to changes in the atomic energy states. The energy absorbed in this region is used in the process of photosynthesis. There exists between these two strong atomic absorption bands a region of high reflectivity, with the wavelength of peak reflection occurring at around 5500 Å. It is this reflection that gives plant leaves a green appearance.

At the long wavelength edge of the chlorophyll absorption (which occurs near the long wavelength edge of the visible spectrum), there is an abrupt increase in reflectivity of green leaves. This reflection remains at a high level from 7000 Å to the molecular absorption bands due to water at 1.35, 1.87 and 2.6 μ. The molecular absorption bands due to water vapor would be excellent indications of the water content of the plant, but it is impossible to obtain measurements due to atmospheric absorption of the energy at the same wavelengths.

The reflection of sunlight from soil has been investigated by several groups (Bowen, 1965; Brooks, 1952; Drovid, 1940). Figure 2 shows typical results from measurements of reflection from soils with various moisture contents. Although the highest reflection occurs near 2 μ, the percentage change is nearly as great at 1 μ where one could use photographic film and where the radiant energy of the sun is considerably higher.

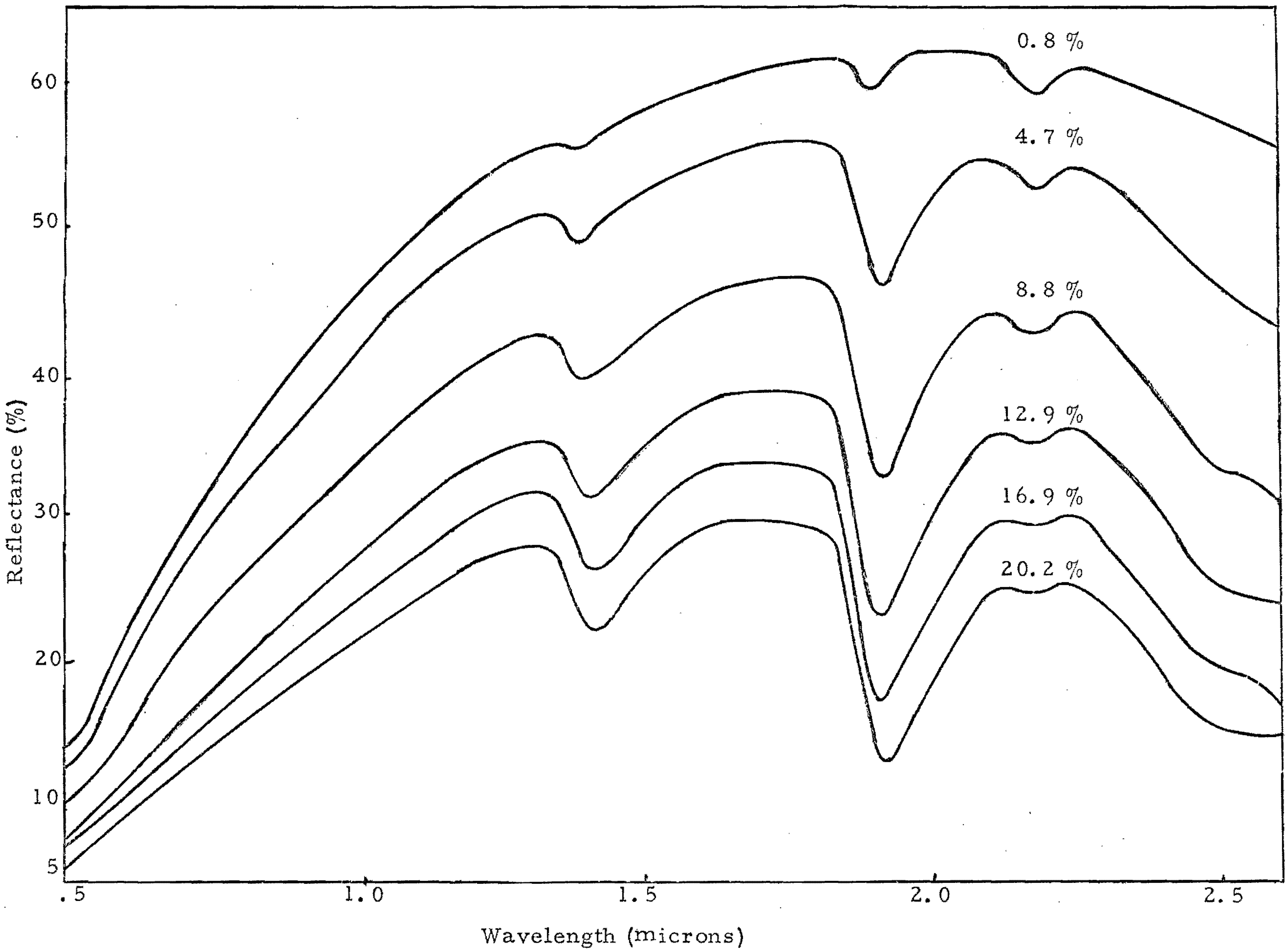

Figure 2. Reflectance vs. wavelength of incident radiation for a soil sample.

Figure 3 shows the change in reflectance vs. water content of a soil for two different wavelengths plotted on semilog paper. The reflection is very nearly a simple logarithmic function of the soil moisture content and can be written as

$$x = a \log y + b$$

where x is the percent moisture and y is the percent reflection, and a and b are constants which depend upon the wavelength and soil type. For the curves plotted in the previous figure,

$$x = -60.8 \log y + 101 \qquad \text{for } 1.0\,\mu$$

and

$$x = -31 \log y + 57.5 \qquad \text{for } 2.0\,\mu$$

A direct and simple measurement could be made photographically or with a photometer which would tell the surface moisture content of a particular soil type. The two major limitations of such systems are that the soil in a watershed area is generally covered by vegetation, and the water content of the soil just below the surface may be nearly independent of the surface moisture.

