SPECTRAL REFLECTANCE CHANGES ACCOMPANYING A POST FIRE RECOVERY SEQUENCE IN A SUBARCTIC SPRUCE LICHEN WOODLAND

A Young Spruce on the 24 YR Burn

SPECTRAL REFLECTANCE CHANGES ACCOMPANYING A POST FIRE RECOVERY SEQUENCE IN A SUBARCTIC SPRUCE LICHEN WOODLAND

by

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Abstract: A sequence of burned surfaces aged 0, 1, 2, 24, and 80 years was investigated regarding changes in the spectral distribution of reflected light. Controls were introduced to isolate diurnal and seasonal effects. The results show gradually increasing reflectance with increasing age of burn. With the establishment of vegetation a new set of absorbtion and reflectance criteria are established substantially altering the spectral characteristics. The apparent effect of a mature forest canopy is ambiguous. Diffuse and overcast conditions reduce the reflectance for all surfaces. Further work is suggested to reinforce results for surfaces with low sampling replication.

Acknowledgements:

My sincerest thanks are given to Dr. Wayne Rouse for the project, for his support and criticism, and for the opportunity of the north; to Dr. P. J. Howarth for the loan of the instrumentation; to Peter Mills for logistical assistance and advice; to Bob Van Dijken, Rick Bello, William Bailey, and Bob Stewart for occasional advice and comments; to Dr. K. A. Kershaw, Eugene Maikawa, and Herb Deruyter for assistance in species identification and advice; to Clay Rubec for some illustrative material; and to Paul Berry for some production assistance.

Dedication:

to the sun for being
to cloudspace and the eagle
to Fran and other fantasies,

to the labmen for inspiration
and enlightenment
when needed most
and least perceived,

to the lab and
other space
for silence,
seclusion,
and peaceful sadness.

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1. Introduction

Fire has been identified as a very important component in the ecology of many natural environments. The subarctic spruce lichen woodland is no exception. Fire in the region of study area has been associated with the mean summer position of the Arctic front and the frequent occurence of lightning and storm activity. (Rouse 1976). The usual result is one of small patchwork burns with limited spatial extent creating a mosaic of various aged vegetation complexes, lakes, and swampy low lying areas. Large extensive burns can and have occured however.

The results of burning are not homogeneous and depend on fuel type, antecedent moisture conditions, the intensity and extent of burning, and the time period involved. Often as a result of changing conditions, during a burn, there will be as much heterogeneity within one burn as there is between burns. These factors will have a direct effect on the vegetation recovery rates.

The microclimatic effects of burn disturbances on a "mature" spruce lichen woodland have been investigated by Rouse (1976), Kershaw and Rouse (1975), Rouse and Kershaw (1971) and others (Rowe and Scotter 1973, Bliss 1973). The obvious albedo effects, the destruction of the surface peat layer, and the variation in the radiation and energy balances have been described in some detail and speculation relating the various effects to the scale and intensity of burning has been undertaken. Rouse (1976) describes the microclimatic changes accompanying the recoveryof artificially and naturally burned surfaces. The interaction of decreased albedo and increased longwave radiation losses have created conditions that are not intuitively obvious but may serve

0 YR Burn

to delay the overall recovery rates. It is important to be aware that recovery rates are quire variable. The apparent sequence at this research site was over eighty years. Although the interlinking can only be a coarse one, given the resolution of measurement, it is possible that long term, even if slight, energy balance effects may have a determining influence on the composition of vegetation complexes and their scales and rates of change with time. Maikawa and Kershaw (1976) and Kershaw and Rouse (1975) have described some of the vegetation changes accompanying the recovery sequence in this region of the subarctic. No indication of direct causality is implied. They suggest that if this environment were not interrupted by fire a progression toward a more closed crown canopy would occur. That this is very infrequently seen testifies to the frequency of burning.

Although substantial radiation and energy balance measurements have been made, there has to date, to the author's knowledge, been no site intensive study of the spectral quality of radiation in such an environment over a recovery sequence. Measurement of bulk albedo values have been made (Davies 1962, Petzold and Renz 1975, Berglund and Mace 1972) and much work on the spectral reflectance of individual species has occured. Much of the latter however has been in laboratory conditions with southern latitude species. Measurements of conifers and lichens have been sparse. (Gates 1965). Part of the problem has been the lack of high quality durable field instrumentation. There is considerable variation in the quality of the field investigations.

This presentation reports on a field investigation of spectral reflectance over five differently aged burned surfaces in the western subarctic. Some trends are identified while other data remains speculative and suggests a need for further investigation.

TABLE # 1 Some Characteristic Albedos (Sellers 1965)

Water surfaces	6 - 8%
Dry sand	35 - 45%
Wet sand	20 - 30%
Moist gray soil	10 - 20%
Green meadow	10 - 20%
Deciduous Forest	10 - 20%
Coniferous Forest	5 - 15%
Tundra	15 - 20%

TABLE # 2 Albedo Values For Burned Surfaces (Rouse 1976)

0 YR Burn	5.2%
1 YR Burn	6.8%
2 YR Burn	8.5%
24 YR Burn	15.7%
Mature	19.0%

2. Theoretical Review

(a) General Considerations of Albedo

The quantity of radiation absorbed at any surface is dependent on the intensity of the incident radiation, the spectral distribution, the angle of incidence of the radiation and the degree to which a surface reflects the radiation.

Incident solar radiation undergoes several types of attenuation in the atmosphere. The diffuse component is caused by these processes of scattering and absorbtion. The blue wavelengths are usually more readily scattered than longer wavelengths when aerosol sizes approach those of the incident wavelengths. The quality of incident radiation is, therefore, first of all a function of atmospheric constituents as well as pathlength through the atmosphere, and the distribution of the extraterrestrial radiation. The selective reflection of different wavelengths will vary with the wavelength and with the angle of incidence of the radiation, for any surface. One may expect diurnal and seasonal effects due to the change in solar geometry. Diffuse components will be altered also but less symetrical patterns will override these, correlated with the presence and absence of cloud cover.

Diurnal variation in reflectance are related to zenith angles of the sun but the strength of this relationship varies with the surface roughness, and the extent of the trapping of radiation through multiple reflection processes. Arnfield (1975) cites an inverse relationship existing between daily albedoes and canopy depths. Cloud cover will also have an effect, decreasing the dependency of albedo on zenith angle; an effect that will be less obvious for flat surfaces or exposed mineral soils. The reflectivity of bare soil increases with decreasing organic content and decreasing water content. If diurnal asymetry exists it is likely due to a change in surface properties although a change in the incident fluxes can occur due to asymetric dust loadings in the atmosphere.

For the purposes of this report the primary differential is the presence and absence of vegetation on the burned surfaces, and the morphology of that vegetation. We will consider the vegetation effects in more detail. Such general characteristics as seasonal changes in air mass, and the quality of air were not considered to be discernible variables due to the sensitivity and regularity of measurement.

(b) Factors Affecting the Spectral Reflectance of Vegetation

The physiological and physical properties of the plant environment are numerous and varied. The complexity of the vital processes within the organism is far more generally appreciated than the complexity of the environmental media which surround it. The physical environment has a multiplicity of factors, is spatially and temporally heterogeneous, and dynamic. Plant physiological requirements are variable, many factors may be synergetic and threshold and biological optima are not static. Understanding radiation interactions is an important starting point to understanding many others. There is some debate, however, about the relative effect of the variation of light quality as opposed to the effect of coarser parameters such as light intensity and duration which are certainly easier to evaluate. Although it is true that variations in light quality affect plant processes differently, each process is somewhat sensitive to all wavelengths and in ecological work analyses of wavelength composition are difficult to interpret. The influence of light quality upon plants differs so much from one species to another that except for generalization no precise physiological roles of different portions of the spectrum have been established. Variations in light quality have never been demonstrated to be great enough to be critical as an environmental factor for land plants growing under natural conditions. (Daubenmire 1974).

Some of the interactions have been investigated and described however. A healthy plant leaf reflects and absorbs incident radiation in a manner unique to its pigments and fluid contents. The general features of this include a high absorbtion and low reflectance in the ultraviolet and blue wavebands less than 400mμ. Reduced absorbtion and higher reflectance occurs for the green wavelengths and similar responses as for the blue wavelengths are seen in the red (550mμ to 650mμ). Very low absorbtion and high reflectance and transmission occurs in the near infrared. (750mμ to 1500mμ). Dips in the near infrared reflectance at 925mμ, 1100mμ, and 1400mμ occur which correspond to the liquid water absorbtion bands. (Figs. 21, 23)

Leaf morphology is one of the primary factors in determining the reflectance spectrum. Cellular structure is large compared to the wavelengths of light but the grana of chloroplasts are approximately the same dimensions and these may produce considerable scattering of the light entering the leaf and the chloroplasts which vary in their locations within the leaf. (Gates 1970). Radiant energy that is absorbed by these segments of the leaf will be converted to heat and fluoresence and then converted photochemically into stored energy.

Pigment absorbtion is caused by electron transition within pigment molecules and their complexes, whereas liquid water absorbtion is caused by the transition of the vibrational and rotational states of the water molecules. The former requires more energy than the

Fig. 2 Some routes for internally reflected light

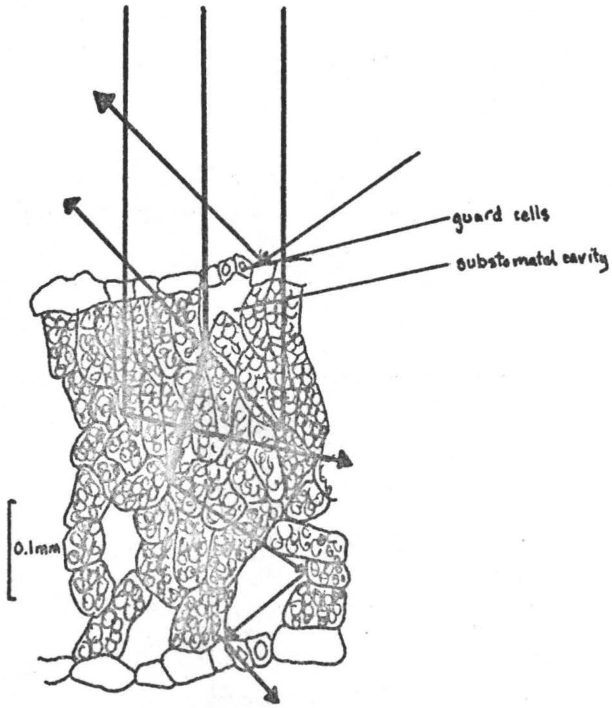
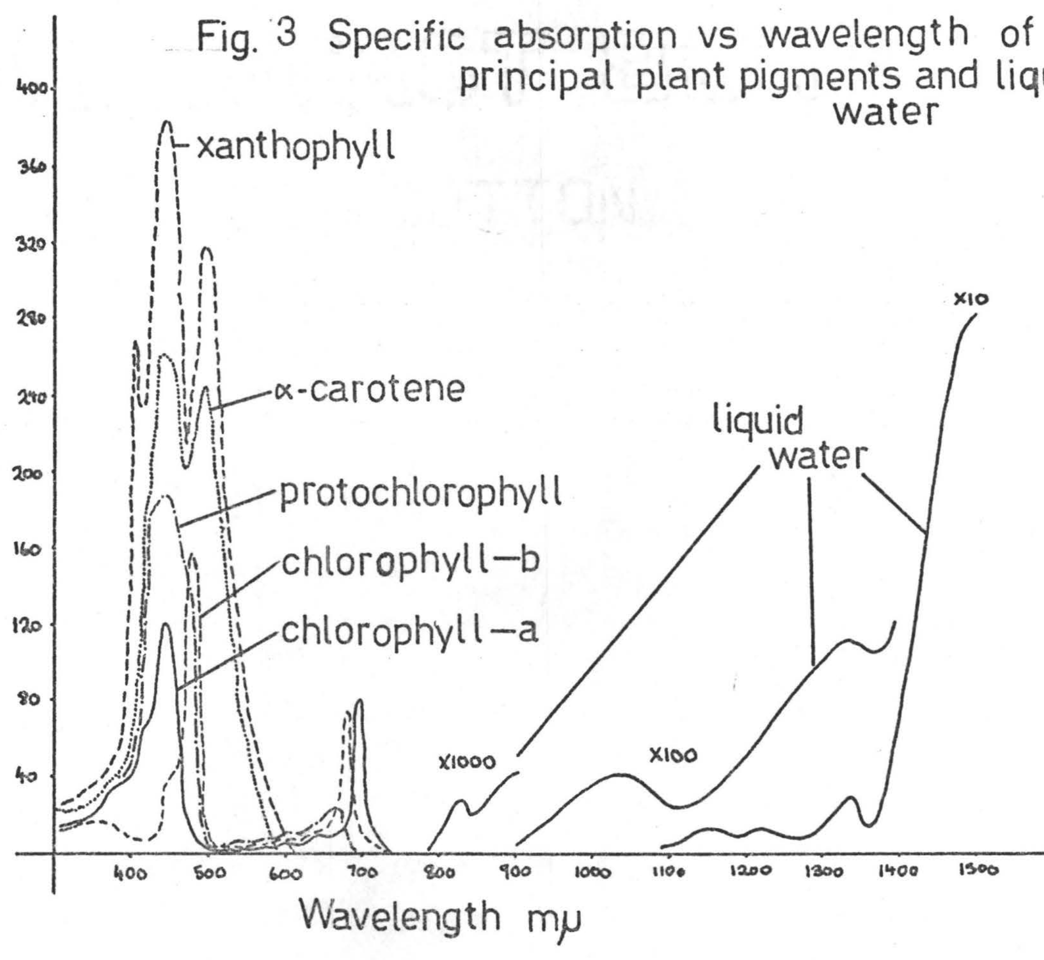


Fig. 3 Specific absorption vs wavelength of the principal plant pigments and liquid water



latter and thus the shorter wavelengths are involved. Figure 2 shows light entering a leaf and a number of possible paths for critical internal reflection. Because of complex reflectances a leaf absorbs and reflects light in wider bands than would be indicated by strict physical reasoning. The presence of pigments other than chlorophyll tends to broaden the absorbed wavebands. (Fig. 3). Other important materials include the cellulose of cell walls, the amount of concentration of water containing solutes, and the degree of intercellular air space. Scattering can occur due to a variety of wavelength scale cell bodies.

At a somewhat larger scale, leaf reflectance can be affected by the thickness of leaves changing the optical path lengths, the degree of waxiness of the cuticle affecting the thickness and transmissivity, and the hirsuteness of the leaf causing generally higher reflectance in the visible wavelengths but lessened effects in the infrared. (Howard 1966, and Billings and Morris 1962).

Gates (1970) shows also that the reflectance depends on the vitality of the spongy mesophyll in the leaf. For thin leaves transmittance was greater than reflectance while the reverse was true for thick leaves. The thick dark leaves of a xerophyte may transmit no radiation at all and reflect very strongly in the infrared. Considerable reflectance can occur at the outermost layers of the thick waxy cuticle which covers succulent plants.

Gausman and Cardenas (1968) show that hairiness increased total and diffuse reflectance in the 750mμ to 1000mμ wavelengths but decreased total and diffuse in the range of 1000 to 2500mμ. The hairs were generally thicker than the incident wavelengths but some scattering is likely to occur. Other identified variables were species, type of hair, the density of hairs and possible interactions such as the changing water status of a leaf as a result of losing hairs. These results were substantiated by Gates (1970).

One of the parameters most identified in the literature relating to many scales of consideration is the water content of the leaf. An increase generally decreases the reflectance and transmittance of the incident light at more than the simple water absorbtion bands. (Thomas et al. 1966). Ward (1969) shows significant increases in the reflectance in the water absorbtion bands produced by drought or high salinity. The effect was only subtle in the visible wavelengths. Reflectance in the wavelengths of 800 mμ, 1000mμ and 1200mμ was significantly increased by low soil salinity even in the absence of visible symptoms.

Directional effects of reflectance have been referred to by a number of authors. Coulson (1966) shows monochromatic effects for short grass, turf, and soils as a function of the angle of incidence. For wavelengths less than 700mμ effects were noticed once angles of incidence exceeded 78.5°. The effects were always greatest for soil and sand. Scott (1968) and Howard (1966) also report on directional effects and the polarization of reflected light.

The change of spectral reflectance throughout a growing season has been demonstrated. As protochlorophyll converts to chlorophyll there is a general increase in red absorbtion and an increase in green reflectance. As leaves turn a darker green infrared reflectance increases while the deep absorbtion cutoff around 700mμ shifts slightly towards longer wavelengths. (Gates 1970). The initial changes in spring can be very rapid but subsequent pigment accumulation can be a very slow process. Near the end of the growing season pigments change rapidly from chlorophyll to anthocyanin and yellow band reflectance is enhanced.

The change in infrared reflectance is not so straight forward, as it is more responsive to cell shape and size and the amounts of inter-cellular space. With plant maturation comes increased reflectance.

Changes in the water content seasonally and changes in the surface coat of a maturing leaf and the positions of the choroplasts may also be factors. (Gausman et al.). It is generally felt, however, that the most sensitive of the changes is due to pigmentation. Other seasonal effects such as "ripening" of fruits are often reported upon but of little overall significance.

For generalized studies of forest vegetation Olson and Good (1962) describe greater variations in reflectance from deciduous tree species as compared to coniferous tree species whose seasonal changes were not as great. Berglund and Mace (1972) show very slight seasonal changes for black spruce vegetation. Coniferous species in general do not exhibit the same leaf morphologies or changes as the deciduous species. Oriented needles show strong polarization effects. Gates (1965) shows very high absorbtion throughout the visible and near infrared wavelengths although due to some aerodynamic factors this need not imply a long term increase in heat loading. Petzold and Renz (1975) show relatively low albedo values of 16% from a spruce lichen woodland. The values of Rouse (1976) are higher at 19%. For a closed crown Berglund and Mace (1972) report bulk values of 6-8%. The complexity introduced by the presence of the canopy is intriguing. Numerous authors report the increased trapping of radiation under such conditions.

Lichen analysis in the literature does not show any prominent features different from the vascular species except for reduced green peaks in the reflectance curves. (Gates 1965). The results of Petzold and Renz (1975) indicate that light conditions are only slightly less favourable for lichens as compared to other green plants. Quispel (1959) shows that reflectivities of lichens differed depending on the extent of the canopy above them. Hale (1967) reports that the increased radiation available in the open tundra environment increases the production of lichen acids and hence increases light absorbtion. Hoffman (1970) found the opposite effect. Overall there is very little published material on spectral reflection of cryptograms. In general the spectral reflectance properties appear very similar to those of vascular species.

The maximum transmission and reflectance gets larger for those wavelengths that have the largest incident magnitudes. This is important in the overall energy balance of a plant. Leaf temperatures can rise as high as 50°C which is close to the critical limit for plant proteins. It is felt that these temperatures could be as much as 10°C higher if plants absorbed more strongly in the infrared. The balance seen in spectral reflectance is very important for efficient heat transfer. The temperatures reached in various parts of the plant determine the rates for physiological processes.

Gates (1970) also notes that the spectral quality of light reflected depends to a degree on the spectral quality of the incident radiation. Fig. 4 shows some of the variations in the quality of incident light under different sky conditions. This indicates that a single value of reflectance or absorbtion should be related to general environmental conditions.

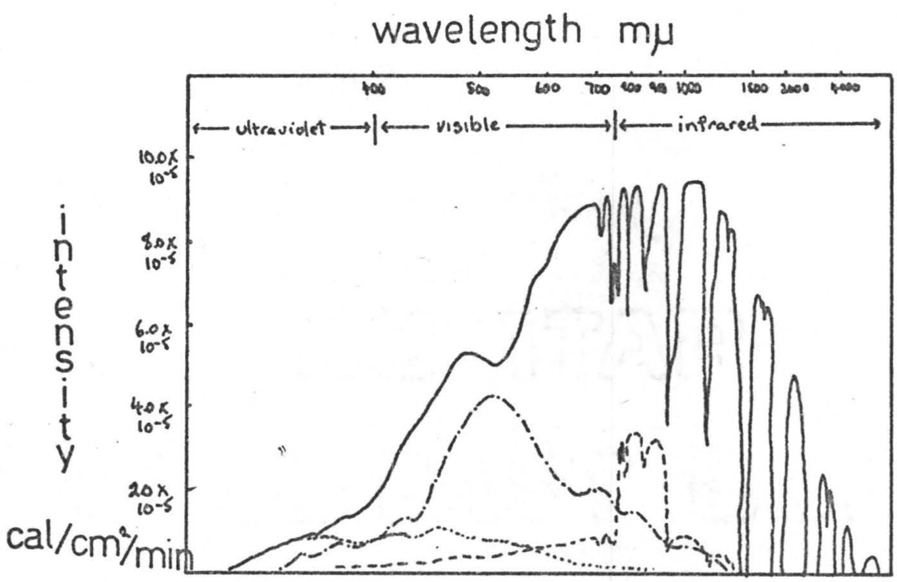


Fig. 4 spectral distribution of light

direct sunlight ————————
cloud light —·—·—·—·—
sky light ....
canopy transmission -------

3. Experimental Design

(a) Site Description

The research site is located approximately eighty-five miles northeast of Uranium City, Saskatchewan. (60 21' N, 106 54' W). The research drumlin is central in a large drumlin field of 3100 km. The region is a mosaic of vegetation types, primarily spruce lichen woodland, the specific distribution of which is closely tied to the frequency of burning. The drumlins are surrounded by dense stunted black spruce growth in the wetter low lying areas bounding the frequent lakes. The understory grades from a nonvascular lichen mat on the drumlin crests into a moss and shrub understory in the wetter areas. The base camp is situated near the end of a drumlin burned about fifty years ago while the main research site is on the margin of a twenty-four year old burn on an adjacent drumlin. (Fig. 6)

The drumlins are of generally uniform size ranging up to 3 km in length and 1/2 km in breadth. Other glacial features include extensive sandy eskers and outwash channels. The morphology and orientation of the lakes and interlinking drainage systems are a function of glacier movement which was from the northeast to the southwest. A variety of local depressions on the drumlins were likely formed through the melting of trapped and buried ice. Very few signs of active slumping processes are present today. These depressions contain a variety of vascular species not found elsewhere on the drumlins.