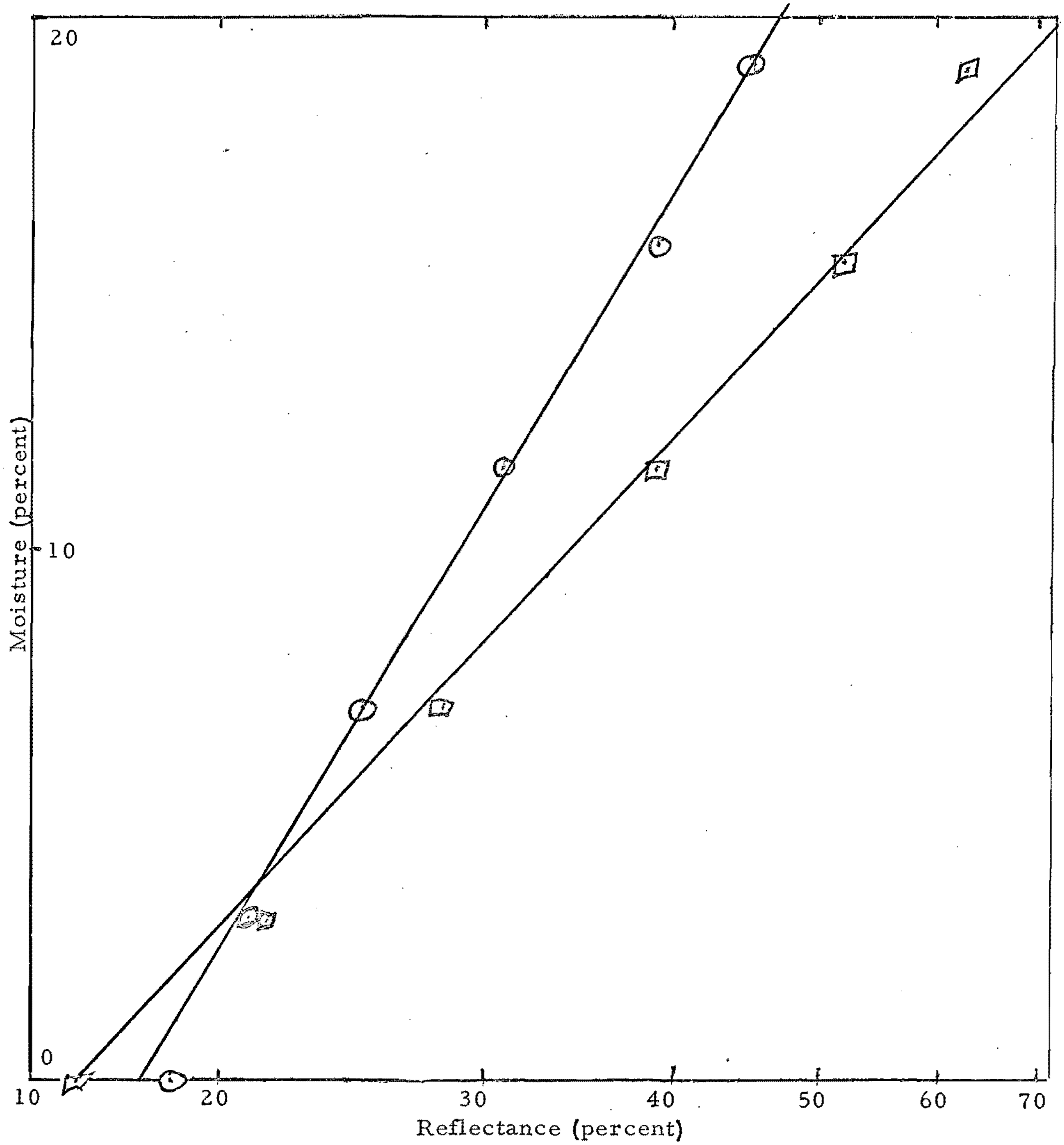

Figure 3. Reflectance vs. water content for a soil sample.

Laboratory Measurements

Area investigated

Of the various methods discussed in the foregoing, the reflection of visible and near-infrared radiation from plants shows particular promise and lends itself to an investigation which can be made in the laboratory; thus it was selected for this study. The measurements were made with the Barlow spectrograph (Figure 4) developed by the Electro-Dynamics Laboratories. The data obtained on the film were further reduced by making densitometer traces with the Joyce Loebel recording microdensitometer. This instrument is shown in Figure 5.

Spectral reflection measurements were made from the following plants: quaking aspen, poplar, blue spruce, bracken fern, western coneflower, grass, and sagebrush. All of these are native to the watershed area in which a future controlled experiment is planned.

Experimental procedure

The plants listed above were grown in a greenhouse until there was sufficient foliage to make satisfactory measurements. Each of the plants was watered and then allowed to use the moisture in the soil until the plants reached wilting stage, in the case of the broad-leafed plants, and for evergreens, until the soil was as dry as possible without permanently damaging the plants. This cycle was repeated several times over a