The drumlins have soils of podzolic formation developed in extensive depositional tills, Bedrock outcrops are present but rare.

Picea mariana is the dominant tree species. Larix larciana, Populus tremuloides, and Alnus rugosa are also present but are rare

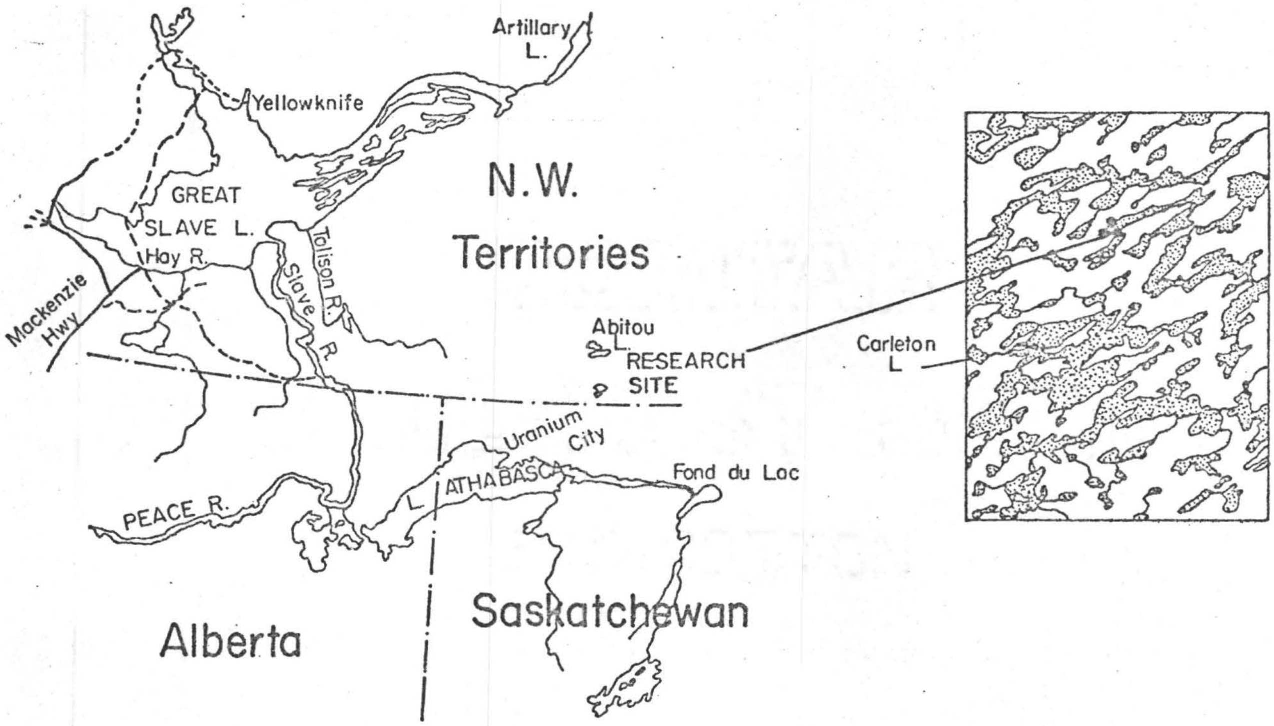


Fig. 5 Site Location

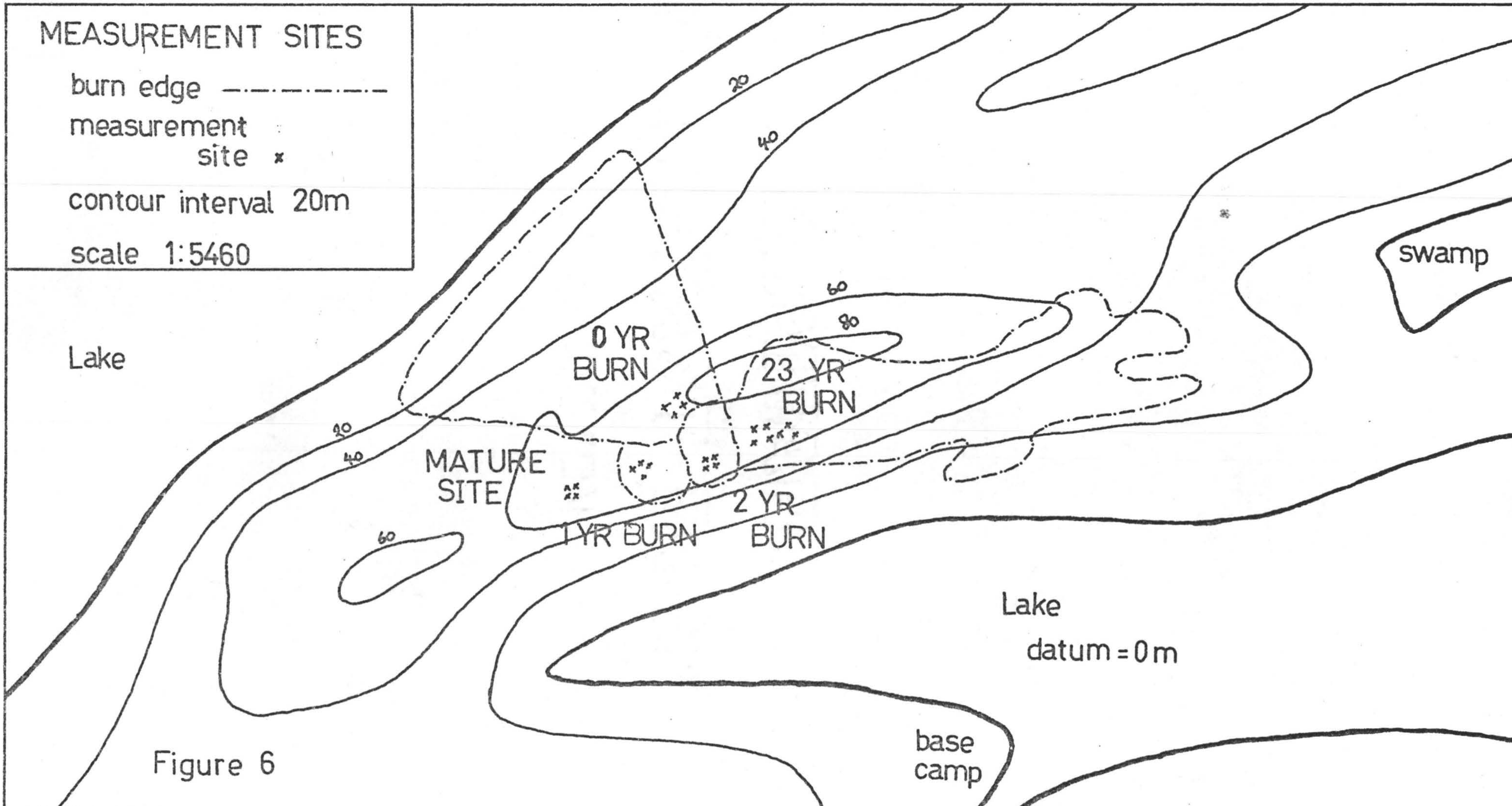

MEASUREMENT SITES
burn edge
measurement site
contour interval 20m
scale 1:5460
Lake
0 YR BURN
23 YR BURN
MATURE SITE
1 YR BURN
2 YR BURN
swamp
Lake
datum = 0 m
base camp
20
40
60
80

Figure 6

and patchy. Betula papyrifera is located on surfaces burned less than seventy years previously and Pinus banksiana is found only on sandy sites and eskers.

The ground vegetation on drumlins has been quantitatively described by Kershaw and Rouse (1975) and is included as Appendix A. More site specific information is also included and consists primarily of lichen species. The wetter sites consisted of Ledum groenlandicum, Myrica gale, Chamaedophra calculata, Empetrum hermaphroditum, Vaccinium oxycoccum, Rubrus spp. and Sphagnum spp.

Specifically a sequence of five burned sites were investigated with the time since most recent burn of 0, 1, 2, 24, and 80 years. The two year site underwent partial reburning after one year which accentuated the destruction of the peat layer. Lists of species present on these surfaces is also included in Appendix A. Spectral reflectance measurements were undertaken over a spatially distributed set of sample points (Fig. 6) chosen to encompass as many diverse surfaces as was feasible within each burn.

(b) Instrumentation

(i) The ISCO Model SR Spectroradiometer

The field experiments to be described were undertaken using an ISCO Model SR Spectroradiometer manufactured by Instruments Speciality Co., Inc. An aluminum frame was constructed for mounting the instrument with a detachable arm for three dimensional levelling and the alteration of the sensing height of the remote probe. The standard measurement height was 60 cm above a particular surface. Figure 7 displays the instrument in field surroundings.

The spectroradiometer measures mean intensities of incident

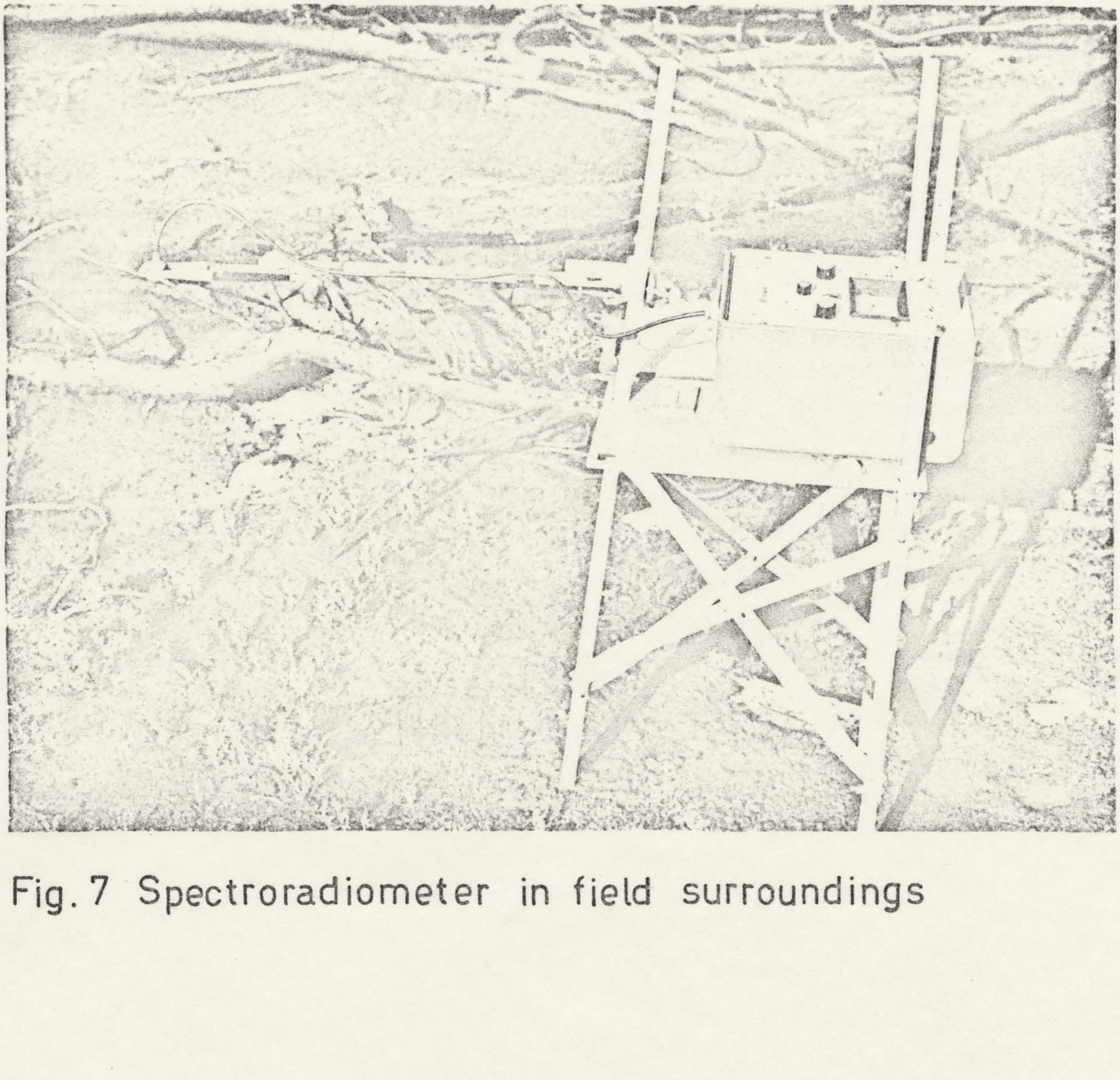


Fig. 7 Spectroradiometer in field surroundings

radiation at various wavelengths from 380 to 1500 mμ. Simple ratios of reflected to incoming radiation provide a wavelength specific albedo.

A broad class of field instrumentation has a similar general design. The incident radiation first enters a set of collecting optics which determines the field of view and the effective aperture. Two separate attachments for the sensing surface are provided. One is simply a fitting to the end of the instrument cabinet while the other is a small circular remote probe on a three foot fibre optic extension. The primary element of both is the diffusing screen which acts as a "cosine filter for assisting conformance to the Lambert cosine law" (instrument manual). Theoretically a given energy flux incident on the surface will be proportional to the cosine of the angle between the line normal to the surface and the direction from which the radiant energy is coming. Radiation from all directions is integrated with respect to the angle of incidence. The sensitivity of the remote probe is approximately one-tenth the magnitude of that achieved when using the direct incidence head. Field applications in this study used the remote probe almost exclusively except for some initial work which considered incoming radiation only.

Present in most field spectroscopes, to aid in sensitivity and stability is an optical light chopper which interrupts the incident light approximately 160 times each second. This wheel also interrupts an internal light source which is used to simultaneously switch on an amplifying component. The principle effect is to reduce instrument "noise".

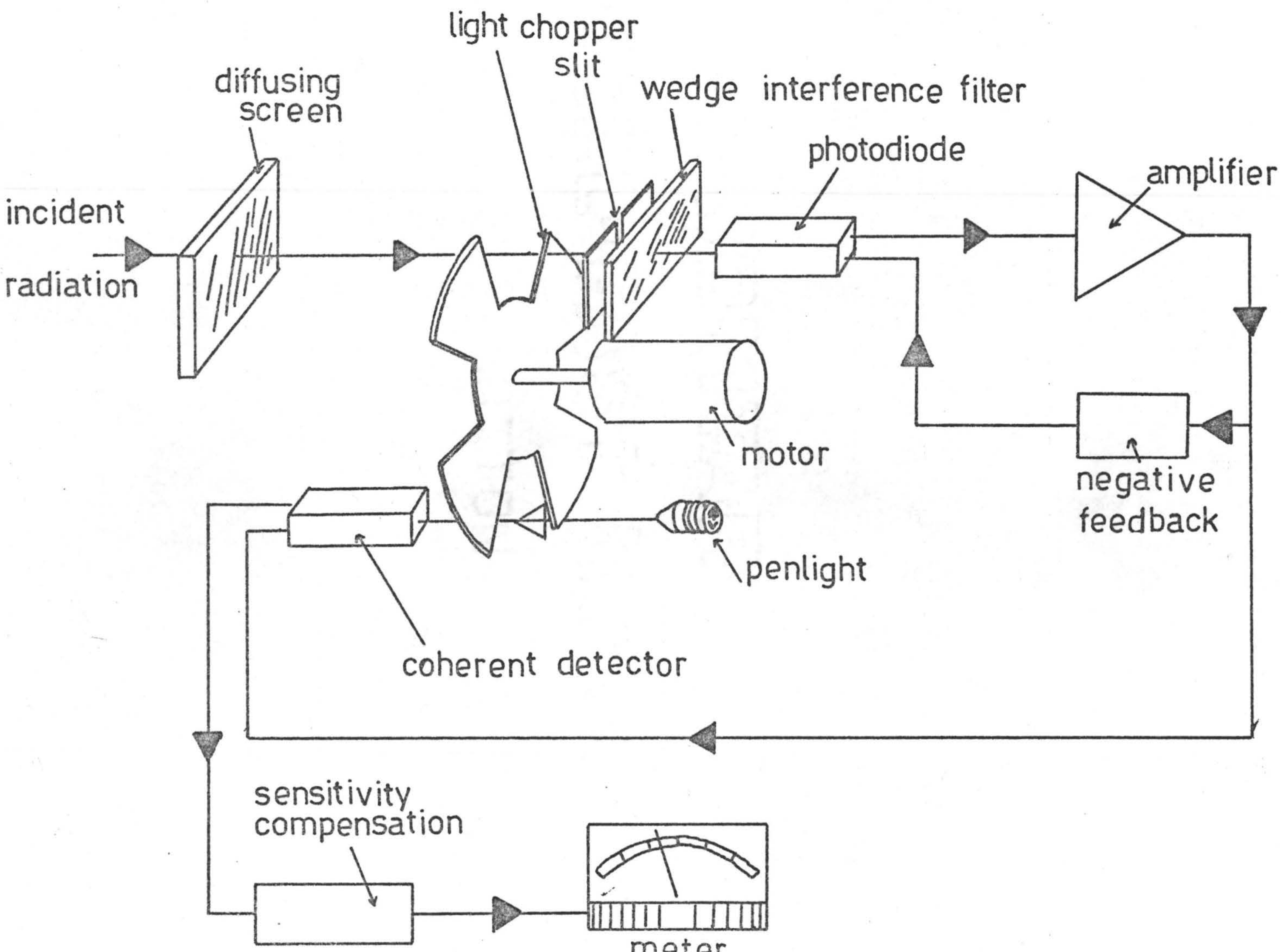
The wavelength selecting unit is most often the distinguishing feature between instrument designs. Types of gratings and prisms are discussed by Holmes (1970) and Sawyer (1963). For multiple scan instrumentation a large selection of fixed range filters can be mounted on a wheel and alternately placed in the optical path. The ISCO SR has an interesting variation in that it uses a continuous filter, with wavelength selection being determined by the location of the incident light on the filter surface. Generally referred to as a "monochromator" this wedge interference filter moves lengthwise and is controlled manually and externally, by the operator, between the chopper and the measuring photocell. The instrument employed in this study was also equipped for a second optical range (750 - 1500 mμ) of reflected infrared wavelengths.

A double measuring photocell is used; a silicon junction photocell for wavelengths 380 mμ to 750 mμ; a germanium junction photocell for 750 mμ to 1500 mμ. These have wide and relatively uniform responses to light at a variety of wavelengths. When a pulse of light strikes these, a voltage is developed across an appropriate resistance which is selected manually by the operator who adjusts the scale range and sensitivity. This is applied to the amplifier which is organized to lessen the need for frequent calibration.

The signal is then transferred to an externally viewed meter and read as a needle deflection.

Control is provided the operator through manual use of a wavelength selector, a scale selector, and a sensitivity selector. Two variable meter responses are possible. The "fast" for use with continuous strip chart recorders or during heterogenous measurement conditions. The error in locating narrow spectral peaks is reduced. The "slow" is useful when making measurements on the higher sensitivity range and at

Fig. 8 Schematic Representation of Spectroradiometer Components



short wavelengths. A greater time averaged output is provided cancelling out random fluctuations. The fact that responses are time-averaged and averaged over the bandwidth is an important qualification to remember in the consideration of our results.

(ii) Calibration and Error Analysis

The point in calibration is to relate how closely the instrument response corresponds to the energy flow into the aperture. Holmes (1970) discusses three general methods that can be used in field spectroscopy. For this instrument calibration would be undertaken using standard lamps (2800^{o}K) provided by the manufacturer. After calibration one should have an accuracy of $\pm 7\%$ at the long wavelengths and $\pm$ 10% at the short wavelengths. Most of this error results from uncertainty in the standard. Also it is assumed the instrument is invariant under the environmental change from the laboratory to ambient field conditions. Other calibration methods include the use of internal and external calibration standards. The former suffer from a lack of consistency. The latter are not viewed simultaneously during measurement and their field quality is difficult to ensure.

Calibration shifts are one potential source of error. It can shift due to dust and dirt collecting on optical surfaces, and as a result of physical shock. The radiometer should only be used over a temperature range of 7^{o}C to 43^{o}C and although the instrument is relatively insensitive to humidity variations the wedge interference filter can be affected by vibration, temperature fluctuations during the measurement period, and barometric pressure fluctuations. All of these were experienced during the transportation to, and use of the instrument at the field site so great confidence is not placed in any absolute values measured. A more accurate instrument could be designed but all of the above factors would be more critical. The result is an instrument limited in resolution but with many sensitivities built out of the design.

This is partially accomplished by a relatively large bandwidth for measurement. The bandwidth of the spectroradiometer is approximately 15 mμ on the 380 mμ to 750mμ range and 30 mμ on the 750 mμ to 1500 mμ range. Finer resolution cannot be achieved. Meter response is averaged over this range and temporally as well. Extreme peaks are damped.

Response to stray light from outside the 15 mμ bandwidth is felt to introduce an error of approximately 0.01%. This will result in too large a reading and limits the accuracy of measurement at low light intensities. The most severe error is felt by the manufacturer to occur at 400 mμ with light sources that are red rich (3.0%). Stray light error is greatest under these conditions because the photocells are more sensitive to shortwave than longwave radiation.

The difference in bandwidths at the overlapping 750 mμ end of each scale means these readings will seldom be equivalent. This was noticed and the narrower bandwidth reading was assumed to be the most accurate.

The degree of manual control must lead to a certain degree of error being assigned to the operator. Mirrors built into the meter afford some freedom from parallax during measurement but errors will result. The manufacturers state that the lower third of the meter range at each scale should not be used as the instrument accuracy drops off. For very low intensities this could not always be avoided. There is also an error value to be assigned to the fact that the wavelength settings are on a continuum filter and slight shifts from measurement to measurement will occur. Absolute accuracy cannot be assured.

For these many reasons the absolute values obtained from the spectral energy measurements are only approximate and in raw form have an error factor of $\pm$ 40%. Correction and calibration charts are published by the manufacturers to alter these data.