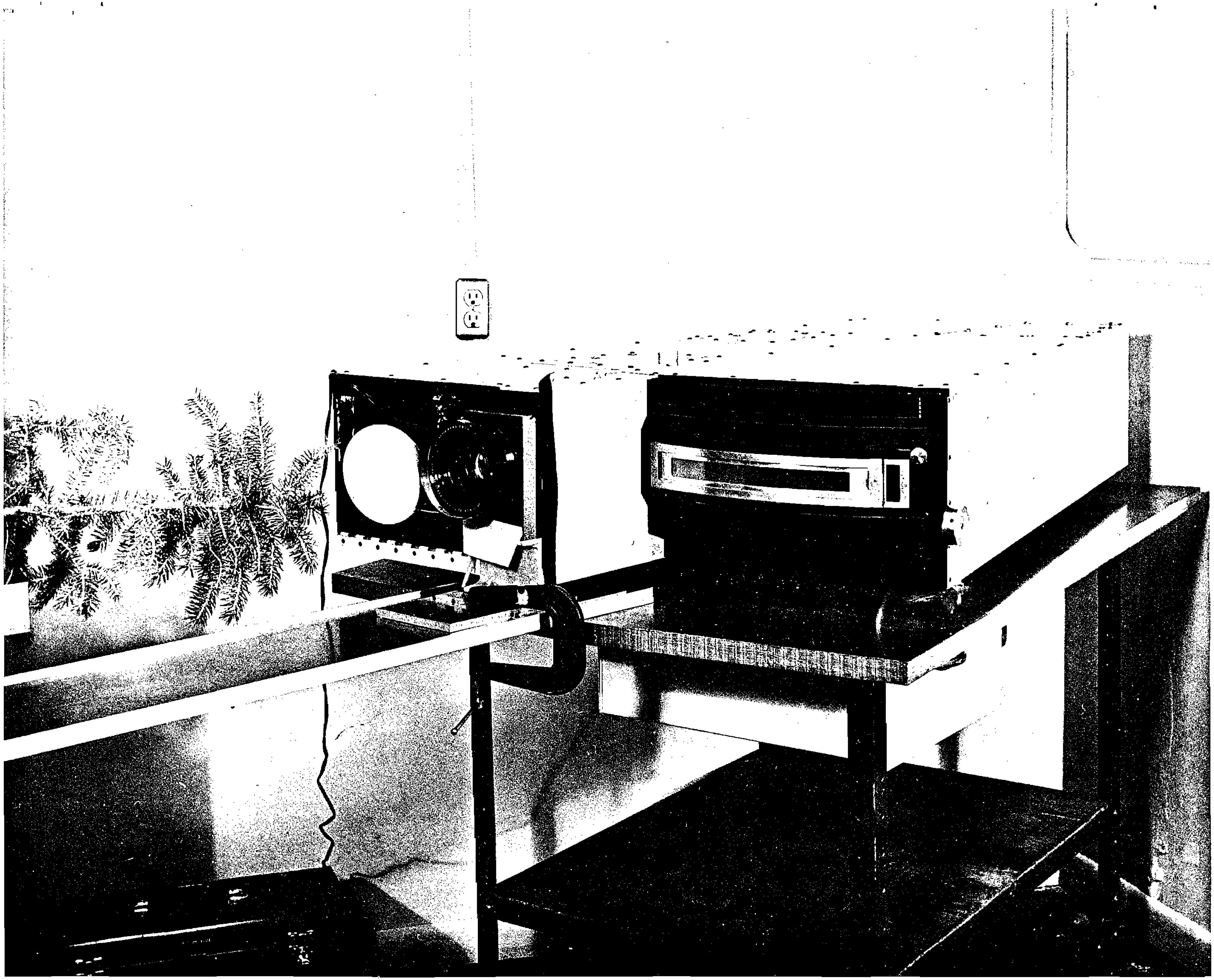

Figure 4. Spectrograph used in reflection measurements

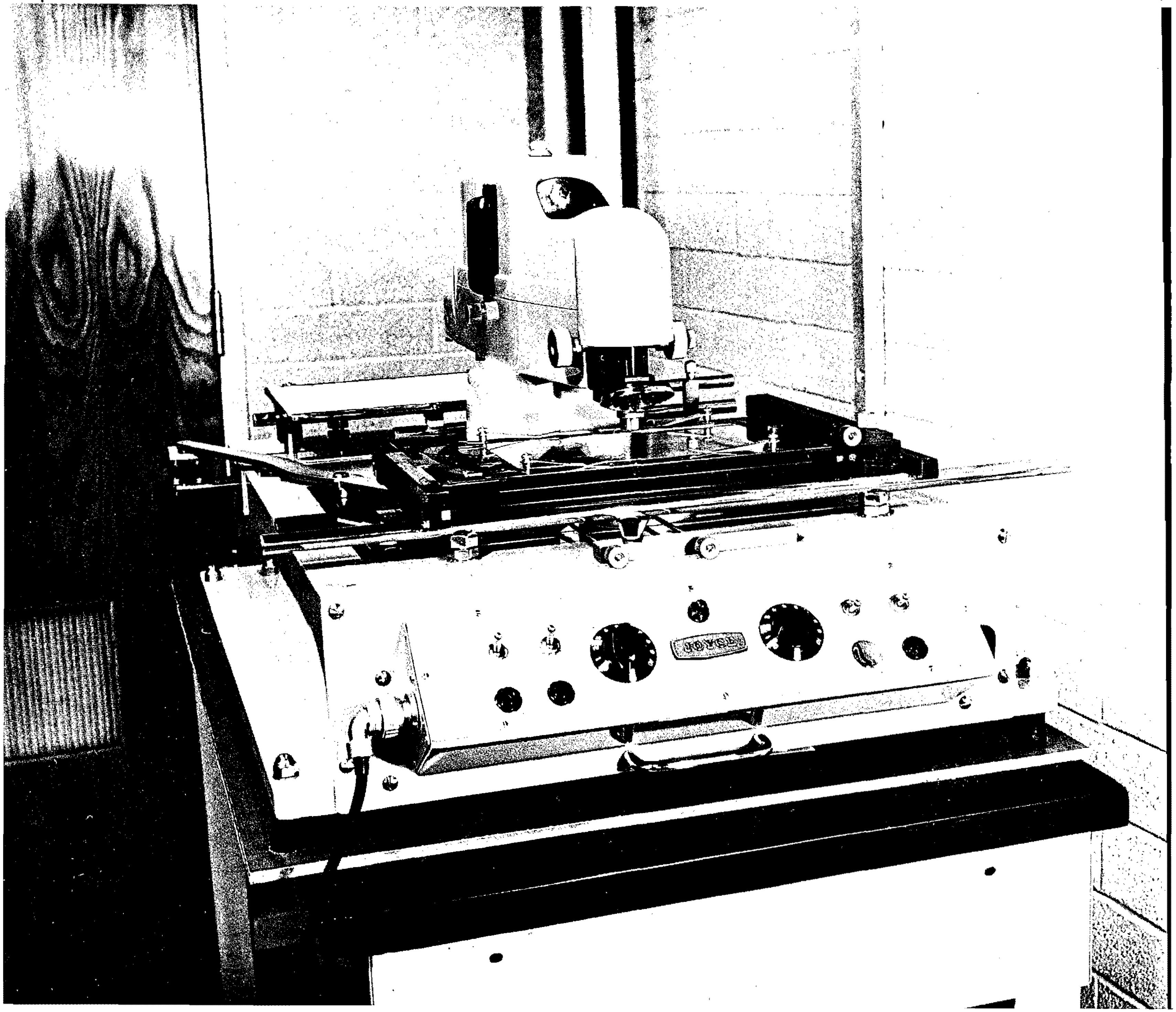

Figure 5. Joyce Loebel recording microdensitometer

period of three months. Spectrographs on film were made of each plant throughout this period. Two typical spectrographic films are shown in Figure 6. Each film is capable of five individual spectral traces, one of which is used for a calibration spectrum of a mercury lamp. This gives a sharp-line spectral calibration. High-speed infrared film was used for the traces in the near infrared. A long-pass filter was used to block all wavelengths shorter than 5000 Å to eliminate second-order effects on the film.

Since infrared film has very little sensitivity in the green, separate traces were made with Tri-X panchromatic film to measure the reflection near 5500 Å. Control experiments to determine film response were made with white paper for which the spectral reflection was known. The results obtained from eliminating all targets and using the black background indicated that there was insufficient energy reflected from the background to cause any significant exposure of the film.

The data recorded on film were further reduced by making densitometer traces with the Joyce-Leobel recording microdensitometer. A typical recording film is shown in Figure 7. The densitometer is so constructed that the vertical alignment on the graph is identical to that on the film. Therefore, by recording the mercury spectrum on the same paper, a direct wavelength reference was obtained. The data recorded in this form were easily compared qualitatively.