In this study, for logistical reasons, no laboratory calibration was undertaken, so no absolute values are quoted throughout this report. For many of the above reasons a new calibration may not have provided any increased accuracy; the field site being as remote and variable as it is. Nor was the primary aim to obtain absolute measurements. The reflectance values are ratios and it has been assumed that this will eliminate most gross errors as the correction terms would cancel. Any other measurements are shown as relative fluctuations only. Although these assumptions cannot be tested, the comparability of the data to other published results and the internal consistency of much of the data, and the use of time and space averages appears to lend some credence to the results. The further assumption that reflectance error is constant across all the wavelengths and at all intensities cannot be tested because of the environmental variability.

(iii) Measurement Geometry and View Factor

For more precise and complex equipment, four vital features have been identified by Holmes (1970). The field of view, the effective aperture, and the focussing capability of the ISCO SR are effectively combined into the coarse adjustment of radiometer height by the operator. Experiments have been reported indicating strong polarization of light

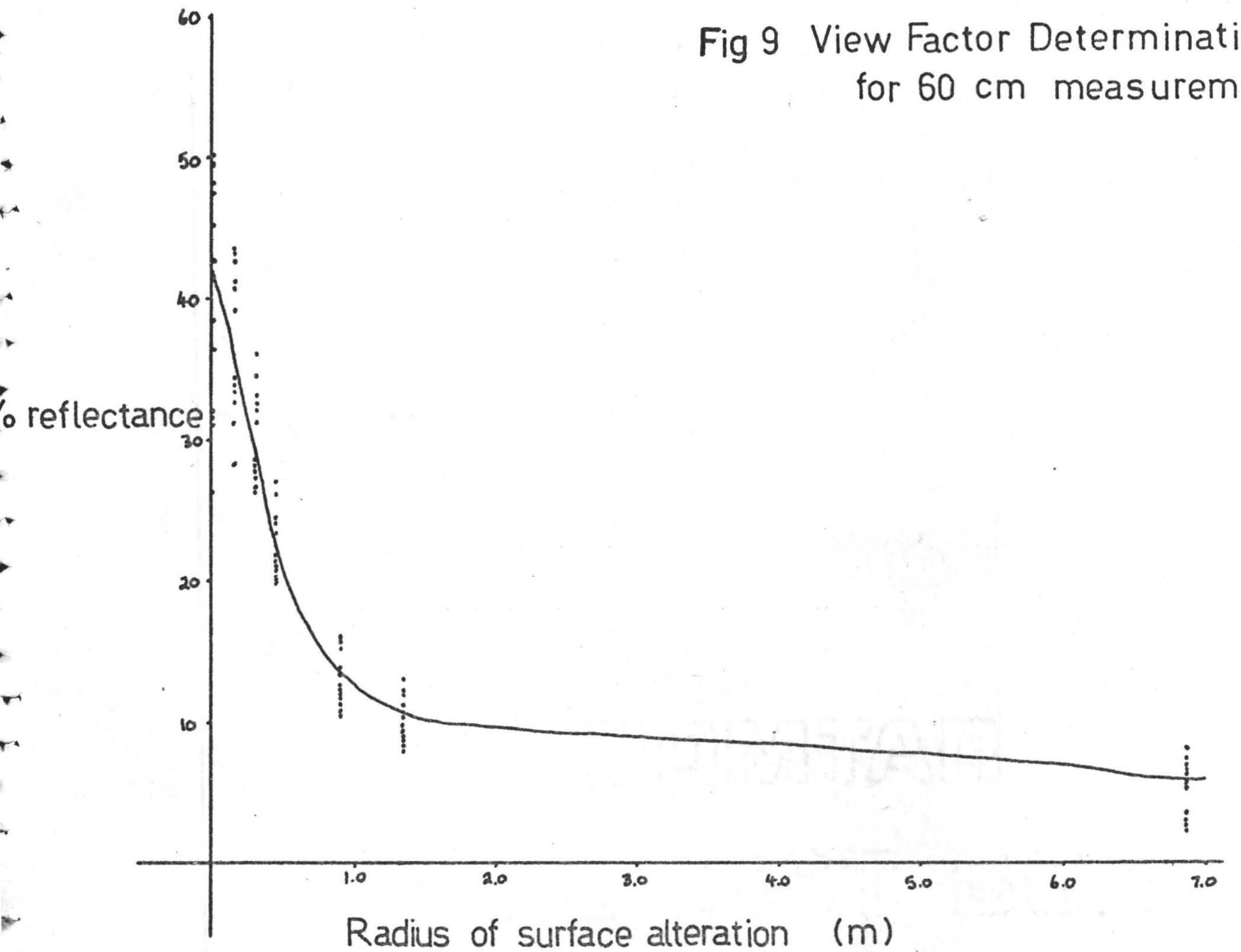


Fig 9 View Factor Determination for 60 cm measurement height

Table 3 Theoretical View Factor Determination (Latimer 1972)

% of energy originating from a circle of specified radius	radiometer height 3m	radiometer height 0.6m
90%	9 m	1.8 m
95%	13.5m	2.7m
99%	30 m	6.0 m

reflected from various vegetation species. (Coulson 1966). Most instruments will be sensitive to this to some degree. In this case however the use of the diffusing screen removes the direct effects. Sampling bias may be introduced but with proper experimental design this can be minimized and will be an inconsistent minor effect.

Although a proper cosine response is claimed by the manufacturer it was decided to test the effective field of view of the instrument. A constant radiometer height of 60 cm was maintained and a light surface was progressively blackened out from a central point. This was done indoors to maintain a relatively constant light intensity. The results are plotted as Figure 9. The curve is a hand fit. Good agreement is achieved with Latimer (1972) and the effective field of view is slightly less than 2.0 m for 90% of the incident radiation.

A consistent theme above has been that standard laboratory calibration is only partially applicable to experimental measurements made in field environments. If meaningful intercomparisons of field results are to be undertaken then it is the responsibility of the field investigator to describe accurately the field and instrument parameters. This would include the geometrical aspects of the measurements, the instrument operating conditions, and the provision of detailed site photography from a height equivalent to that of the radiometer. Only through reporting procedures such as these can measurements at the scale used here be of any value.

(c) The Measurement Program

The wide variety of factors discussed previously emphasizes the need for considerable forethought about the extent and scale of a measurement program. There are a large number of effects one must control in

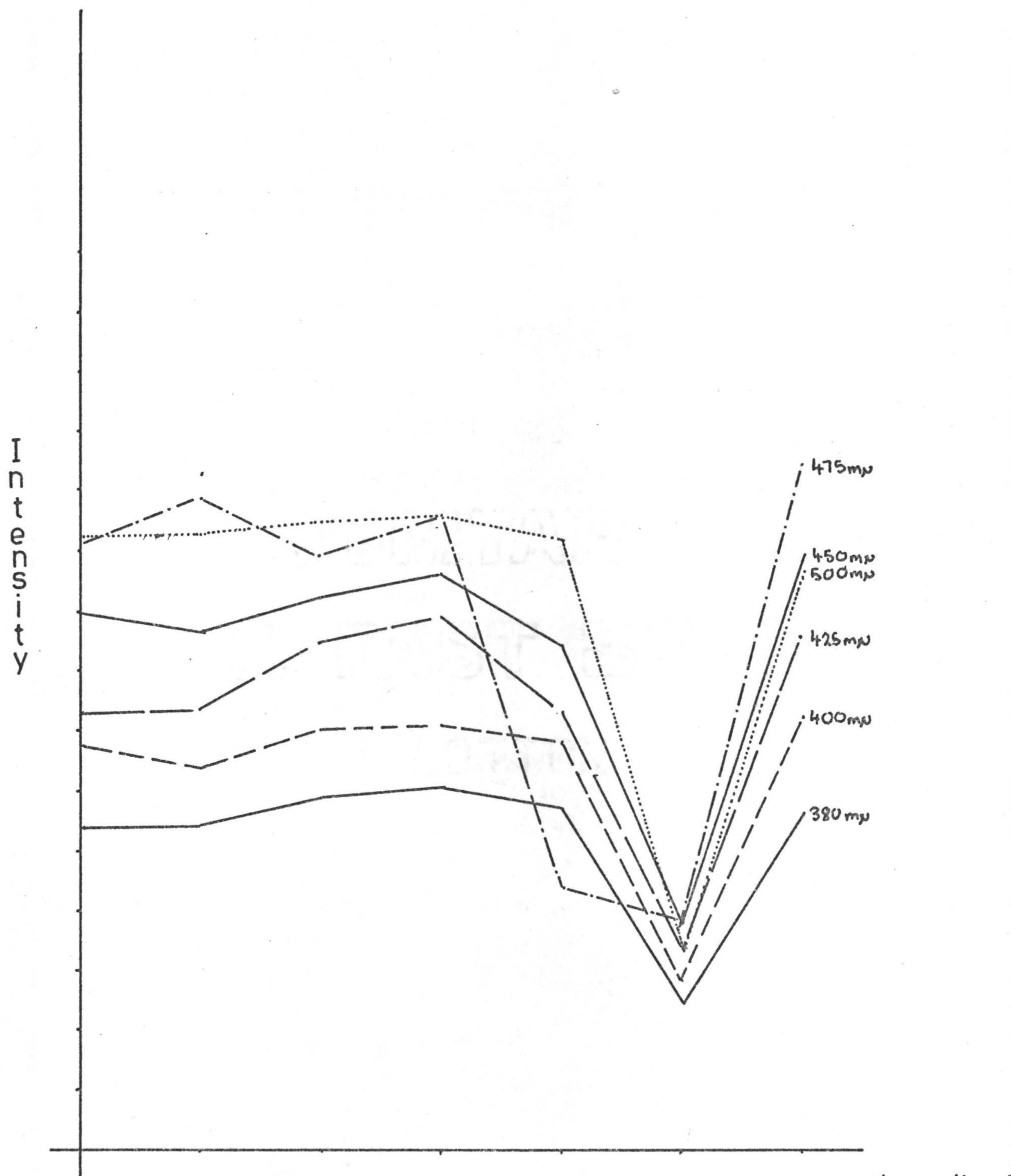


Fig. 10 Wavelength Short Term Fluctuations

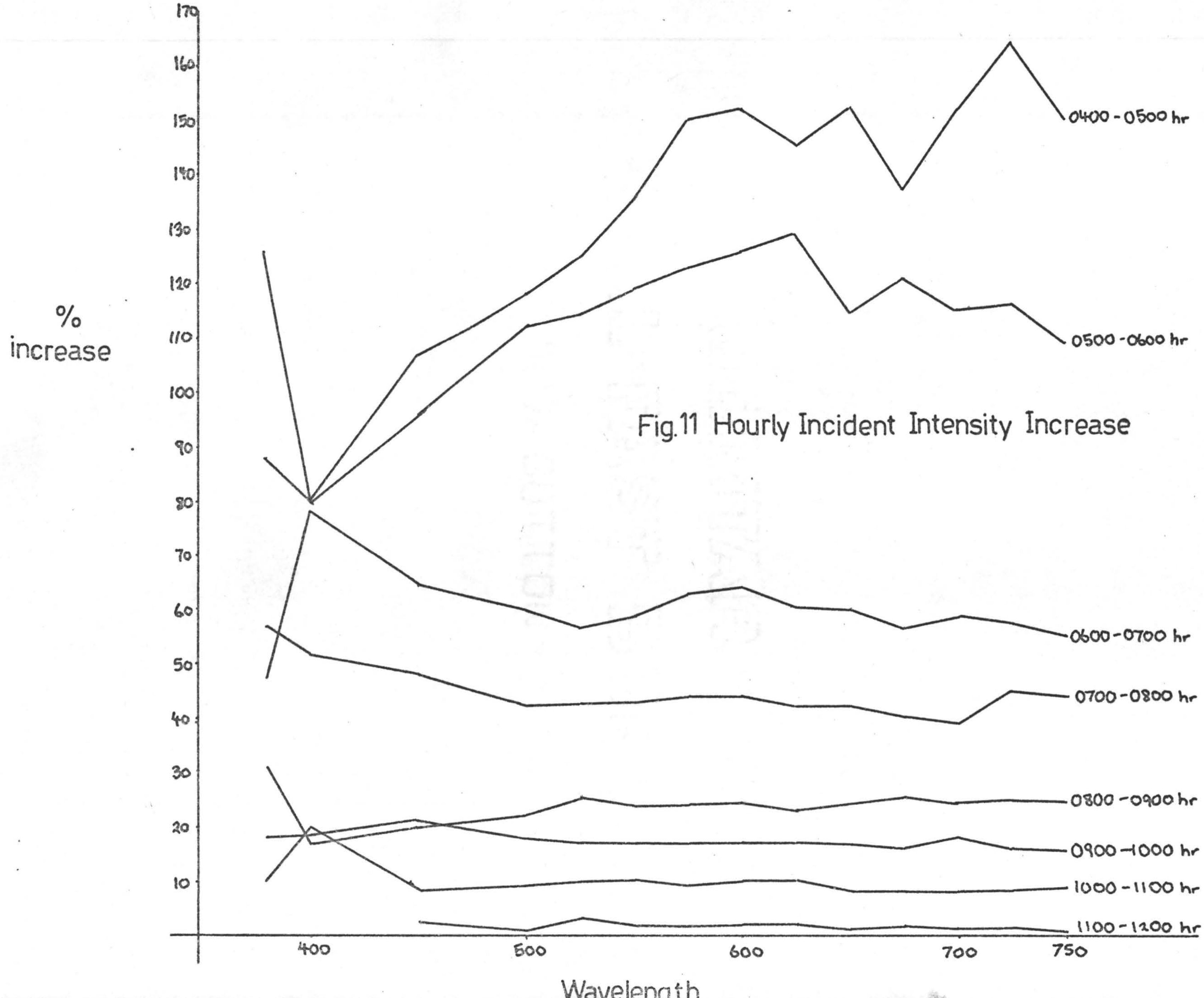


Fig. 11 Hourly Incident Intensity Increase

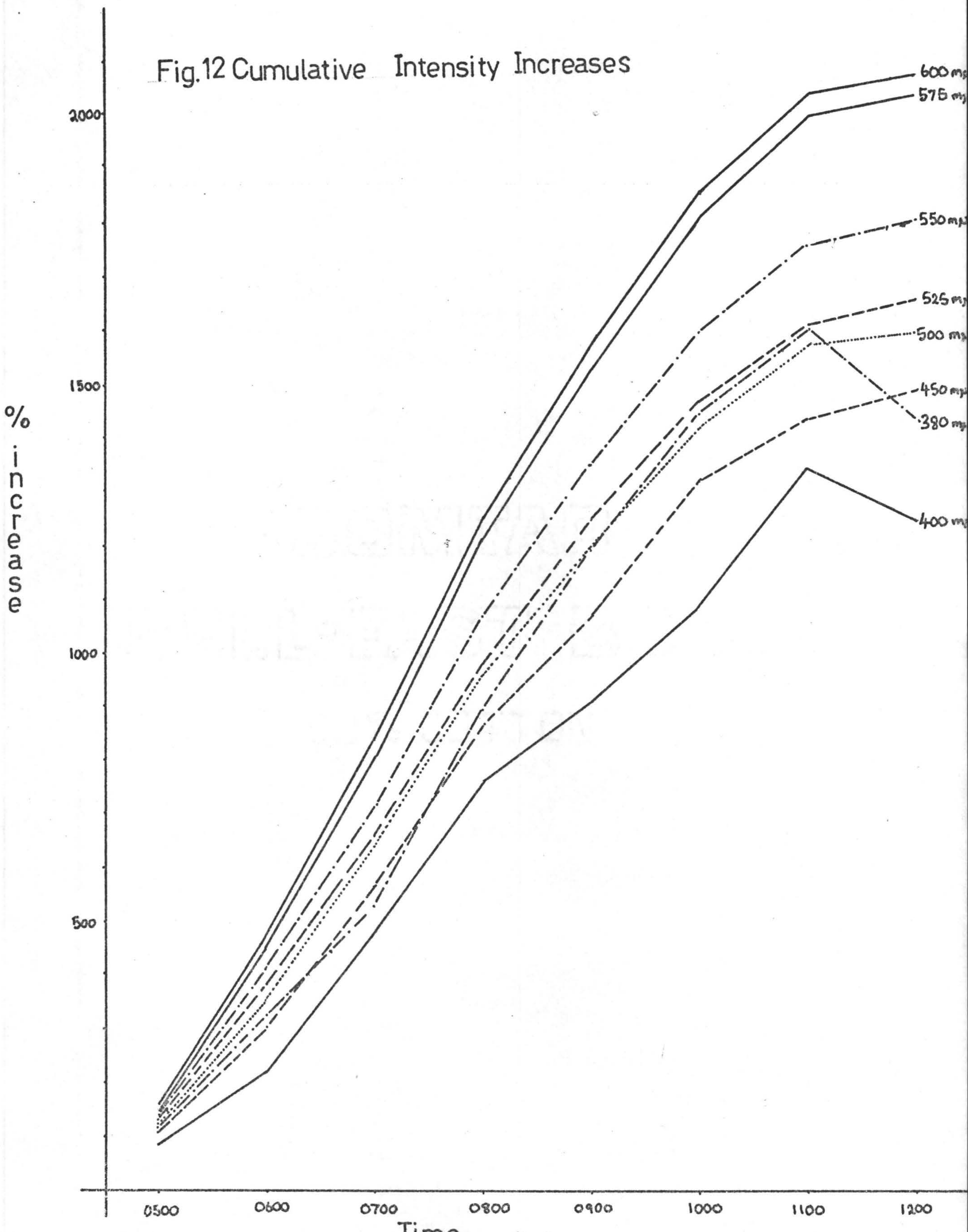


Fig. 12 Cumulative Intensity Increases
600 mμ
575 mμ
550 mμ
525 mμ
500 mμ
450 mμ
380 mμ
400 mμ
2000
1500
1000
500
% increase
0500
0600
0700
0800
0900
1000
1100
1200
Time (hr)

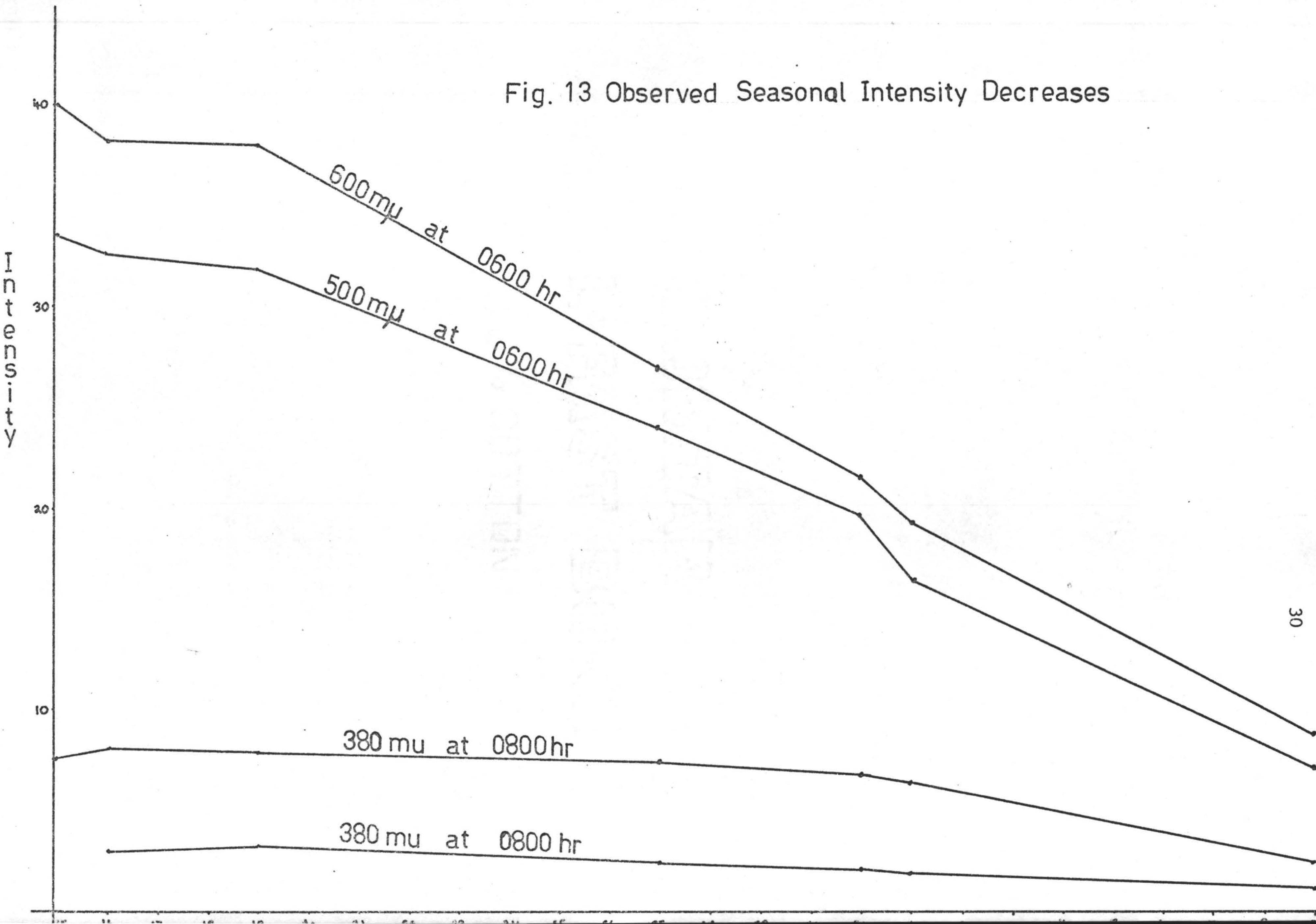


Fig. 13 Observed Seasonal Intensity Decreases

order to reduce the overall variability and produce meaningful results.

Short term variations in incident radiation under cloudy sky conditions, demonstrated in Figure 10, make it necessary to sample only under steady state conditions in order to show diurnal effects. Figures 11 and 12 show some of the diurnal spectral quality changes. Data were not reliable in the hours immediately following sunrise because solar zenith angles were changing too rapidly. Cloud formation during early afternoon meant the most consistent and accurate measurements were obtained between 0800h and 1200h.

Seasonal variation in vegetation and changes in incident radiation due to changing day length require that data be compared for various parts of the season before being pooled. (Fig. 13)

Changing surface moisture conditions due to rainfall and storm activity must be considered when intercomparing data from different sites. Temperatures were checked to ensure the operating range of the spectroradiometer was not exceeded.

All the subarctic surfaces are heterogenous to some degree and sampling replication is necessary in order to increase the reliability of the generalized surface reflectance values. Two sites in the mature lichen woodland were sampled from the 10 m level of an instrument tower. Four sites were used at each of the 0, 1, and 2 year burns and seven sites were employed in the 24 year burn. These were chosen to illustrate as many diverse facets of each surface as possible (Fig. 6). A few individual species were measured to show some of the more specific physiological effects. These included Cladonia spp., Alnus rugosa; both natural and detached leaf, and detached branches of Picea mariana. The lake and swamp surfaces were measured but without extensive replication.

4. Results

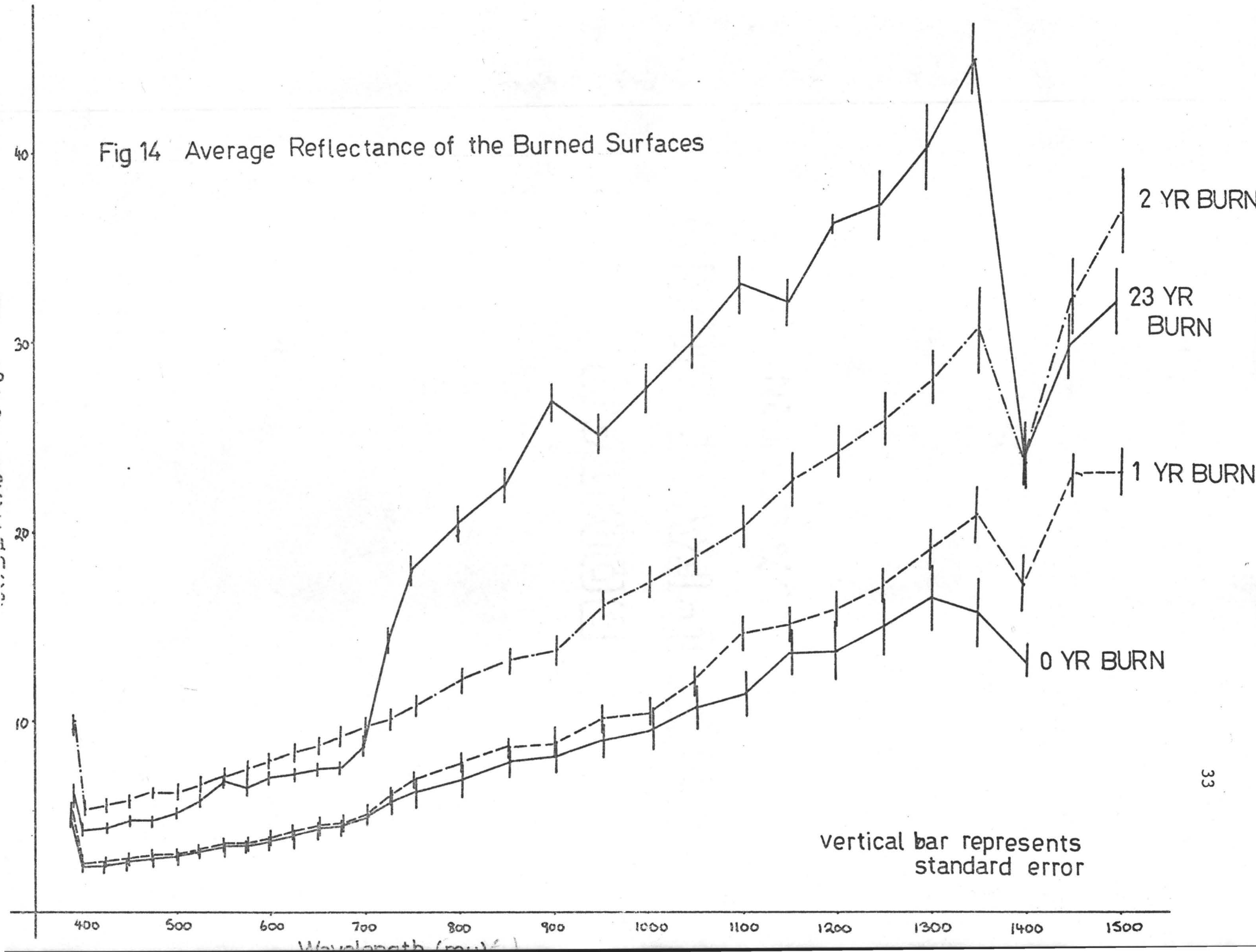
Figure 14 shows percent reflectances for the 0, 1, 2, and 24 year burns using comparable pooled data. The general trend shows an increase in reflectance with increasing age of burn. The results for the reburned two year old surface depart substantially from those of the younger burns probably due to the exposure of the mineral soil. The 24 year burn shows the effect of the revegetation with decreased blue and red reflectance and a slight indication of a green peak. The infrared reflectance is enhanced and a cutoff in the 700 mμ to 750 mμ waveband is established which is not evident in the younger burns.

Data comparing the surfaces under clear sky and overcast conditions are presented in Figure 15. In all cases the clear sky values are in excess of those from the primarily diffuse overcast measurements, particularly in the case of the 24 year burn. Some ambiguity exists for the 380mμ and wavelengths beyond 1300mμ. Greater error is likely in those wavelengths due to the low intensity of the incident radiation. The difference in the measurements increases with age. The data from the mature lichen woodland do not follow this trend however (Fig.16). Clear sky and overcast curves for this oldest surface show no difference except in those wavebands most subject to measurement error. The overall reflectance is substantially lower than that for the 24 year old burn.

The measured clear sky and overcast data for the mature woodland can be compared to the theoretical values in Table 4. The values here are simple combinations of data measured from detached spruce boughs and an open lichen mat site. The theoretical values are all substantially greater than the measured clear sky reflectance for the mature site.

Some representative data from lichen covered surfaces are shown

Fig 14 Average Reflectance of the Burned Surfaces



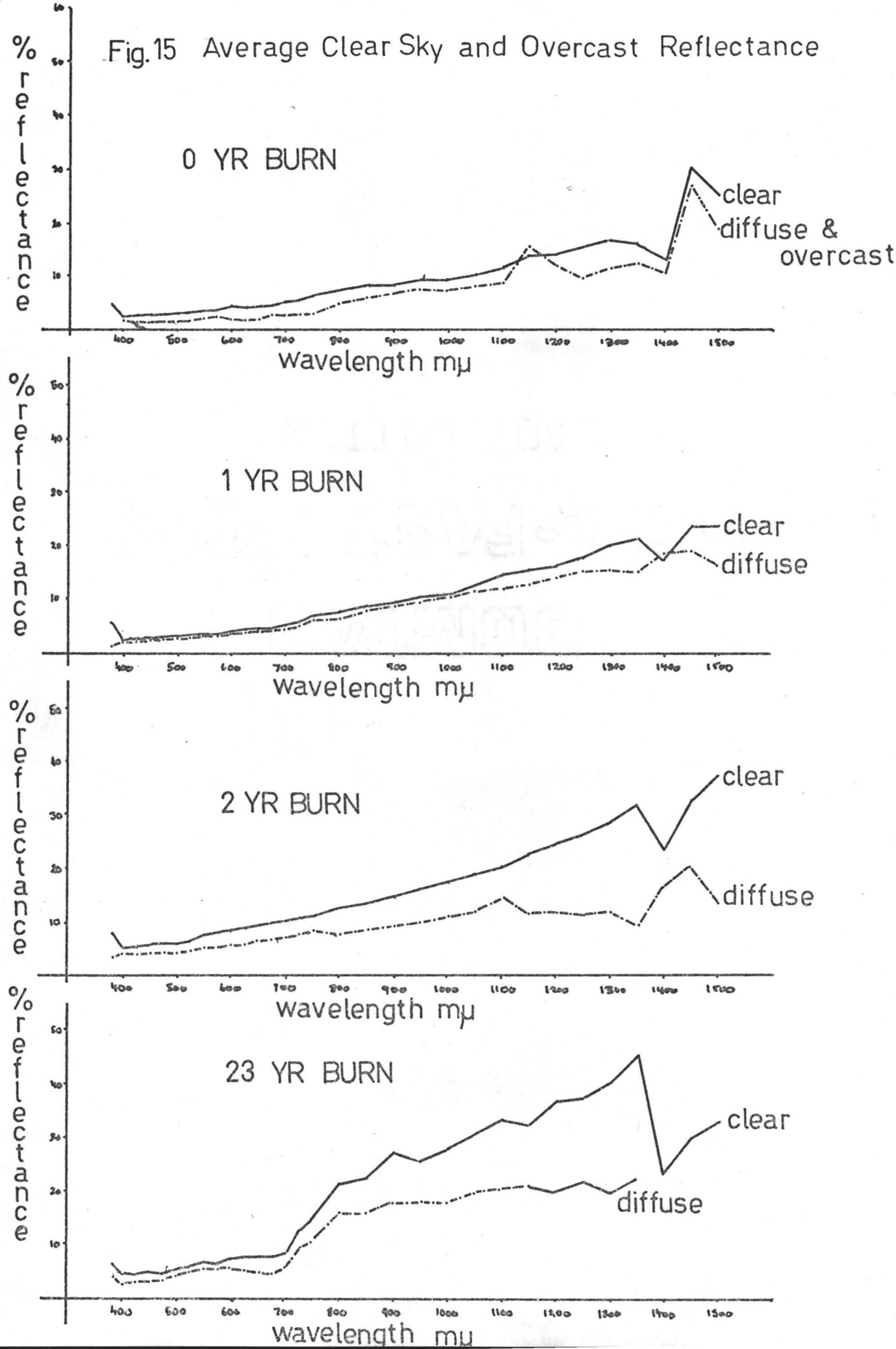


Fig. 15 Average Clear Sky and Overcast Reflectance

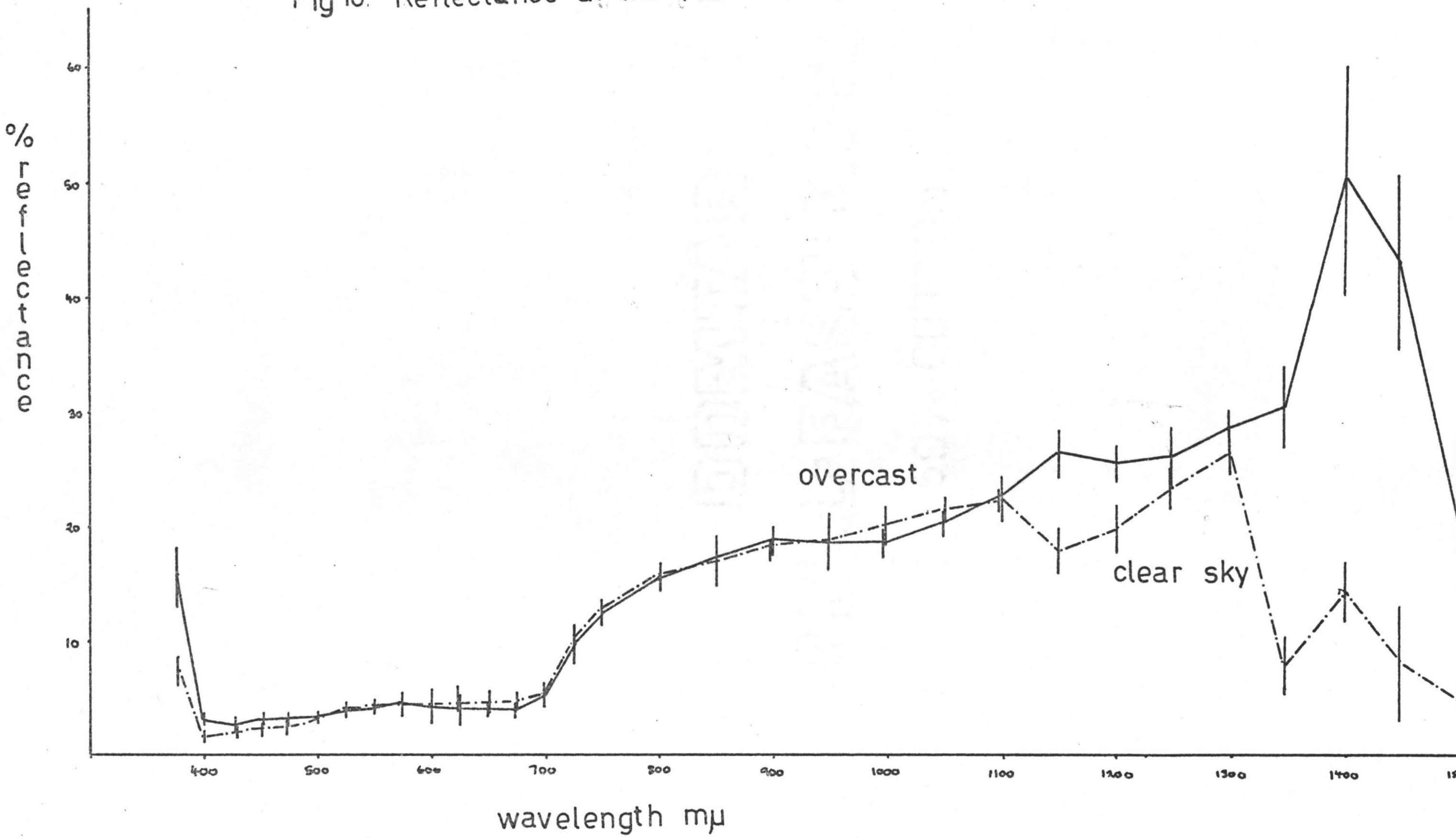


Fig 16. Reflectance at the Mature Site

in Figures 17 and 18. These surfaces were near the drumlin crest with only scattered spruce trees present. They were dominated by Cladonia spp. In composition they varied from sites in the mature woodland which had a greater number of vascular species and a considerably larger % cover of Stereocaulon paschale, another nonvascular lichen. The clear sky and overcast measurements are distinctly different. The mean clear sky reflectance is a composite of some variable sources. Two examples of these are also displayed. The lower of the two represents a homogeneous lichen mat. The higher values are from a more heterogeneous mat with some vascular species included. The mean reflectance curve for the 24 year burn is included in this comparison for reference purposes. The clear sky reflectance for the lichen mat is generally higher than the 24 year surface and the overcast measurements are greater in the visible wavelengths.

Appendix B shows the physical characteristics of each measurement site and gives their average reflectance characteristics. They are accompanied by species descriptions in Appendix A. Camera angles for the photography are variable but the height was constant at 1.5 m.

Figure 19 represents bulk albedo values for the sequence of burned surfaces. Graphical results obtained through planimetry were compared to arithmetic averages of wavelength specific albedos and also to arithmetic averages weighted for incident intensities. The three techniques provided similar results and agree qualitatively with Rouse (1976).

A method of ratioing infrared to visible wavelengths has been used by several authors to characterize plant vigour and canopy depths. Figure 20 shows the ratios of 800 mμ to 550 mμ wavelengths for all the surfaces measured, for a variety of daytime hours, spread throughout the season. Most are site averages for both clear sky and overcast conditions.

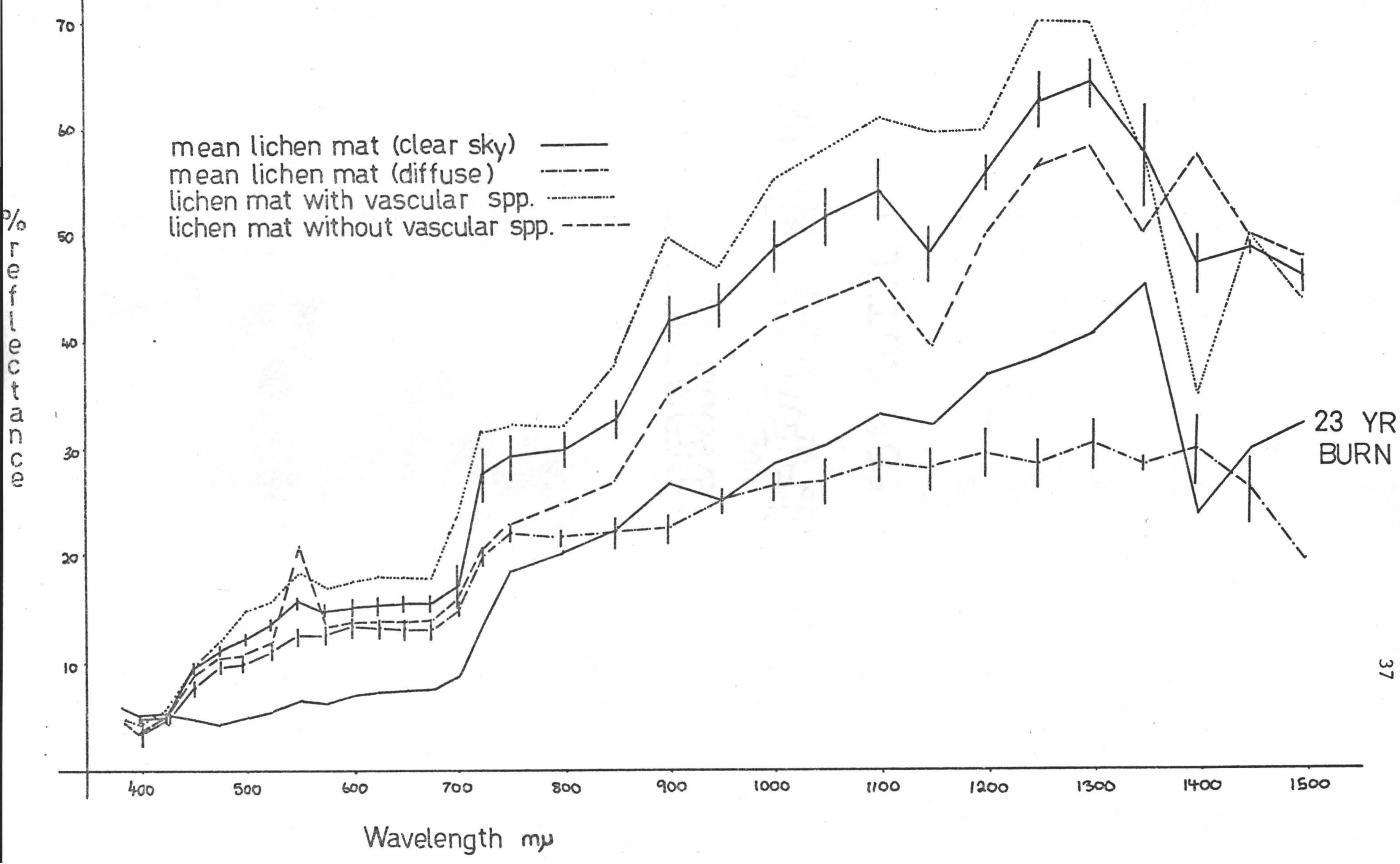


Fig.17 Reflectance From Lichen Covered Surfaces

Fig. 18 Comparative Lichen Reflectances

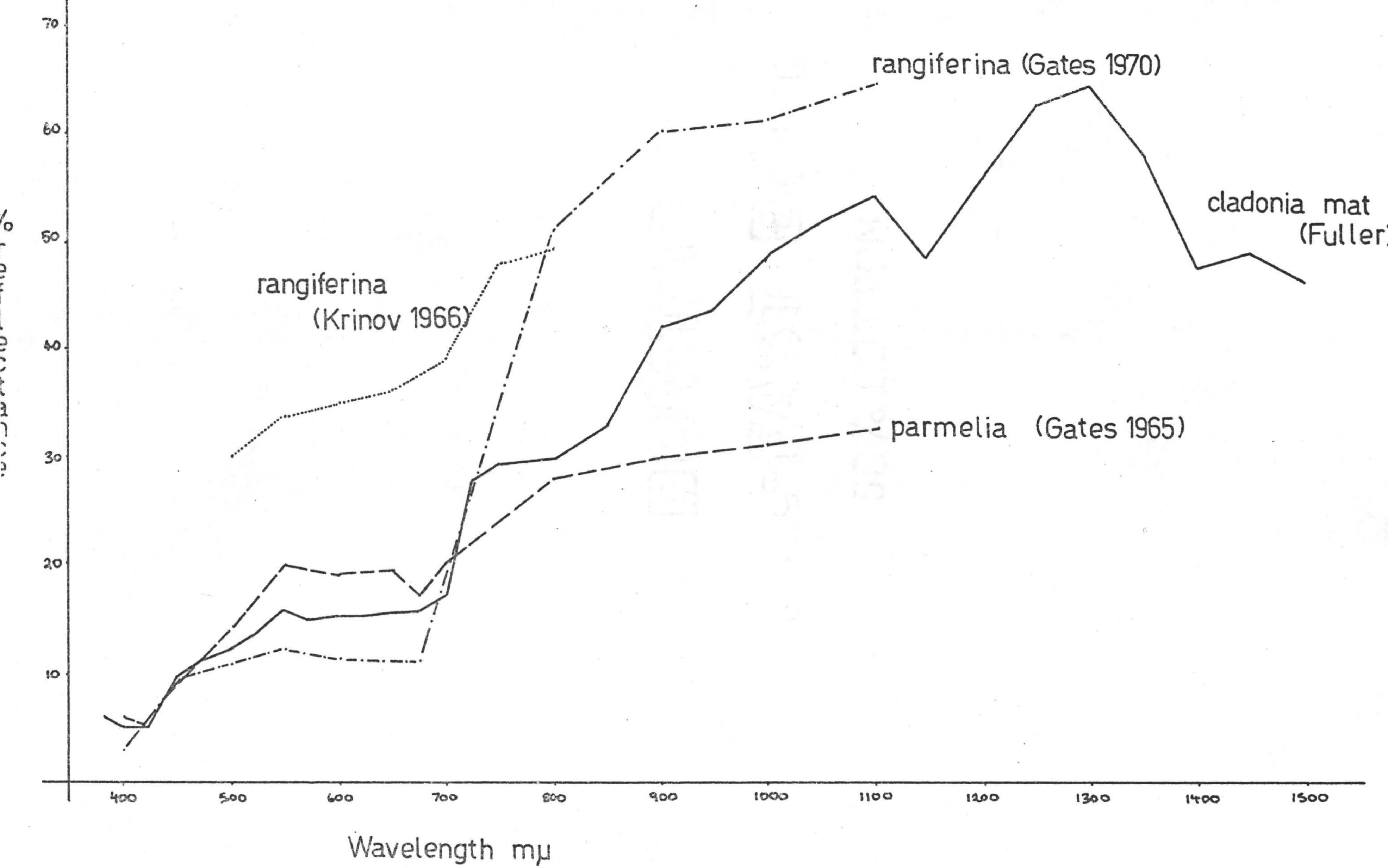


TABLE # 4 Theoretical Mature Site Reflectance

% Spruce	%Lichen	Visible	Infrared	Mean
100	0	7.31	36.20	21.75
90	10	8.07	37.39	22.73
80	20	8.84	38.57	23.71
70	30	9.60	39.76	24.68
60	40	10.36	40.95	25.66
50	50	11.20	42.14	26.63
40	60	11.88	43.32	27.60
30	70	12.64	44.51	28.58
20	80	13.34	45.70	29.52
10	90	14.10	46.88	30.49