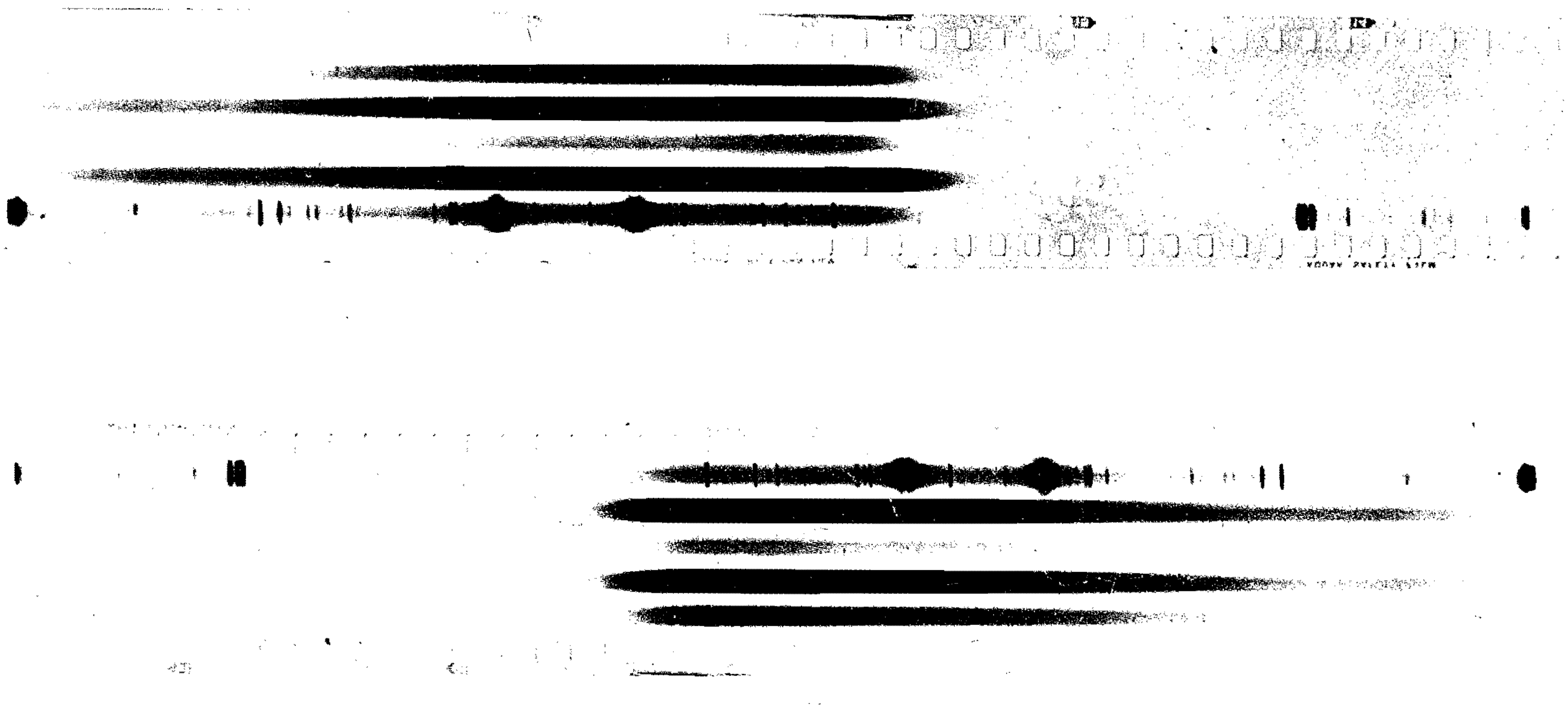

Figure 6. Typical spectrographic film.

Figure 7. Densitometer trace from film.

Experimental data and results

Figure 8 shows typical infrared densitometer traces of each plant studied. With the exception of the sagebrush, all of the plants measured have the same general spectral characteristics. The data obtained for each type plant are given in Tables 1 through 9. Spectral curves showing each type plant under wet and dry conditions are shown in Figures 9 through 12. The data obtained illustrate a marked reduction in the infrared reflectance from the plants under conditions of extreme water stress. This reduction begins before any noticeable wilting or visible color change takes place. Colwell (1963) obtained similar results from diseased trees. Most of the explanations he uses for the loss in infrared reflection of a diseased plant are applicable to plants under water stress.

Figure 13 is a schematic illustrating the reflection and absorption of sunlight by a green leaf. The blue and red colors are largely absorbed by the chloroplasts and are used in photosynthesis, while the green colors are reflected by the chloroplasts. The infrared radiation is not affected by the chloroplasts but is reflected by the spongy mesophyl. When the plant does not have sufficient water, the spongy mesophyl cells begin to collapse, thus causing a reduction in their ability to reflect the infrared radiation. If the plant is stressed beyond its ability to recover, the chloroplasts will eventually be lost. The chloroplasts are not affected nearly as soon as the mesophyl; consequently, two plants which show very

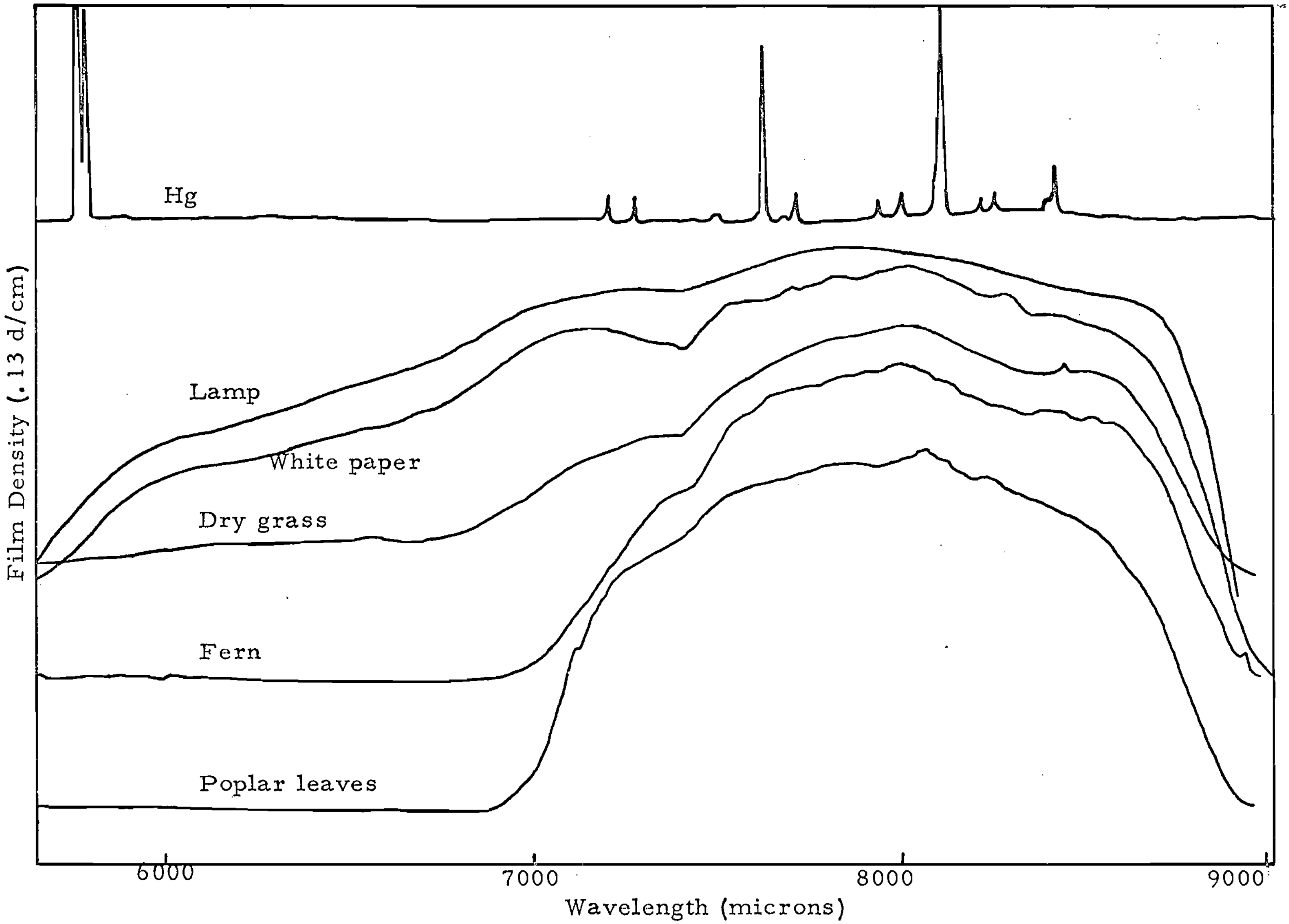

Figure 8. Comparison of reflection from various plants.

Table 1. Infrared reflectance of Quaking Aspen leaves.

Sample No.	Film Density 8000 Å	7150 Å	No. Days Since Last Watering
1	1.01	.65	0
2	.94	.59	0
3	.99	.65	0
4	1.01	.68	1
5	.97	.46	1
6	.83	.39	2
7	.99	.68	2
8	.97	.62	2
9	.92	.52	3
10	.95	.62	3
11	.88	.46	3
12	.99	.55	4
13	.92	.52	4
14	.79	.47	4
15	.88	.35	5
16	.87	.48	6
17	.81	.48	6
18	.77	.44	6
19	.88	.55	7
20	.78	.53	7
21	.73	.27	8
22	.78	.27	8
23	.85	.35	8

Table 2. Visible reflectance of Quaking Aspen leaves.

Sample No.	Film Density 5500 Å	No. Days Since Last Watering
1	0.39	1
2	0.43	2
3	0.42	4
4	0.40	8
5	0.36	8 (wilted)

Table 3. Infrared reflectance of Poplar tree leaves.

Sample No.	Film Density		No. Days Since Last Watering
	8000 Å	7150 Å	
1	.95	.52	0
2	.95	.55	1
3	.97	.65	2
4	.89	.40	4
5	.86	.42	6
6	.77	.36	7

Table 4. Visible reflectance of Poplar tree leaves.

Sample No.	Film Density 5500 Å	No. Days Since Last Watering
1	.50	1
2	.46	2
3	.52	3
4	.56	4
5	.48	6
6	.50	7

Table 5. Infrared reflectance of Blue Spruce.

Sample No.	Film Density 8000 Å	No. Days Since Last Watering
1	.52	1
2	.53	1
3	.62	1
4	.51	4
5	.56	4
6	.50	7
7	.58	7
8	.49	7

Table 6. Visible reflectance of Blue Spruce.

Sample No.	Film Density 5500 Å	No. Days Since Last Watering
1	0.27	1
2	0.25	1
3	0.30	1
4	0.34	4
5	0.28	4
6	0.26	7
7	0.30	7
8	0.25	7

Table 7. Infrared reflectance of Bracken Fern leaves.

Sample No.	Film Density 8000 Å	7150 Å	No. Days Since Last Watering
1	.71	.40	0
2	.70	.35	1
3	.82	.35	2
4	.66	.26	4
5	.65	.22	7

Table 8. Infrared reflectance of grass.

Sample No.	Film Density 8000 Å	7150 Å	No. Days Since Last Watering
1	.72	.40	0
2	.82	.29	0
3	.83	.27	1
4	.78	.33	3
5	.71	.22	5
6	.66	.19	6
7	.33	.10	7*
8	.30	.13	8*

*Some of the grass appears to be dead.

Table 9. Infrared reflectance of sagebrush.

Sample No.	Film Density 8000 Å	7150 Å	No. Days Since Last Watering
1	.26	.11	1
2	.28	.14	3
3	.28	.12	7
4	.27	.13	10*

*Sample very dry and did not recover.