measured mean reflectance = 10 .7%

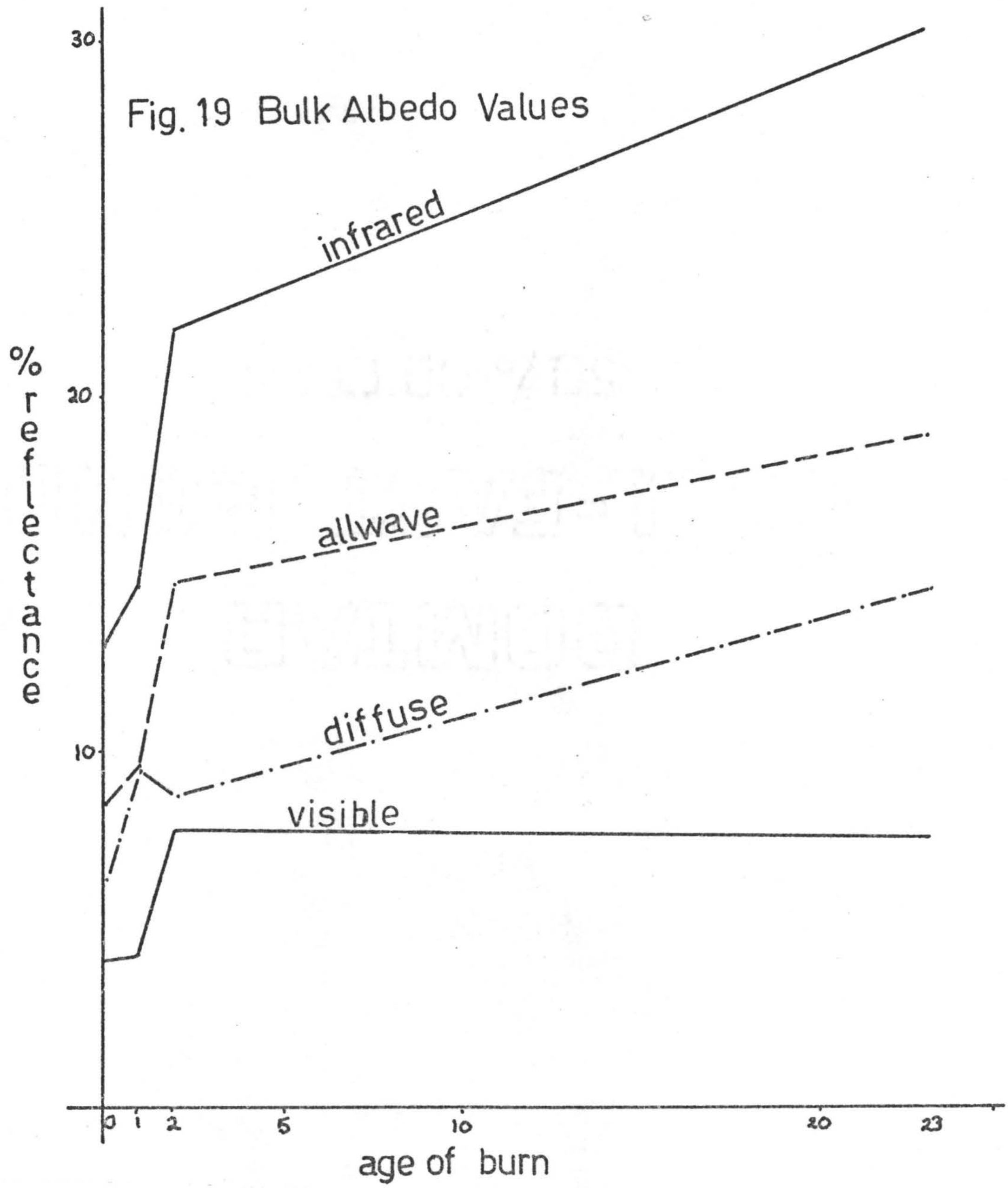
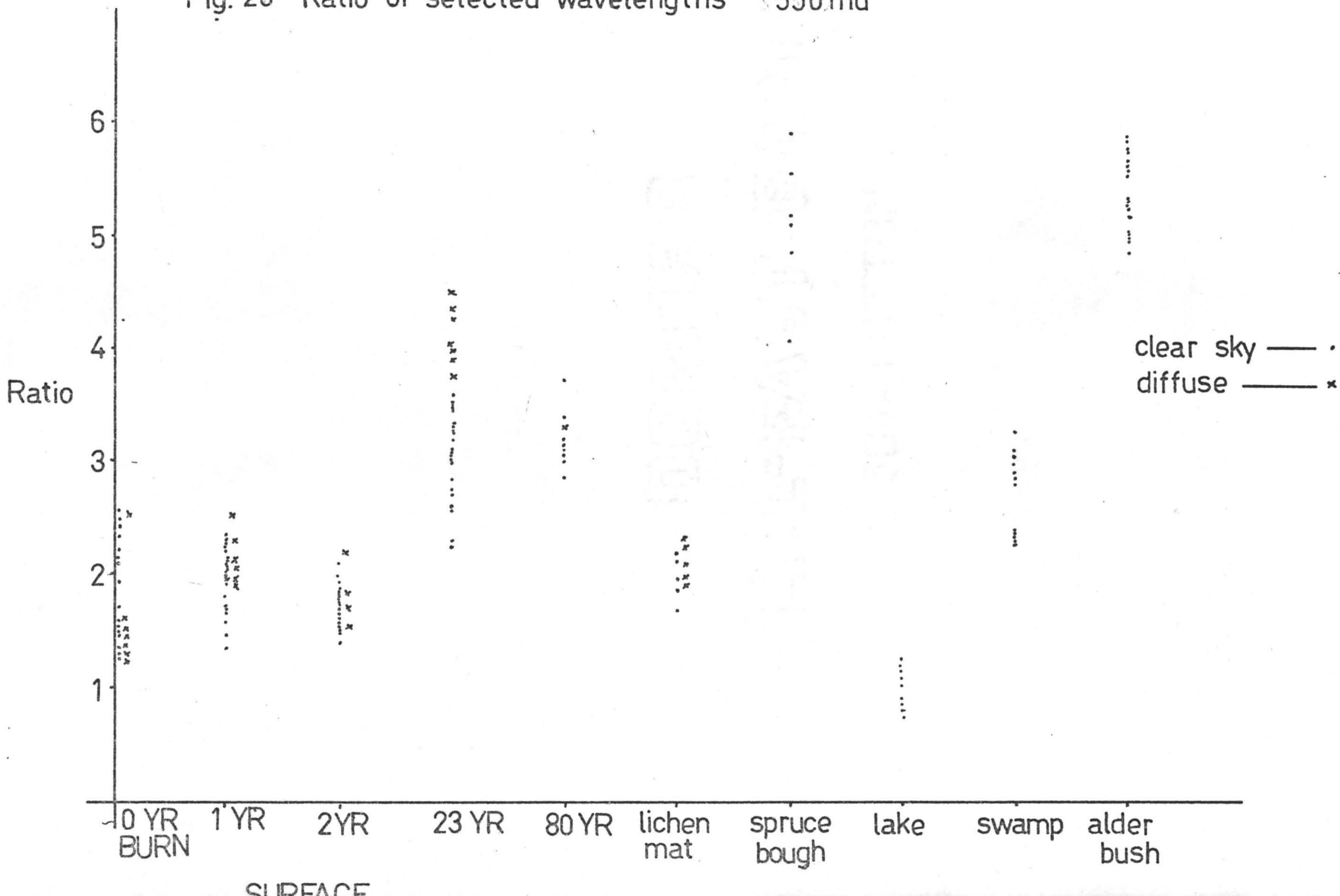

30
20
10
% reflectance
Fig. 19 Bulk Albedo Values
infrared
allwave
diffuse
visible
0
1
2
5
10
20
23
age of burn

Fig. 20 Ratio of selected wavelengths $\frac{800 \text{ mu}}{550 \text{ mu}}$



These will be discussed in more detail.

A few selected experiments were undertaken to see if the previously reported physiological effects in single species could be exhibited using an instrument with the accuracy level of the ISCO SR. Figure 21 shows reflectance curves for a mat of detached alder leaves before and after wetting. Infrared reflectance is decreased. The ratio of 800mμ to 550mμ wavelengths is approximately 3.75 to 4.00 which is lower than that for the natural alder bush. Figure 22 suggests a consistent diurnal trend in the reflectance from the natural alder site. The effect is primarily noticeable for wavelengths longer than 750mμ. No replication was undertaken so error levels are unknown. This effect was only marginally and not consistently seen in the burn site replicates and was not evident in measurements over the spruce forest. As seen in Figure 23 there was no seasonal trend in the detached spruce bough study. Despite the fact that these branches had no water or nutrient supply, no significant differences appeared with time, in the visible reflectance. The changes in the infrared reflectance are not consistent but do occur and are likely related to atmospheric moisture or the time since the most recent rainfall. Discoloration was not apparent in the branches, and no loss of needles occured until after the measurement period had ended.

Figure 24 represents some measurements for the local lake and swamp sites. The lake data could only be obtained in the early morning hours. The swamp measurements are the average over one day. No species identification was undertaken but the characteristic shape is altered from that of a pure water surface. The vegetation cover was subjectively estimated at 15% but the water was quite shallow.

Fig 21 Reflectance of Detached Alder Leaves (Alnus rugosa)

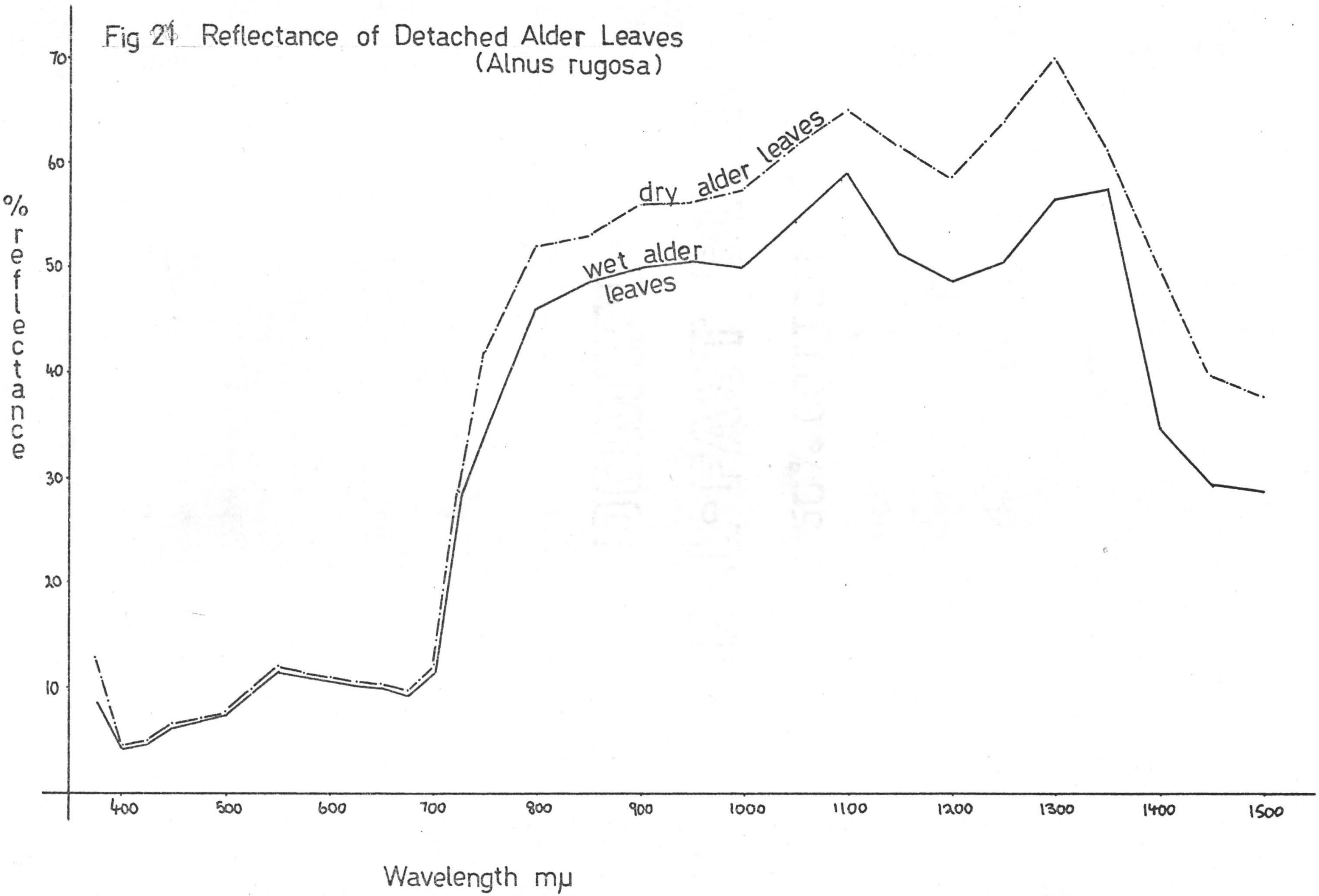
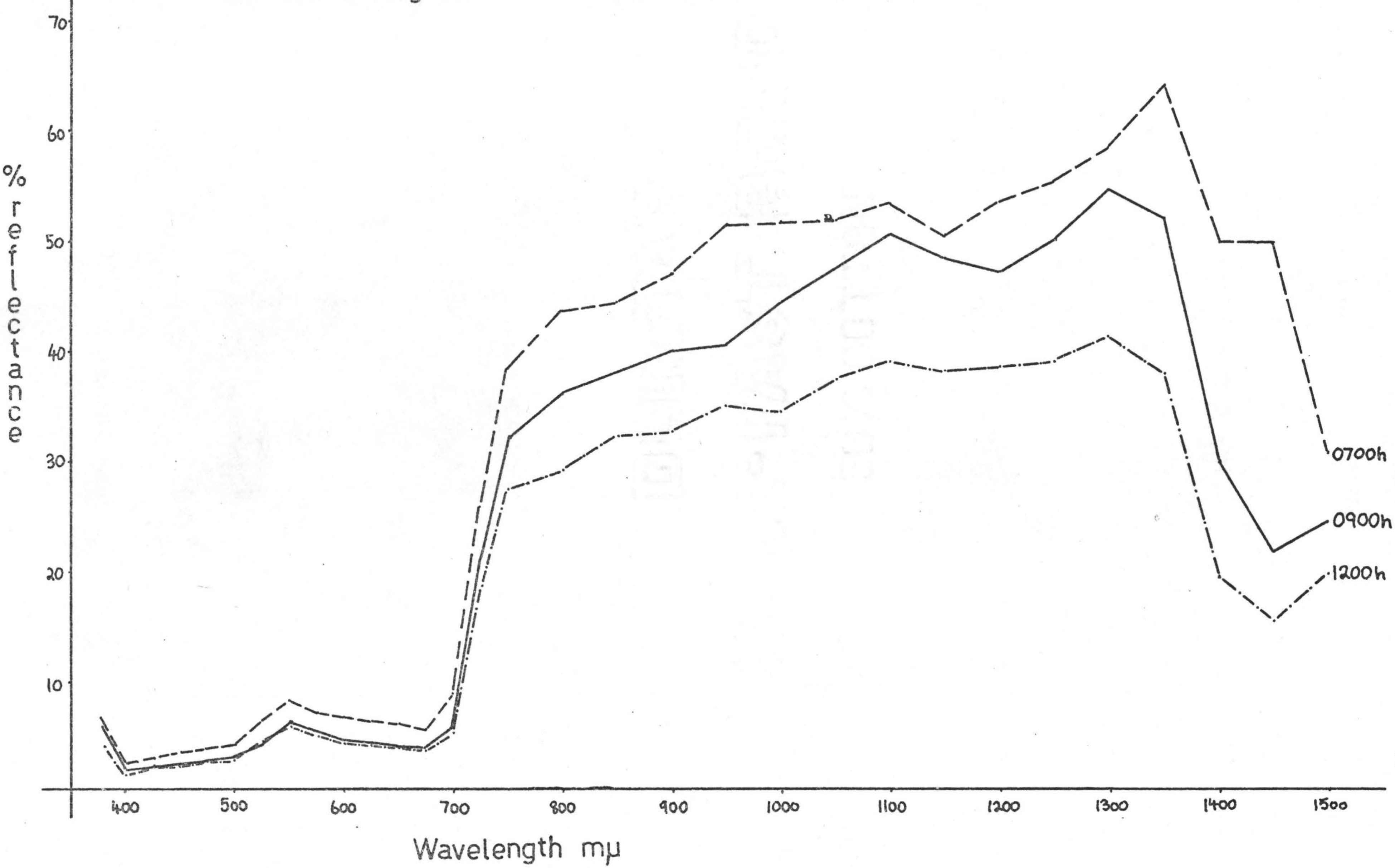


Fig 22 Alder Bush Temporal Reflectance Sequence
(Alnus rugosa)



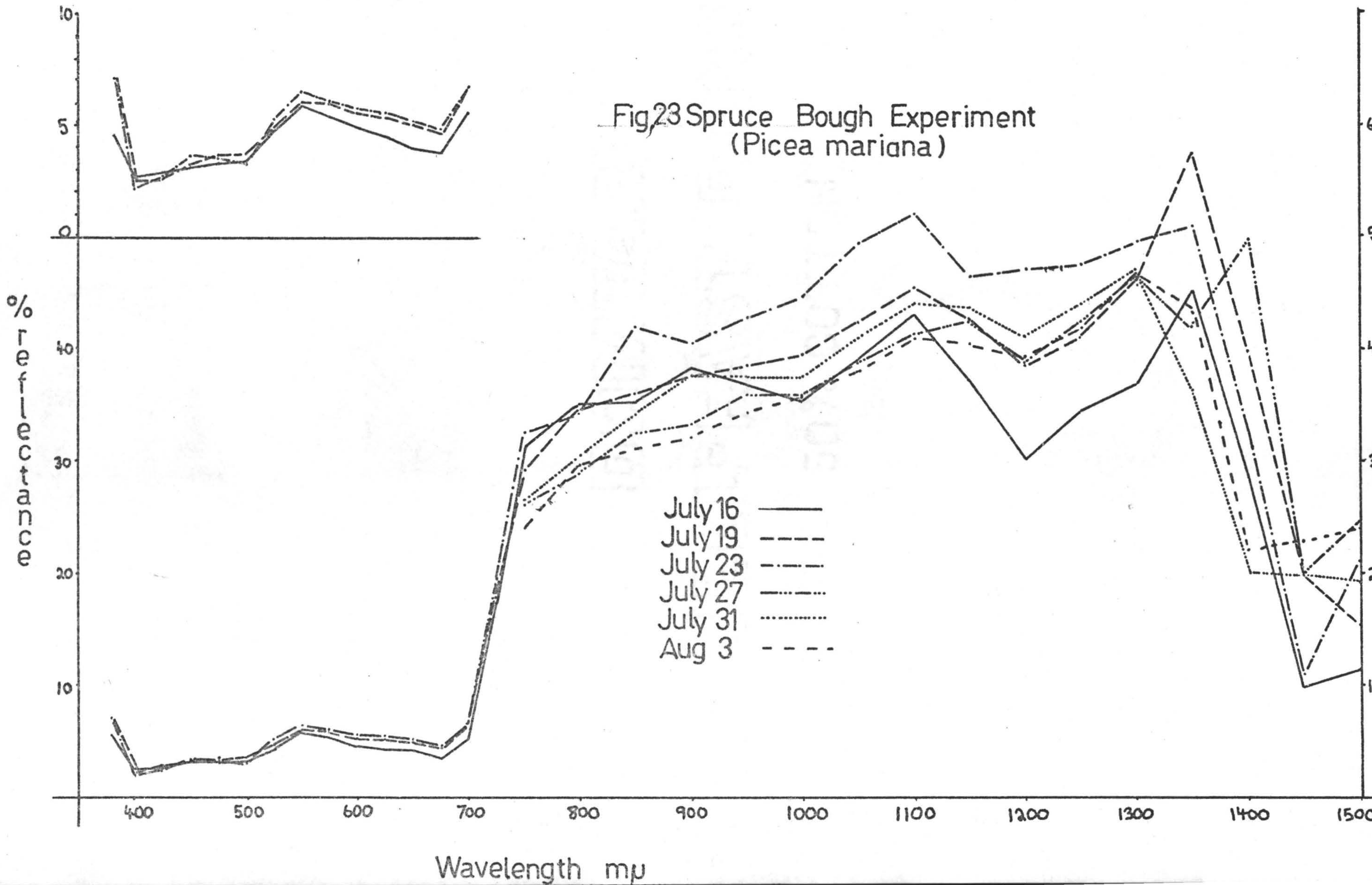


Fig 23 Spruce Bough Experiment
(Picea mariana)
% reflectance
Wavelength mμ
July 16
July 19
July 23
July 27
July 31
Aug 3
0
5
10
20
30
40
50
60
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500

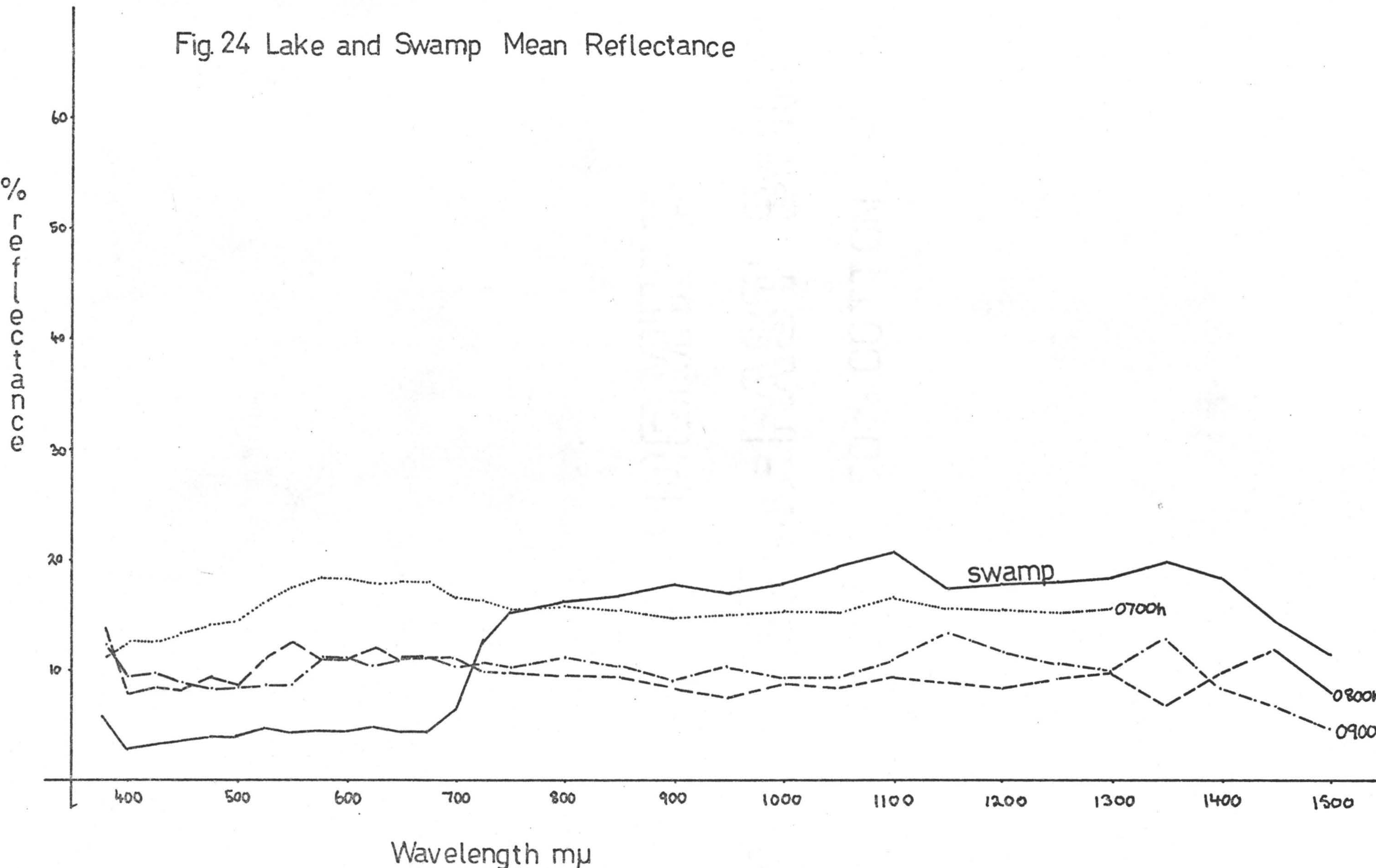


Fig. 24 Lake and Swamp Mean Reflectance

5. Discussion

The most significant result found in this study is the increasing reflectance with increasing burn age, until the mature woodland is established. This agrees with the findings of Rouse (1976). A freshly burned surface is quite charred and blackened and exhibits a gradually rising curve of reflectance from short to long wavelengths. This gradual rise is similar to the results of other investigators for bare soil and non-biotic surfaces. (Scott 1968).

With increasing age the erosion of the surface and deep seepage processes will reduce the charcoal in the upper layer and it becomes visibly lighter. An increase in reflectance can be seen between the 0 year burn and the 1 year burn. The 2 year burn, which was subject to reburning, has exposed mineral soil and is lighter than either of the two younger surfaces. The 24 year burn shows the obvious effects resulting from the establishment of photosynthetically active vegetation. The reflection in the blue and red wavebands is reduced while a peak in the green is established. These effects are more obvious in the individual site data. (Appendix B). The substantial increase in infrared reflectance occurs at 725mμ to 750mμ. The data beyond 1300mμ are ambiguous for all surfaces.

Substantial qualitative disagreement arises between the data for the mature lichen woodland and the bulk albedo measurements presented by Rouse (1976). Whereas the measurements in this report show an overall decrease across the spectrum when compared to the 24 year burn, Rouse (1976) shows an overall increase. There are a number of possible reasons for this disagreement. These include different sampling methods over the mature site, different measurement heights, and different instrumental view factors. The Swisstecco radiometers used by Rouse give a total integration for all short wavelengths whereas the ISCO SR is limited to measurements across the 400mμ to 1300mμ wavebands. Thus different quantities are being measured. The data presented by Rouse are arithmetic mean values of albedo throughout a day, over several days, without a weighting factor for the energy regime at various hours. The spectroradiometer data do not span as great a temporal sequence and were gathered under more idealized atmospheric conditions. The overall trends, however, one might expect to be the same. The generalized value for the mature woodland reflectance of 10.7% is a close approximation of the values presented by Petzold and Renz (1975) of 12.2% and by Berglund and Mace (1972) of 6-8%. These were for different canopy densities. The distinguishing difference between the mature site and the 24 year burn is the presence of the complex forest canopy which is considered to be a very efficient radiation trap. The lichen dominated understory however is much lighter and reflection will be enhanced.

The departure of these two sets of measurements is important because of its energy balance implications. A continued decrease in the shortwave energy balance with burn age would not occur but would increase again for the mature site after reaching its lowest level for the 24 year burn. If the degree to which the higher surface temperatures affect the longwave balance is not proportional then the net radiation differences between the two surfaces would be increased.

One initial attempt to rationalize the difference in results involved the manipulation of data from detached spruce boughs, which was assumed to be representative of a species specific albedo, and data from the open lichen mat. Table 4 represents the calculated weighted albedo values that result from various combinations of the two. The results are higher than either the measured data in this report or that from Rouse (1976). Obviously more species are involved than Picea mariana and Cladonia spp. so some error can be expected as a result. The substantial difference however must be due to the fact that the measurements used in the manipulation are from experiments where no extensive canopy exists.

No complete explanation of the discrepancy between the data for the mature site in this report and that of Rouse (1976) will be possible without further measurement.

The decrease in reflectance for overcast sky conditions was not expected. It is greatest for the reflected infrared wavelengths and also increases with the age of the burn. Petzold and Renz (1975) imply that the isotropic properties of diffuse solar radiation passing through a cloud layer would tend to increase albedo. Their data, however, were ambiguous and they did not differentiate between clear sky and diffuse measurements. Other authors (Sellers, 1965, Gordon and Church, 1965) although not explicitly stating so appear to agree with the above position. The Russian data comparing clear sky and overcast conditions are also ambiguous. (Steiner and Guterman 1965).

In comparing direct beam and diffuse radiation from a clear sky for a flat surface the physical effects would be more straightforward. The absence of directional or specular components in diffuse radiation should result in a higher albedo for that portion of the total radiation. This would depend also on the angle of incidence. In comparing clear sky and overcast conditions the situation is not strictly physically analagous and there are several more complicating factors. Both situations have radiation fluxes with direct and diffuse components although the direct beam radiation given overcast conditions is reduced and often not considered to be significant. Any directional component of the reflected radiation will be very small. The work of Gordon and Church (1966) and Gordon (1964) shows that for relatively smooth surfaces the specular component is greatest at large zenith angles. With the onset of overcast conditions there were decreases in albedo and these were greatest at large zenith angles while the effects for small zenith angles were not great. For the research site in this report the northern latitude, combined with the predominance of early morning measurements ensures that the zenith angles were normally large. In the Gordon and Church (1966) report the opposite effect is noted for a pine forest, attributable to the effects of the complex canopy. For clear sky conditions the directional reflectance effects were not great at any zenith angle and the occurence of cloud cover means very little as the reflection process was already complex and considerable quantities of radiation were trapped within the canopy. The results reported here for the mature lichen woodland agree.

The spruce canopy in this environment is not a closed one. The lichen mat has a substantially higher reflectance at all wavelengths and viewed from above the visual impression one gets is of a very highly reflective surface. For the predominant zenith angles during the measurement period however the surface is a very dark one. Even with reduced cover densities the effective canopy seen by the incident radiation is composed of mature spruce.

For the three burned surfaces the maximum reduction in reflection under overcast conditions occurs with the 2 year burn, which has the lightest surface. One would argue that the magnitude of the specular component for this surface would be the greatest and hence subject to the greatest change with overcast conditions. The 0 and 1 year burns still retain a charred surface of lichen detritus whereas the 2 year burn has this material removed.

The 24 year burn has the largest reduction of any of the surfaces particularly for the reflected infrared wavelengths. Although it is a more complex surface than the younger burns and is vegetated it does not have an extensive complex canopy structure. The bulk albedo value is higher than that of the 2 year burn but this in itself is no indication that the directional effects will be more significant. Following the earlier arguments it appears there would be counterbalancing effects. Other factors may also play a role however.

The actual conditions of measurement must also be considered. The research season was punctuated by frequent if not large rainfalls. The effect of increased surface moisture will be seen primarily in the infrared wavelengths for the vegetated surfaces where the reflectance is the highest. The predominant Polytrichum spp. mat shows distinct morphological and visible colour changes under varying moisture conditions. Variation in plant water status and turgor make if difficult to sort out the effects of these variations and those effects of the vegetation canopy, particularly for a surface like that of the 24 year burn where the canopy effects are not overriding ones.

The complexity that is inherent in the vegetated surfaces is also exhibited in Figures 21, 22, and 23. Water on the surface of plant leaves affects the infrared reflectance to a greater extent than the reflectance in the visible wavelengths, in agreement with other sources, (Gates 1965, 1970). The temporal sequence on a clear sky day for Alnus rugosa could be an effect of zenith angle changes but also may be related to changing water relations or structural effects in the leaves. Similar trends were occasionally noticed for the burned surfaces but these were not consistent. More specific investigations should consider short term soil moisture variations.

The reflectance curves for the lichen mat agree with the general findings of other investigators. The visually lighter appearance is observed in an increased reflectance for wavelengths from 400 mμ to 700mμ. Green peaks are noticeable even for the averaged data and the large increases in infrared reflectance for other species are present. The latter effect is of greater magnitude than any other surface measured and it compares favourably with the findings of Petzold and Renz (1975). Any albedo measurements will be difficult to intercompare directly, however, as species composition is important and also the depth of the lichen mat is a significant variable as it can provide a variable canopy of sorts. The water status of the lichen mat is also important as it drastically influences structure and colour changes. This is well exhibited by the large differences in infrared reflection from various lichen covered surfaces under clear sky conditions and those measured under overcast and wet conditions.

A useful summary technique is the ratio of selected infrared to visible wavelengths; in this case 800mμ to 550mμ. Scott (1968) reports a series of these for different vegetations. For single leaf measurements the ratio is normally about 3:1. For natural vegetation stands this increases to 5:1. Howard (1966) feels this may be a view factor effect but a more significant cause would be due to the multiple stacking of leaves which would increase the infrared reflectance while not affecting the visible values. This is shown clearly in the results by the 5:1 ratio for the alder bush and spruce boughs while the surfaces with lesser complexity such as the 24 year burn and the detached alder leaves are much closer to 3:1. Hoffman (1968) reports these ratios being lowest for succulent, thick cuticle species; intermediate for thinly leaved species and slightly higher for cryptograms. The data in this report show the lowest ratios for water and burned surfaces as would be expected when the differential reflectance is much lower and there are no physiological effects to be considered. The data for the 24 year burn are the most ambiguous. This reflects the great heterogeneity of that surface. The mature woodland is also low at 3:1 but it must be noted that the lichen canopy while being highly reflective has a ratio of approximately 2:1. The combination of the two species apparently has some effect. For the lichen surfaces the light colour has produced higher visible reflectances but not proportional increases in the infrared reflectance, although the magnitude is also large. The data would likely be more comparable to Hoffman (1968) if a wider range of cryptogram species were included.

6. Summary

A sequential pattern can be firmly established for the changes in spectral reflectance accompanying a post fire recovery sequence in the subarctic spruce lichen woodland. It begins with a gradual lightening of the surface layers through erosion and is followed by alterations due to the establishment of photosynthetically active vegetation. It then becomes complex and less predictable as the vegetation canopy becomes more complex.

In this study there is little ambiguity regarding the effect of overcast sky conditions on the spectral reflectance. It is substantially decreased due to decreased effects of directional reflectance and the wetter surface conditions normally associated with overcast skies. There is no decrease for the complex vegetation canopy in the mature lichen woodland.

Generally in a natural environment the indication of direct causality in energy processes is complicated by many interacting physical and biotic effects. A properly designed experiment is required to isolate individual effects.

Further research into many of the possible dimensions explored here would be very useful particularly for the mature lichen woodland.

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APPENDIX A

Cover Values For Some Selected Measurement Sites

Species	Site		
a) Lichens	Average Mature	Tower	24 YR Burn
Cladonia stellaris	17.31 (9.78)	12.6	1.08 (1.98)
Cladonia uncialis	8.48 (5.34)	12.1	1.20 (1.10)
Cladonia amaurocrea	4.17 (3.80)	5.6	0.16 (0.06)
Cladonia gracilis	2.15 (2.98)	1.30	1.20 (1.10)
Cladonia mitis	0.73 (2.09)	10.2	
Cladonia botrytes	0.10 (0.33)		3.04 (2.94)
Cladonia gonecha	0.83 (0.82)	.70	1.56 (1.46)
Cladonia cristatella	0.11 (0.35)		1.40 (1.30)
Cladonia cornuta	1.46 (1.43)	1.30	1.14 (1.04)
Cladonia coccifera	0.78 (0.71)	1.30	0.68 (0.58)
Cladonia macrophylla	0.39 (0.43)	.90	0.32 (0.32)
Cladonia subulata	0.04 (0.10)		0.38 (0.38)
Cladonia crispata	1.50 (1.71)	2.30	0.26 (0.16)
Cladonia rangiferina	1.01 (1.77)	.20	
Cetraria islandica	1.54 (1.37)	2.60	0.24 (0.14)
Cetraria nivalis	9.16 (9.37)	30.60	0.52 (0.32)
Stereocaulon paschale	22.03 (24.13)	11.00	
Pelitigera apthosa	0.08 (0.09)		
Pelitigera scabrosa	1.06 (1.38)		
Nephroma arcticum	0.10 (0.36)		
Lecidea uliginosa	0.85 (1.94)		7.58 (7.48)
Biatora granulosa	1.40 (2.80)	.40	9.94 (9.74)
b) Mosses, Liverworts, and Lycopods			
Ptilium crista-castrensis	0.26 (1.22)		
Polytrichum piliferum	4.13 (13.62)		58.62 (50.62)
Polytrichum juniperinum	0.87 (1.93)	.30	3.42 (3.03)
Dicranum spp.	0.46 (1.06)		
Hylycomium splendens	0.31 (0.72)		
Pleurozium shreberi	1.26 (2.79)		
Ptilidium ciliare	4.40 (6.02)		
Lycopodium spp.	0.09 (0.36)		
c) Vascular Plants			
Arctostaphylos uva-ursai	0.08 (0.35)		
Ledum groenlandicum	2.77 (2.85)		4.44 (4.44)
Vaccinium vitis-ideae	15.26 (7.19)	13.8	7.86 (6.64)
Vaccinium uliginosum	1.85 (2.57)	0.60	1.84 (1.84)
Vaccinium myrtyloides	0.58 (1.10)		.98 (0.98)
Geocaulon lividium	0.98 (1.34)	0.60	
d) Remainder			
twigs	19.75 (10.32)	33.1	1.80 (1.70)
bare ground	3.39 (11.32)	2.0	

APPENDIX A (ii)

Species Present on Recently Burned Surfaces

0 YR Burn

- none present with no apparent regrowth throughout the season

1 YR Burn

site A - Vaccinium myrtiloides
site B - Ledum groenlandicum
site C,D - Vaccinium myrtiloides
- Vaccinium uliginosum
- Salix spp.
- deadfall

2 YR Burn

all sites - Ledum groenlandicum
- Carex spp.
- Lycopodium spp.
- deadfall

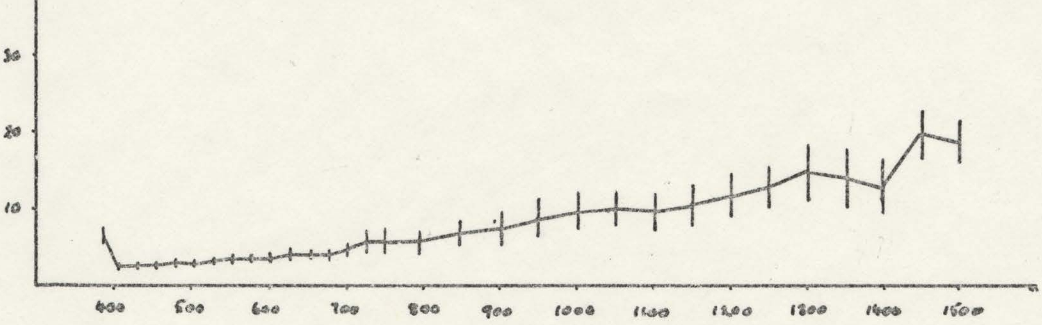
24 YR Burn

site A - Vaccinium vitis-ideae
- Polytrichum juniperinum
- " piliferum
- Cladonia spp.
site B - Arctostaphylos uva-ursai
- Polytrichum piliferum
- Cladonia spp.
- Cetraria spp.
site C - rock, bare ground
-deadfall
- Cladonia spp.
site D - Cladonia spp.
-Picea mariana
- Vaccinium vitis-ideae
site E - Carex spp.
- Vaccinium vitis-ideae
- Picea mariana
- Cladonia spp.
site F -Picea mariana
- Vaccinium uliginosum
- Polytrichum juniperinum
- Cladonia spp.
site G - Ledum groenlandicum
-Polytrichum juniperinum
- Vaccinium vitis-ideae
- Cladonia spp.
- deadfall

APPENDIX B

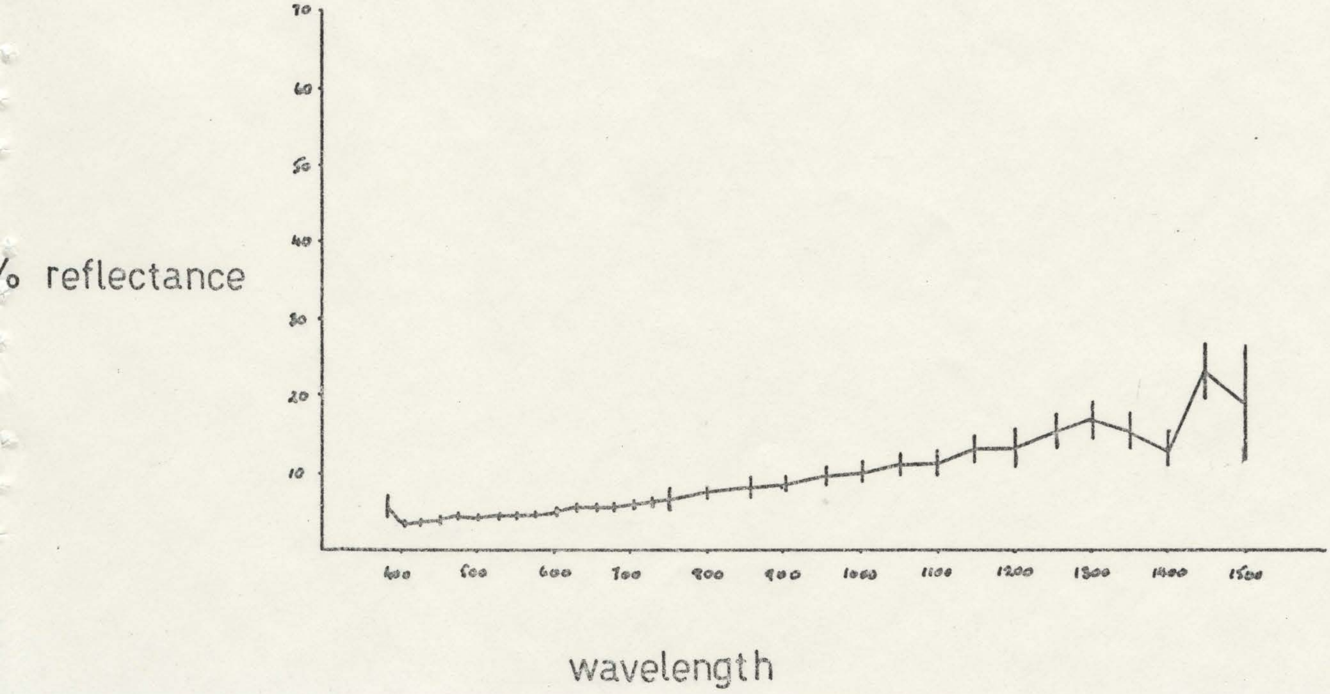
Site 0 YR A

% reflectance



wavelength

Site 0 YR B



70
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% reflectance
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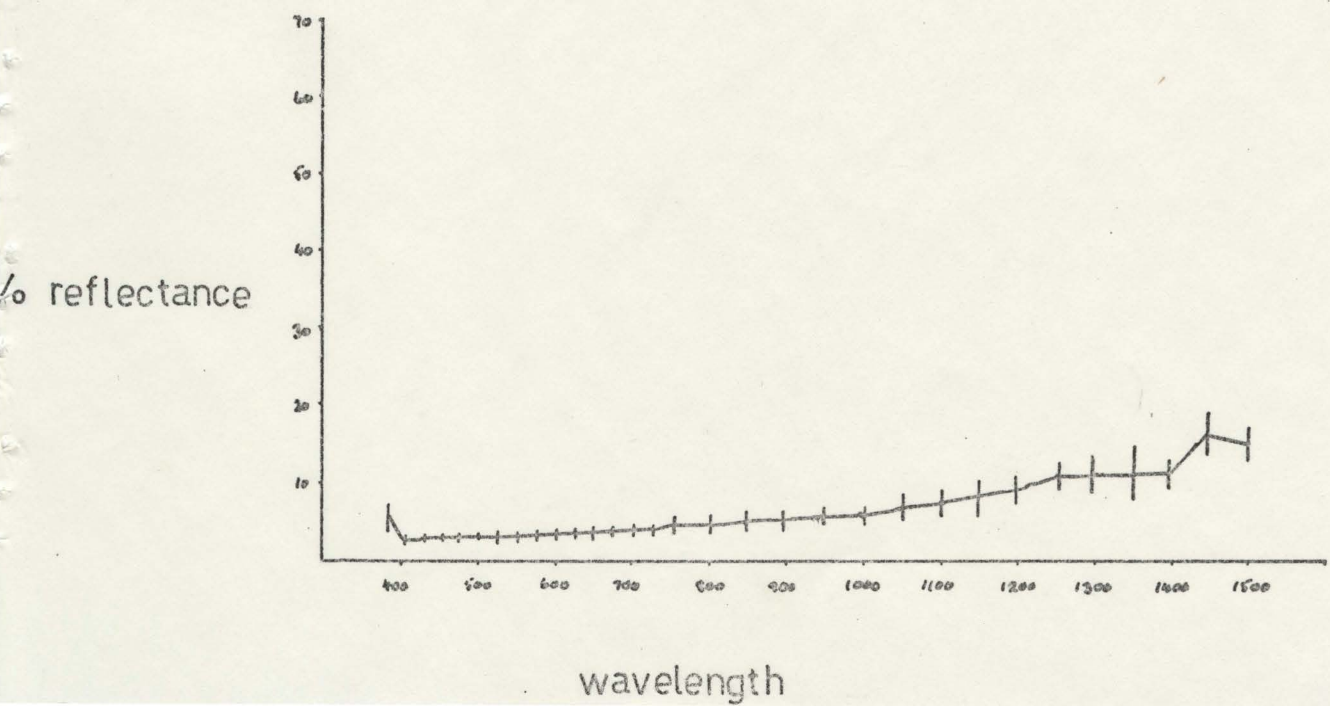
wavelength