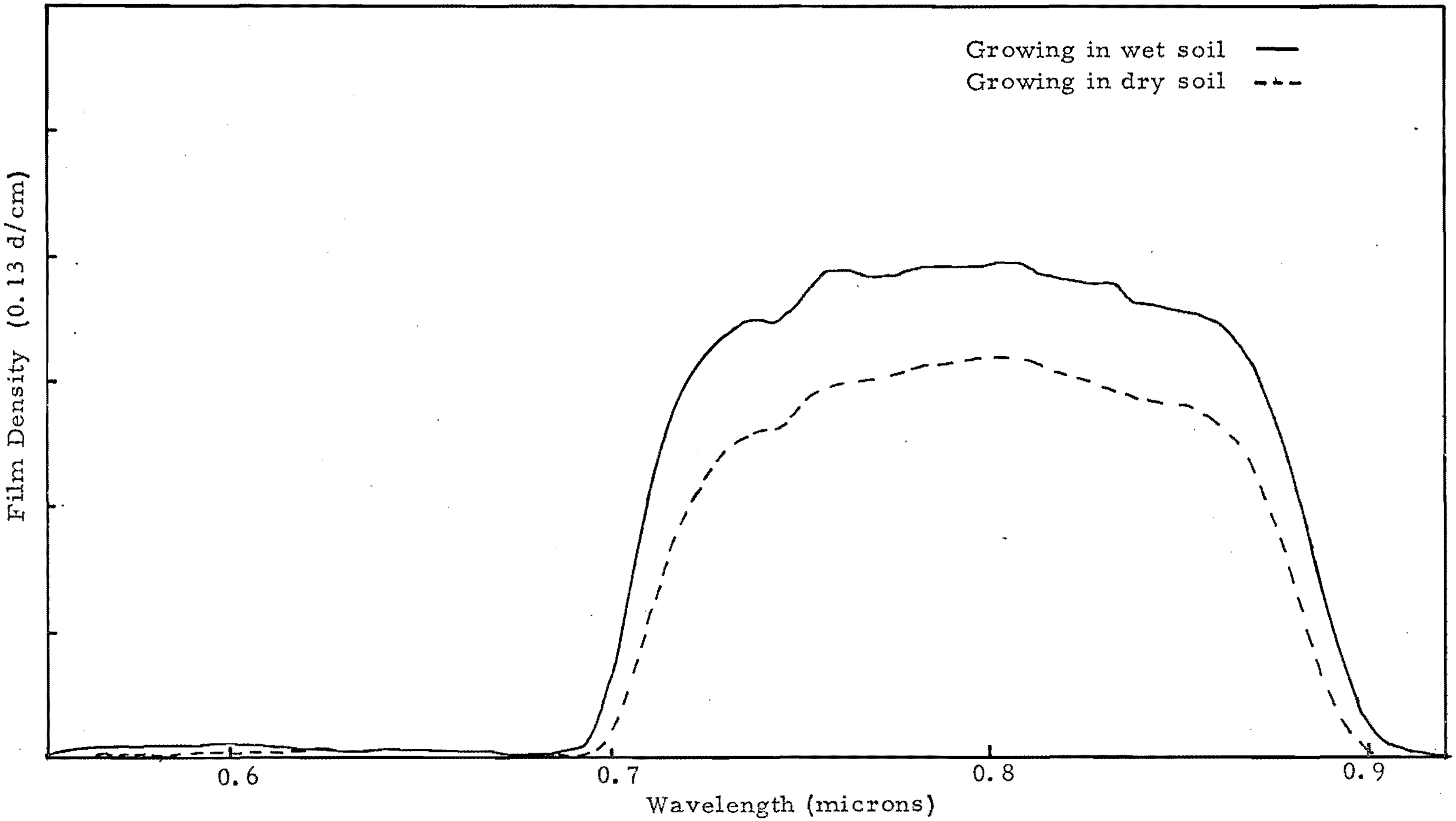

Figure 9. Reflectance of Poplar leaves.

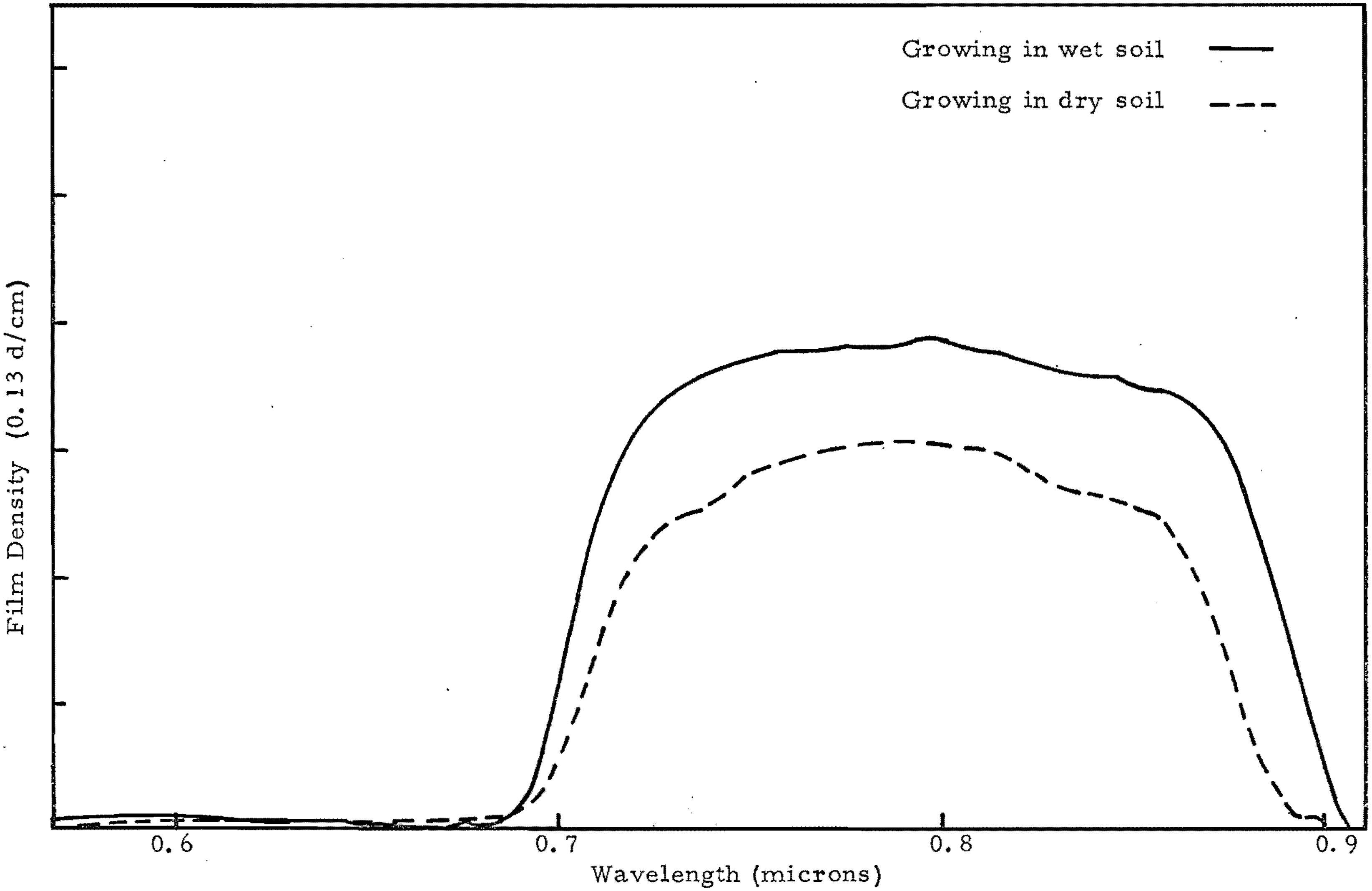

Figure 10. Reflectance of Quaking Aspen leaves.

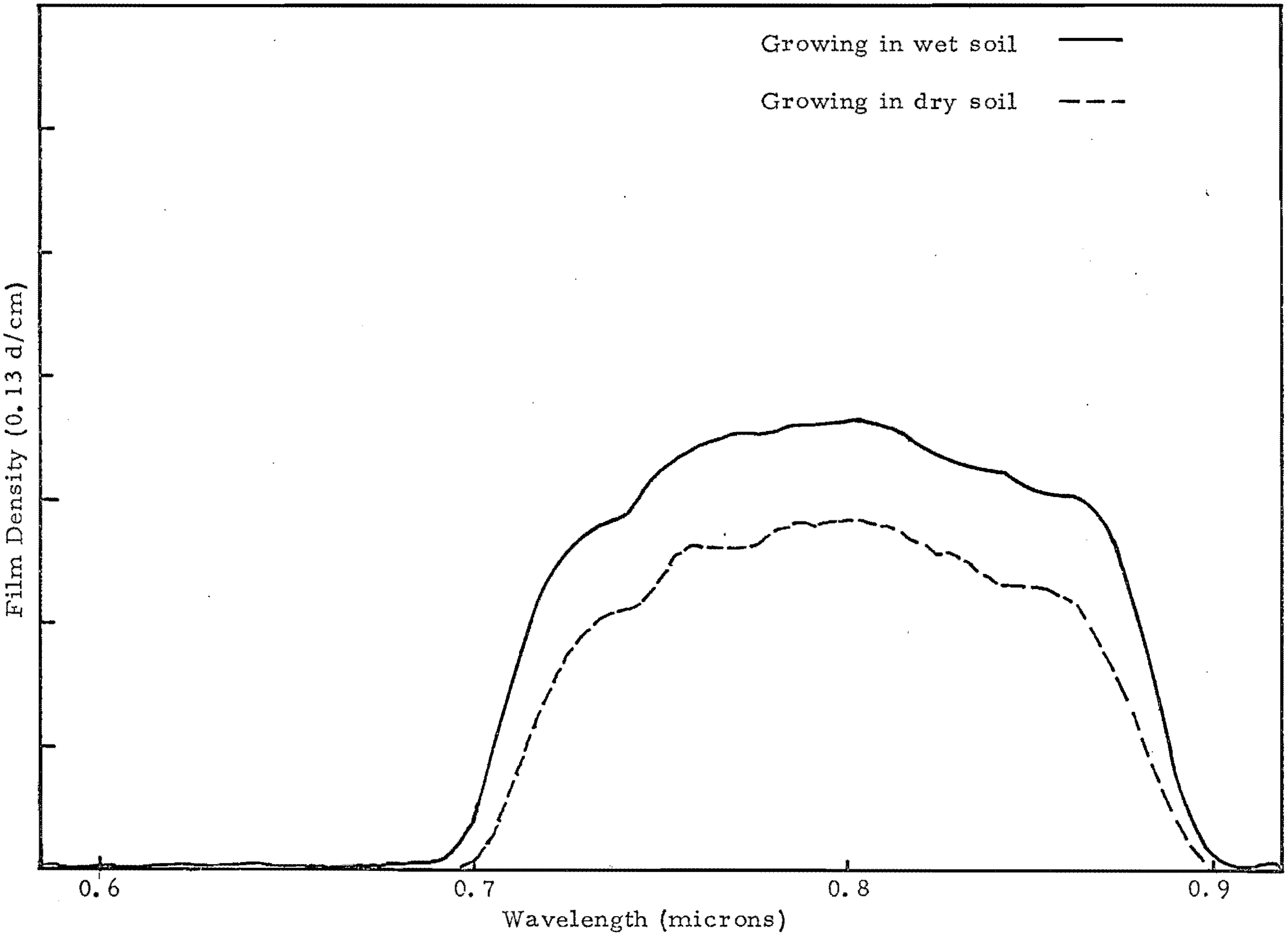

Figure 11. Reflectance of Bracken Fern.