Site 0 YR C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% reflectance
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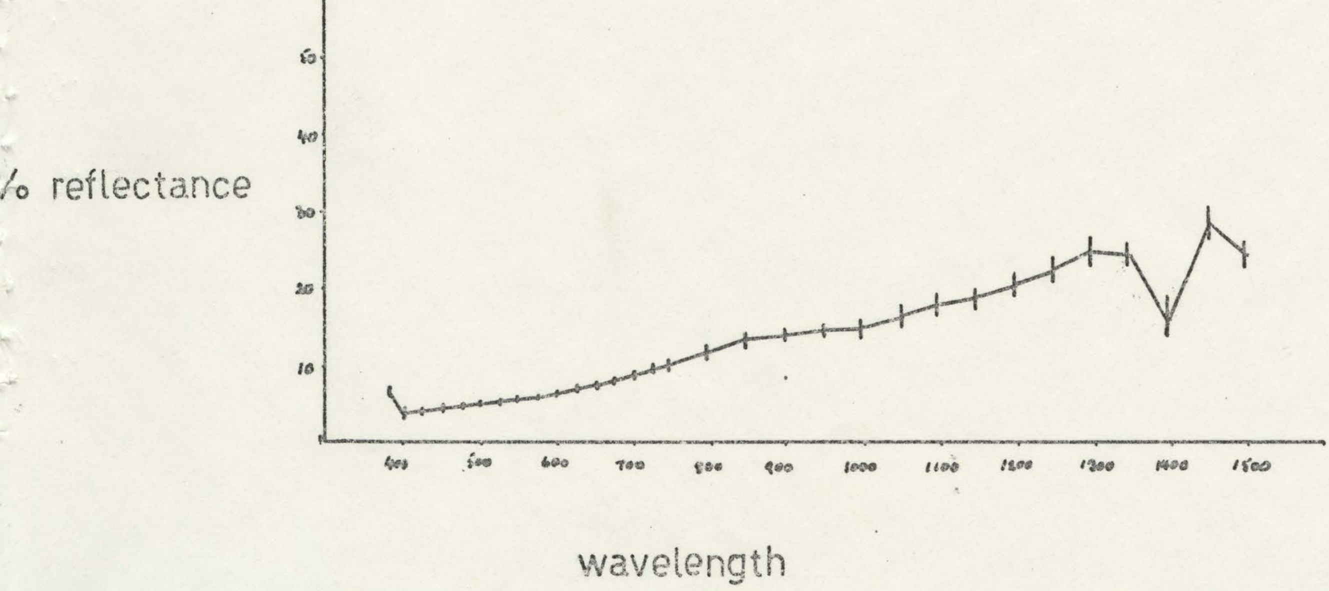
wavelength

Site 0 YR D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% reflectance
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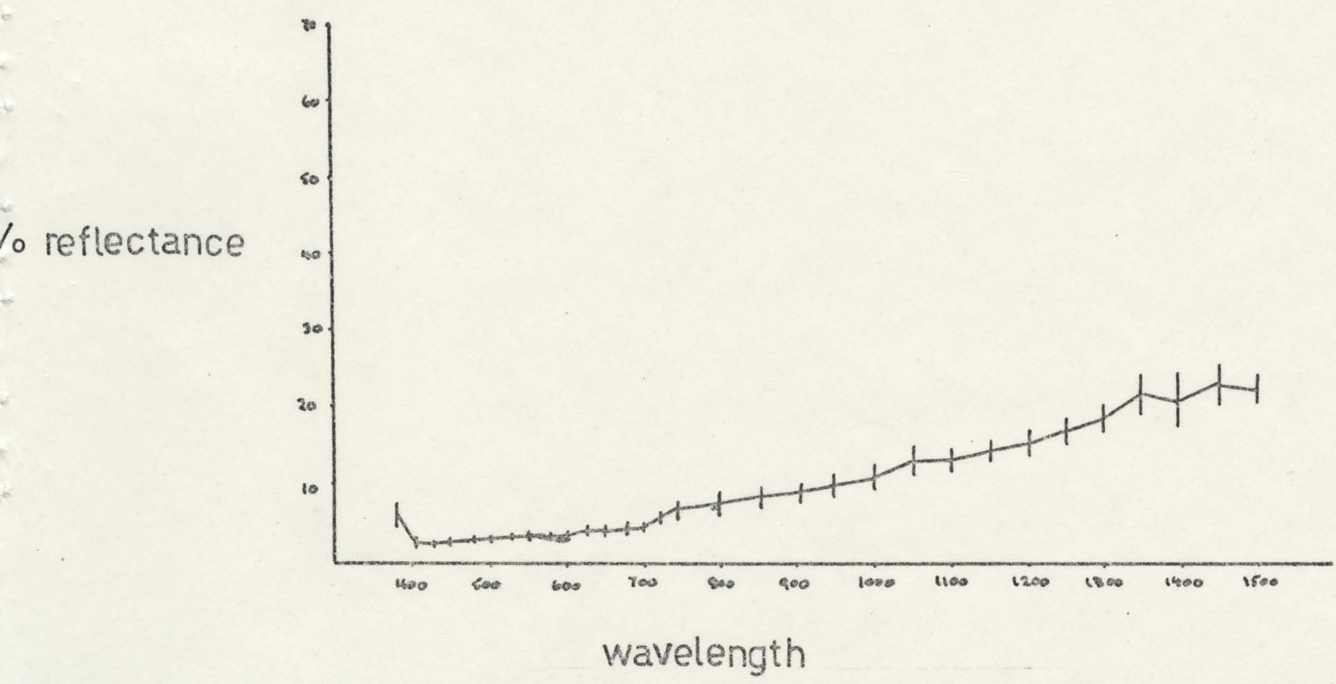
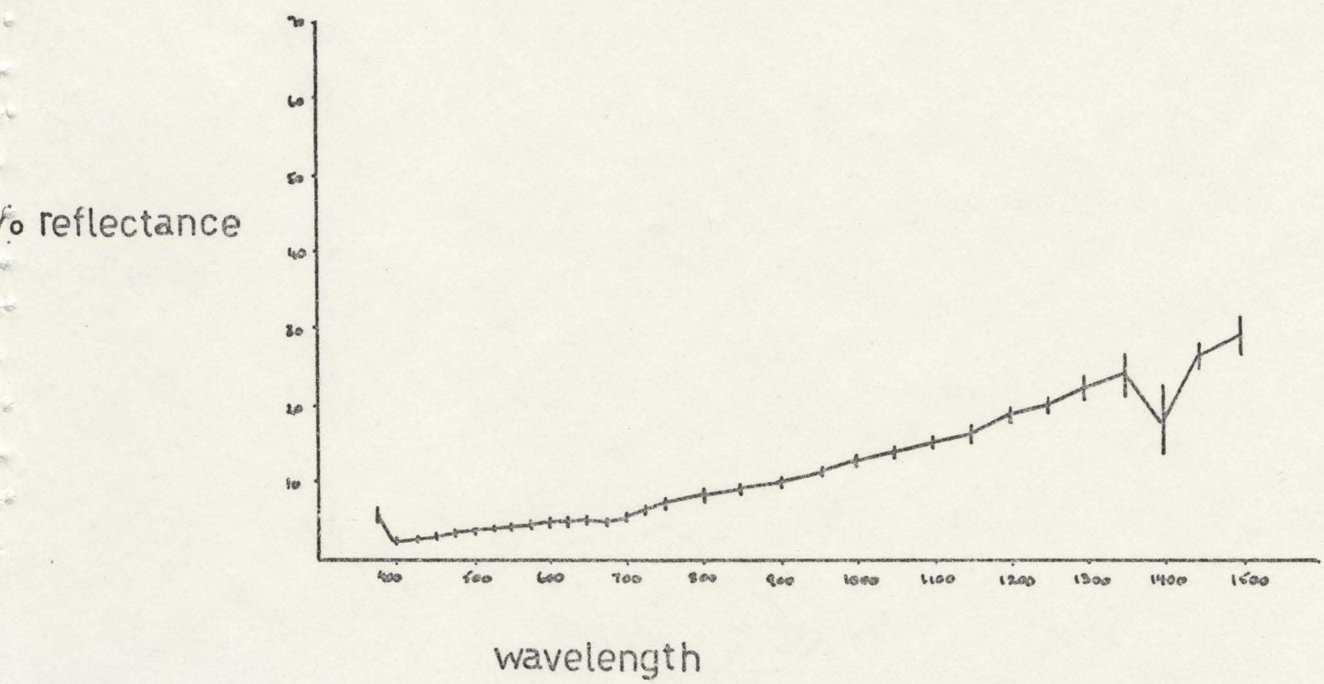
wavelength

Site 1 YR A



Site 1YR B


% reflectance
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wavelength

Site 1 YR C

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% reflectance
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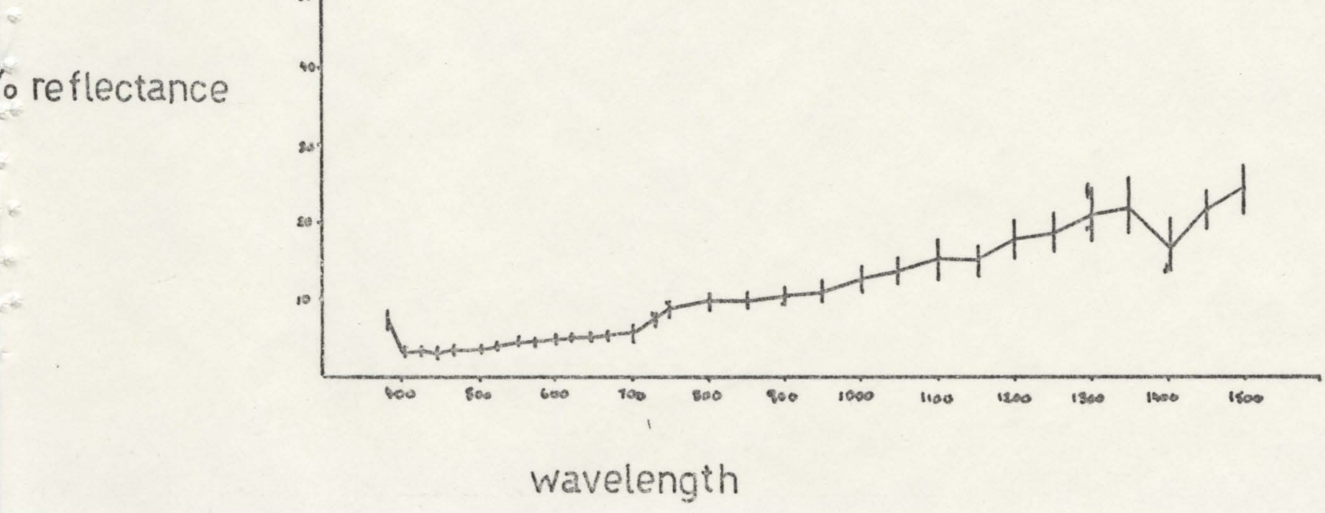
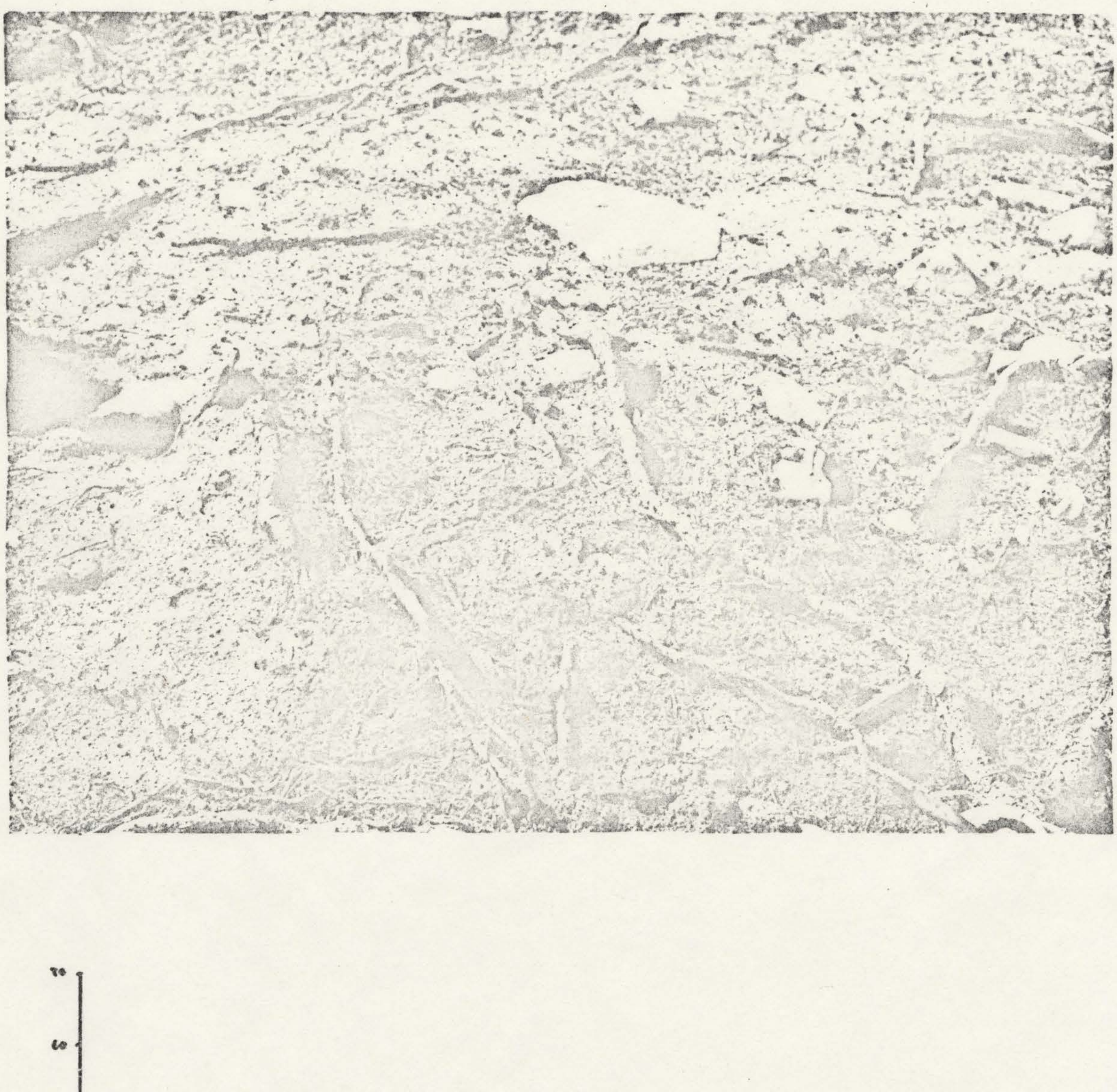
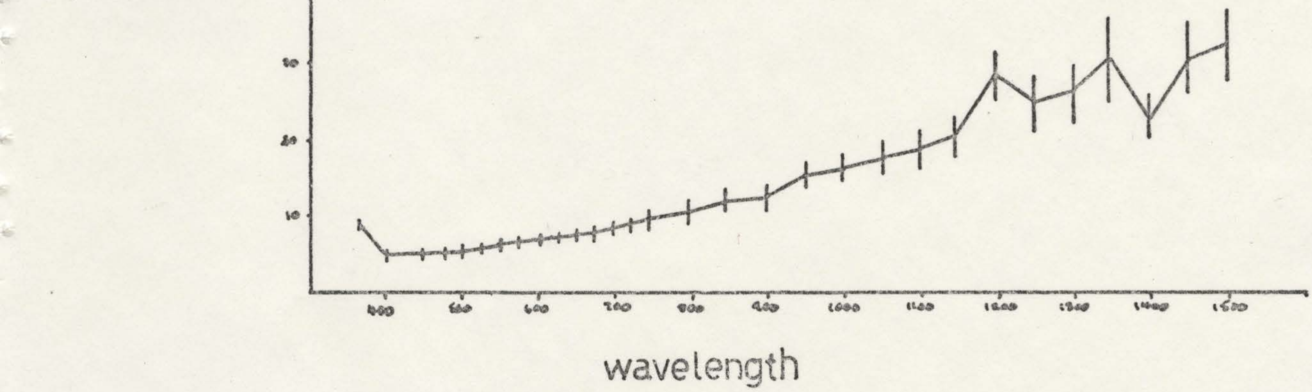
wavelength

Site 1YR D

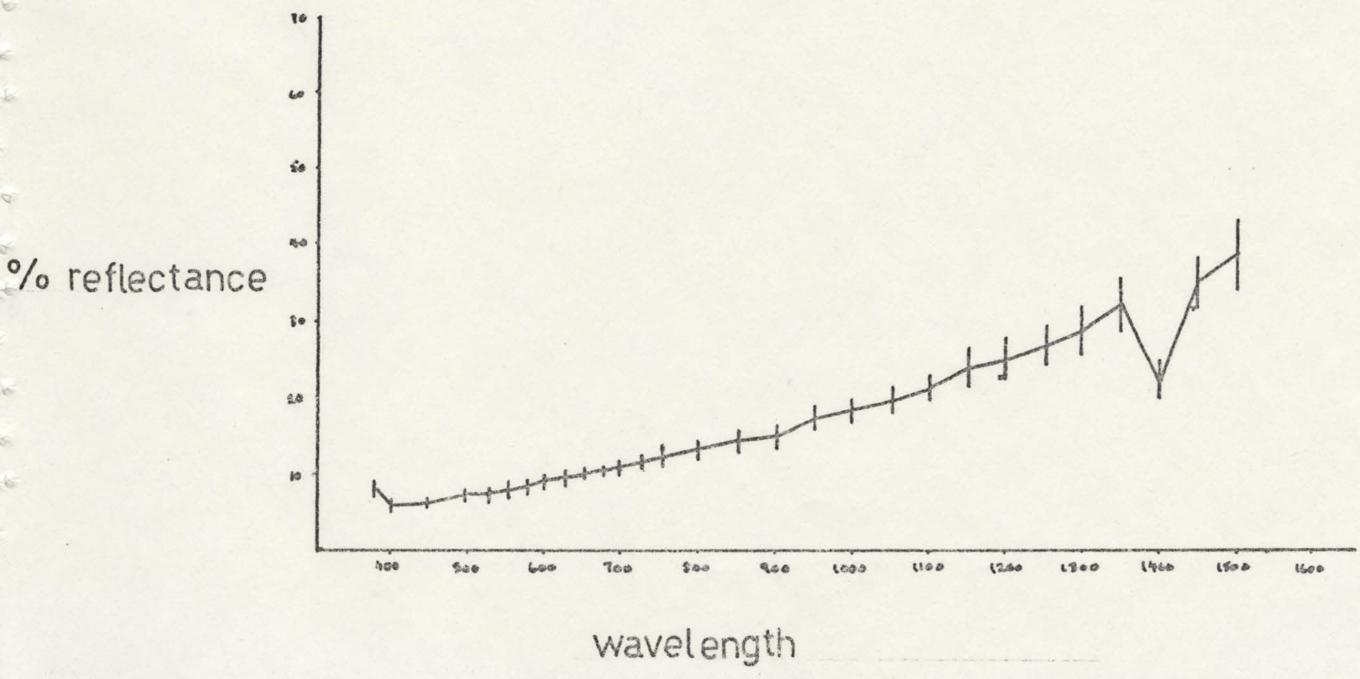


Site 2 YR A, B

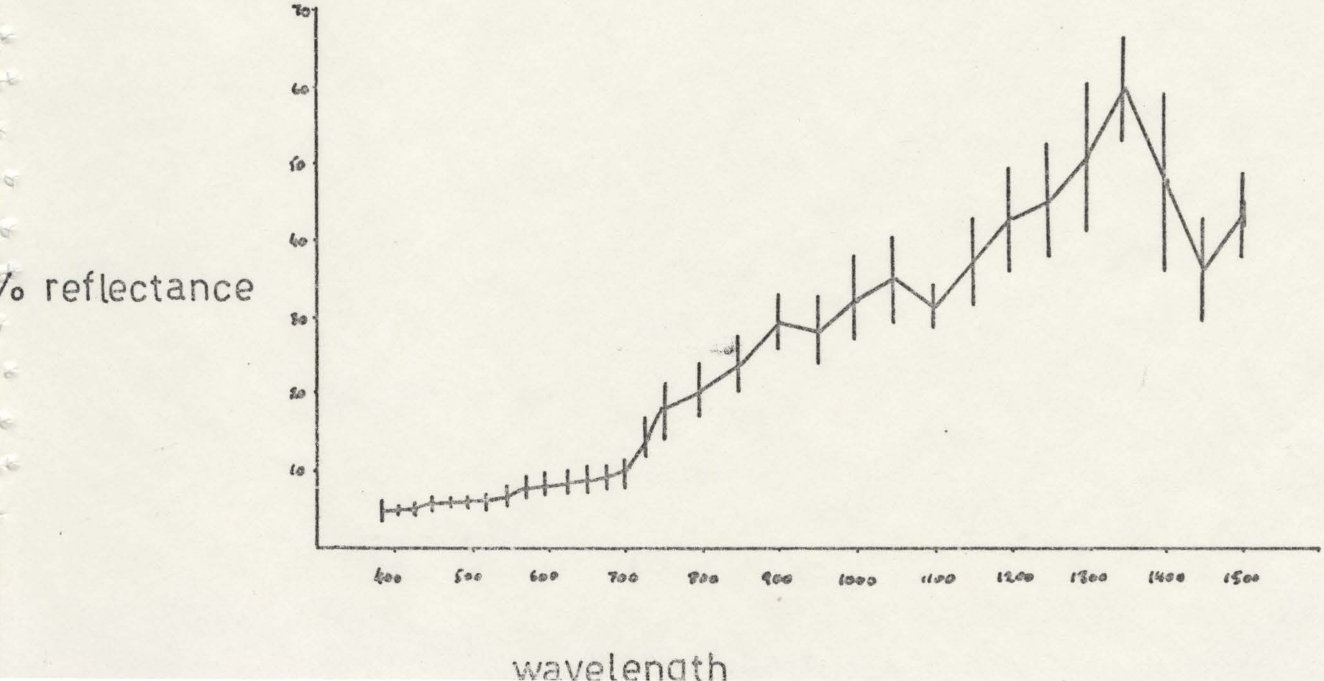




Site 2 YR C, D



Site 23 YR A


% reflectance
wavelength
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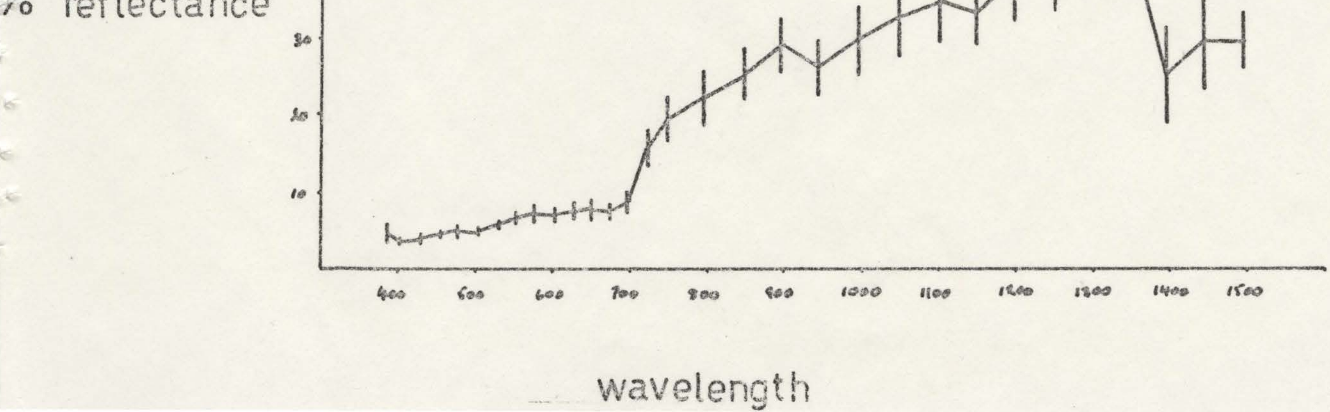
Site 23 YR B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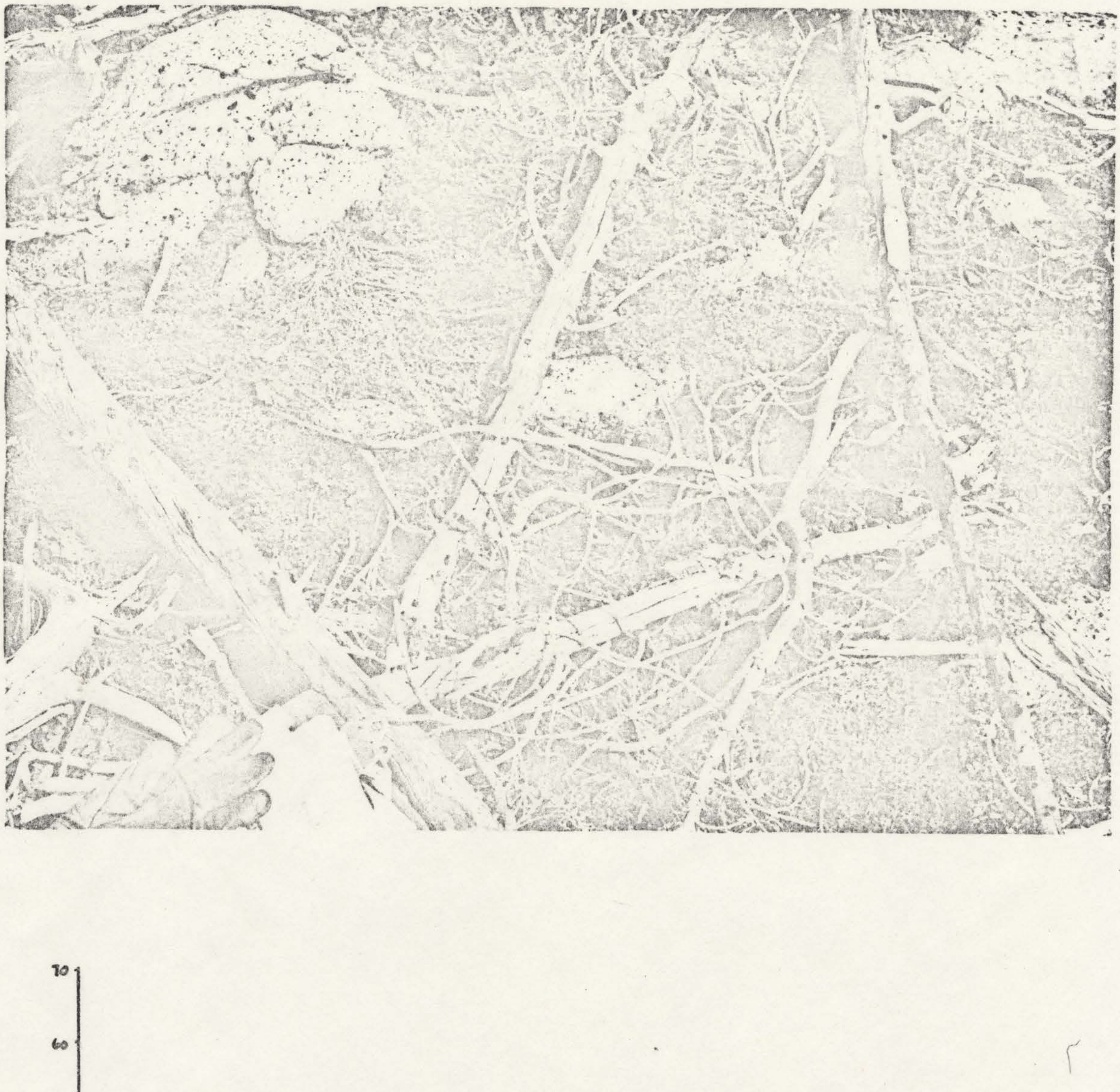
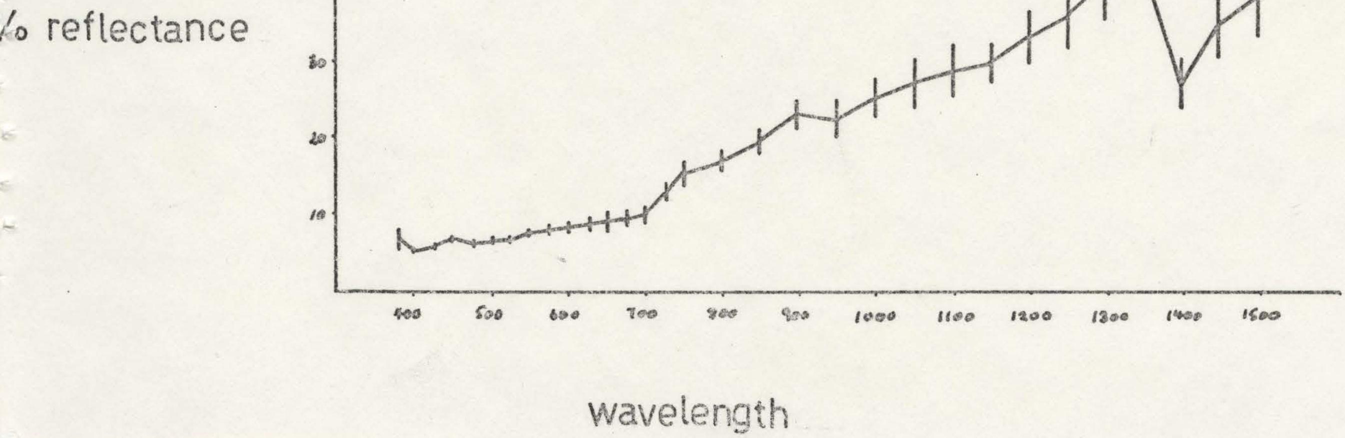
wavelength

Site 23 YR C

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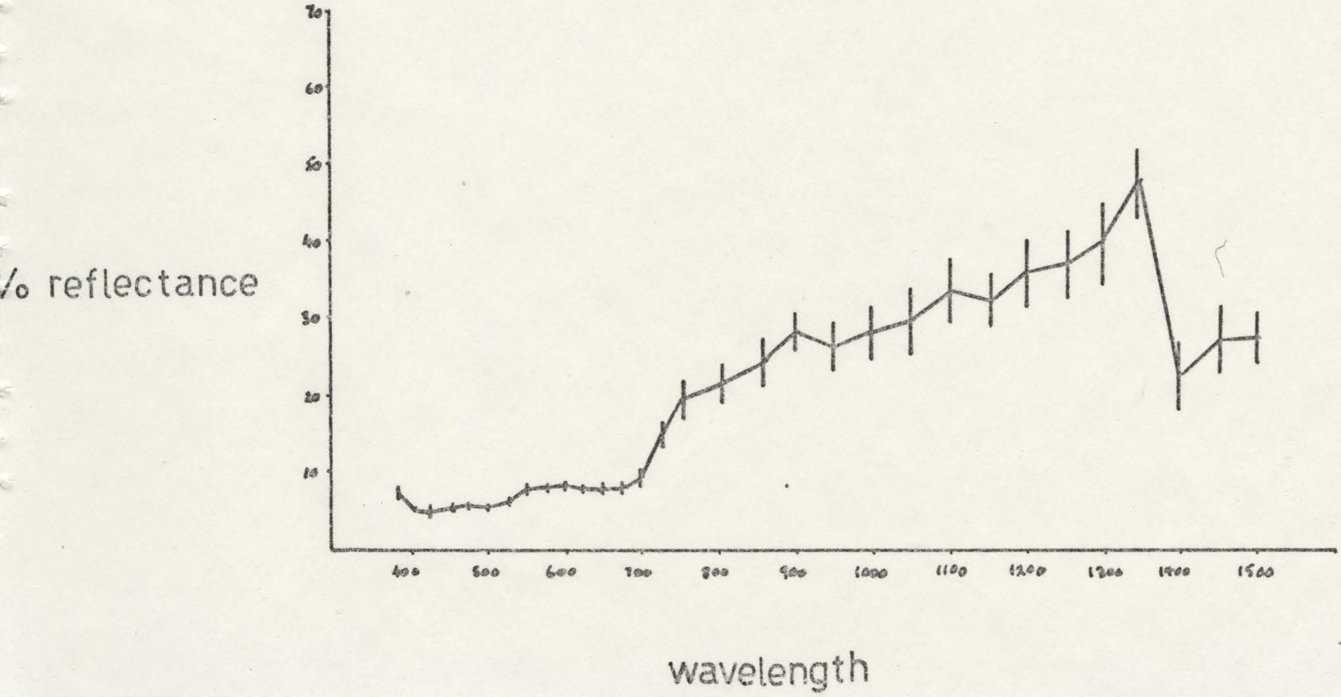
wavelength

Site 23 YR D



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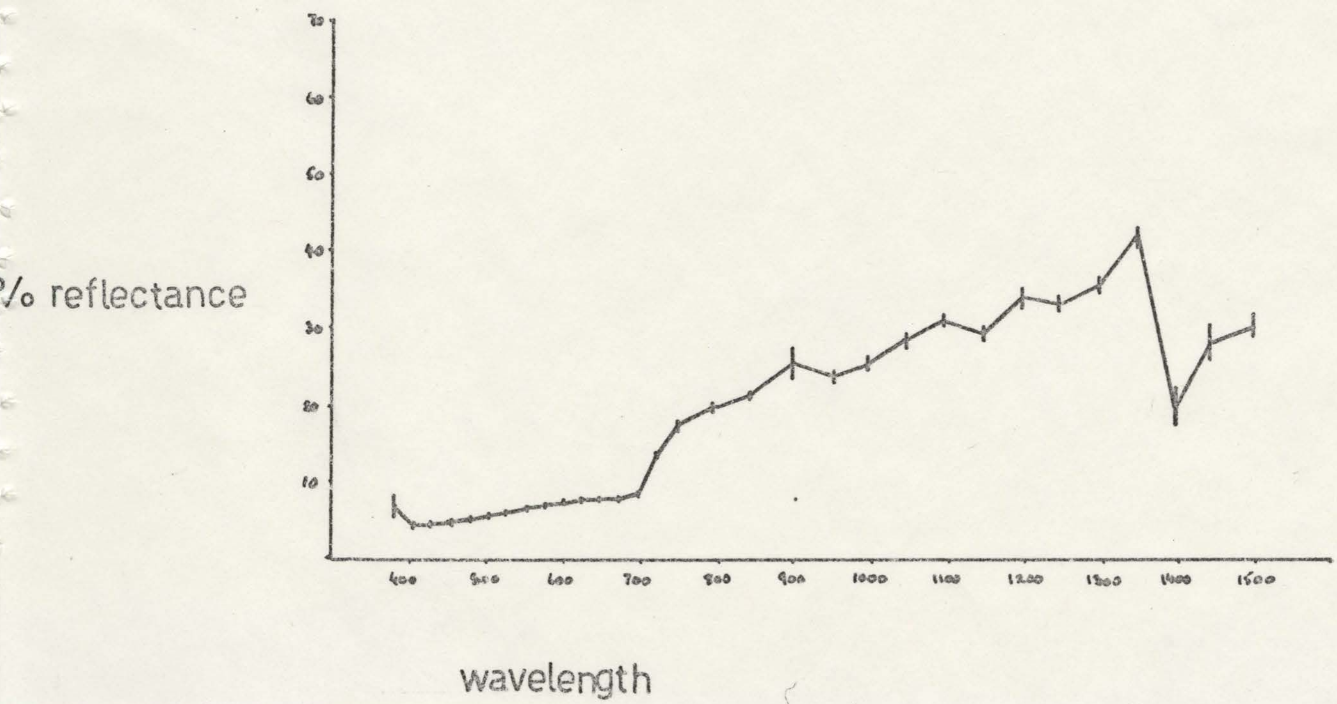
wavelength

Site 23 YR E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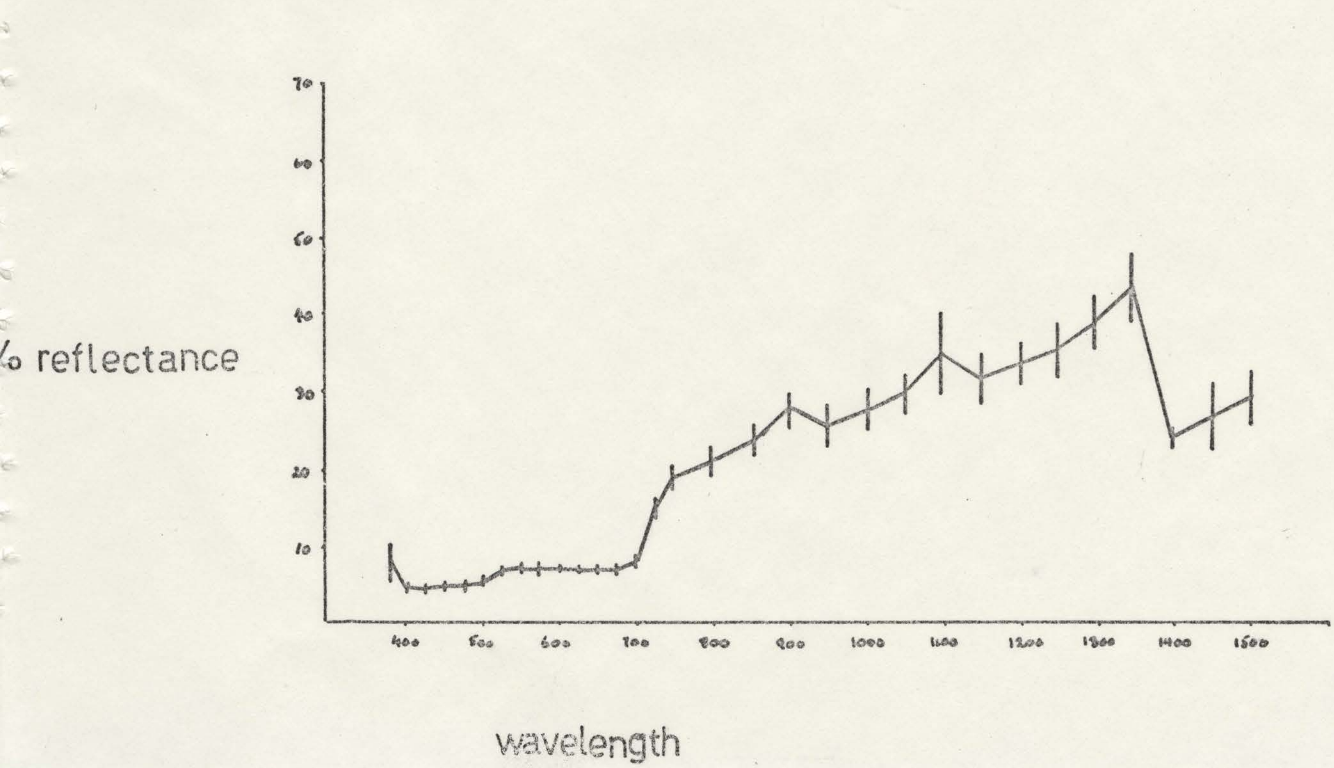
wavelength

Site 23 YR F


% reflectance
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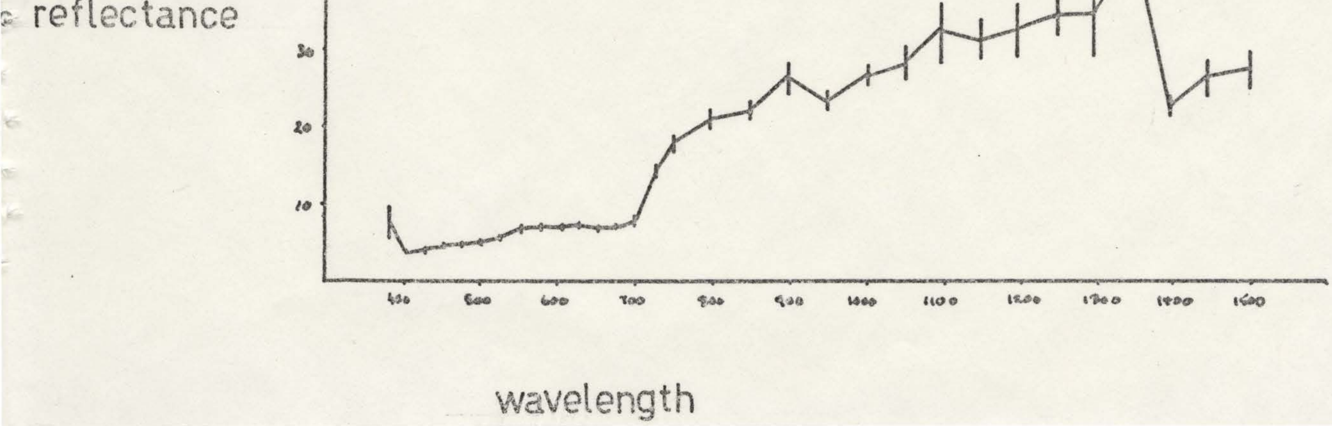
wavelength

Site 23 YR G



Lichen Mat A