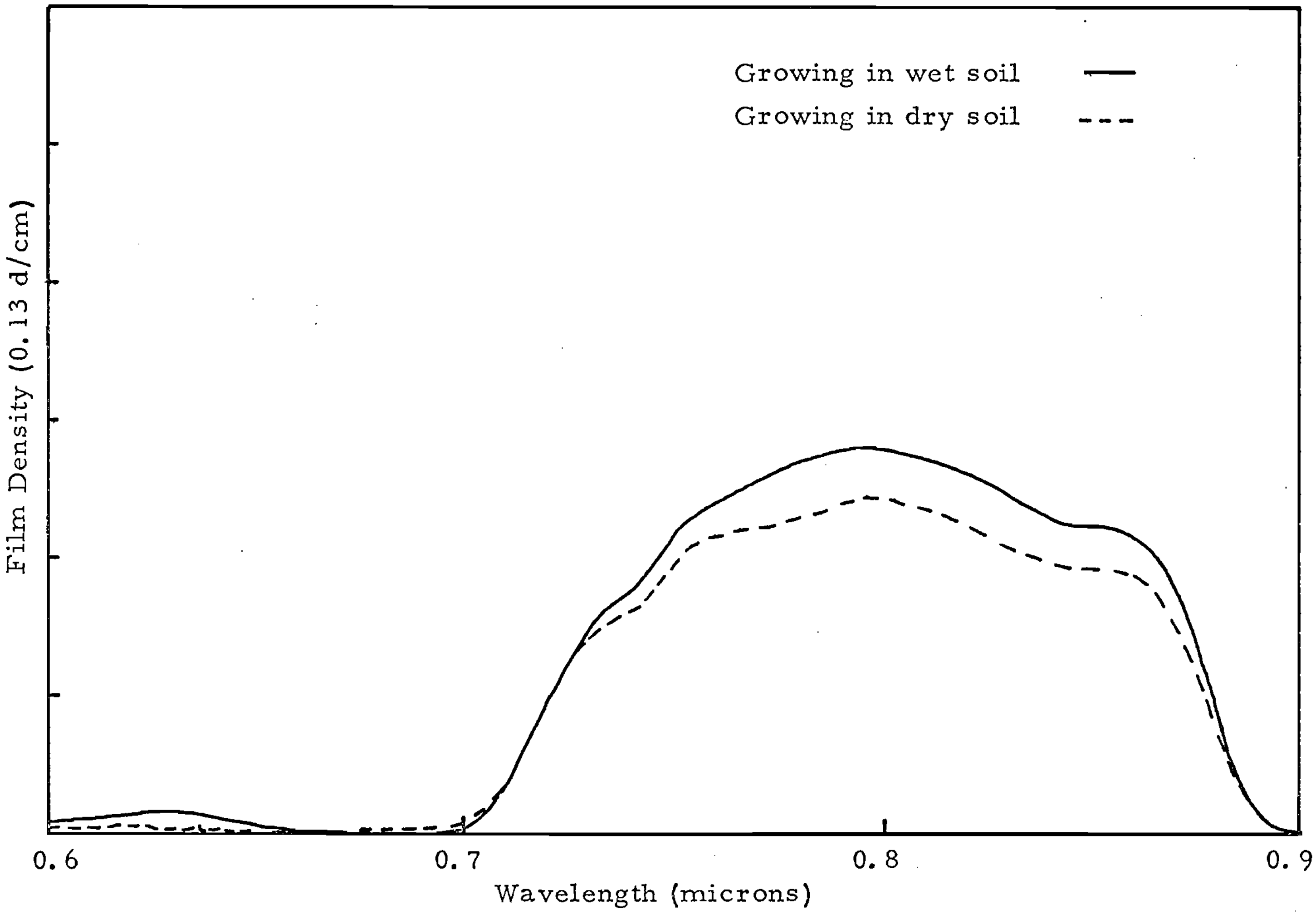

Figure 12. Reflectance of Blue Spruce.

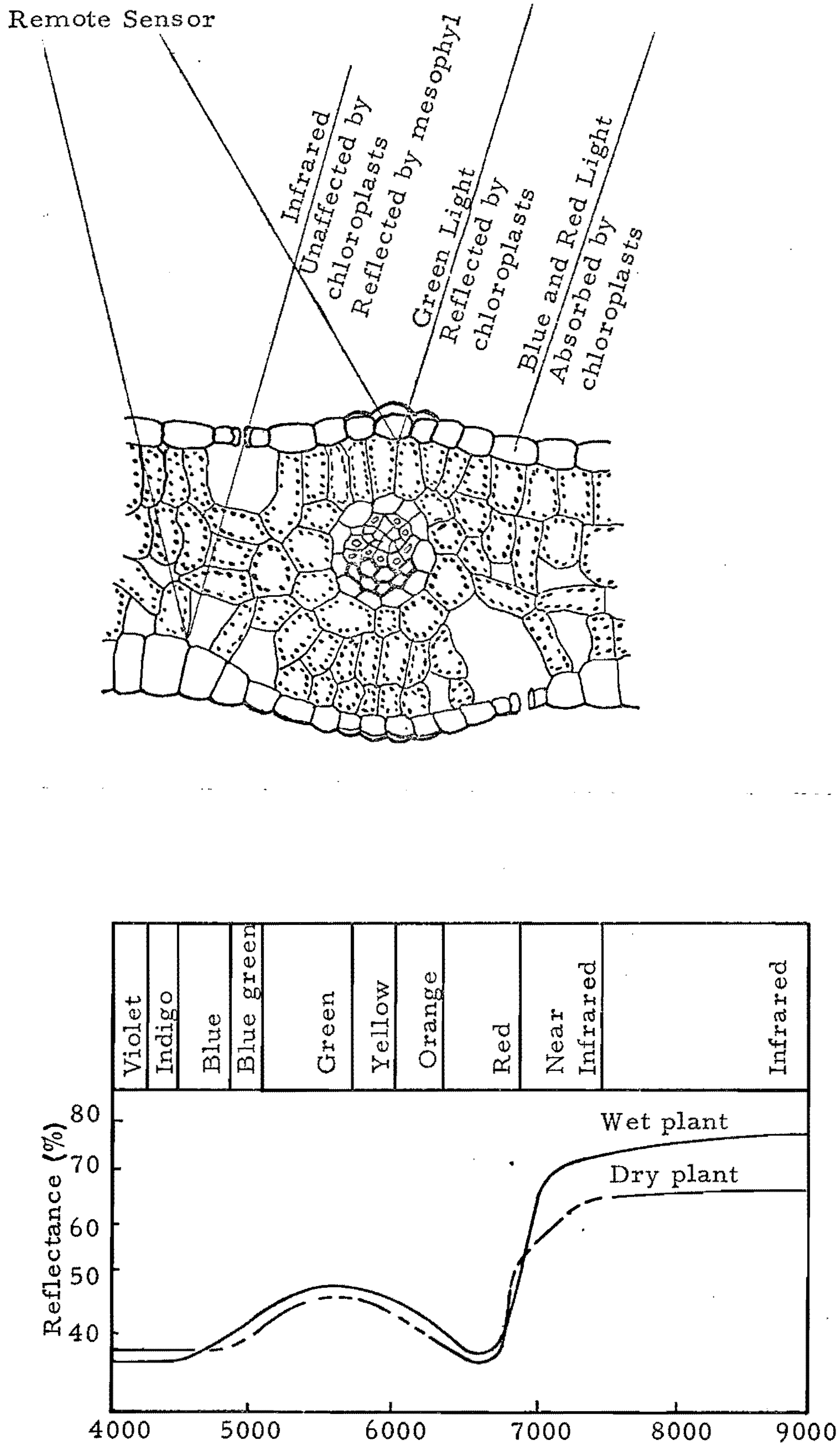

Figure 13. Schematic illustrating reflection and absorption of a green leaf.

little difference when viewed or photographed with visible light may appear significantly different in infrared photographs.

Conclusions

Of all suggested economically feasible methods of determining water conditions, two areas show particular promise: (1) A temperature profile map in the 4 to 6 or 8 to 14 μ region, accomplished by means of a filter wheel radiometer, would be valuable. Research beyond the scope of this study would be necessary to relate the temperature profile to water conditions. (2) The experiments made in our laboratory indicate a definite correlation of water conditions to infrared reflectance of plants. Further study is necessary to determine if the conditions which may exist in the watershed area will mask the results and provide variations which are greater than those due to water stress.

The data collected by airborne remote sensors must be interpreted with the aid of additional information collected on the ground. The amount of ground information required to give a general interpretation of water conditions will be significantly reduced by use of the data obtained economically and easily from the air.

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