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SPECTRAL CHARACTERISTICS OF GREENLAND LICHENS

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ABSTRACT Spectral reflectance measurements conducted during two field campaigns in west Greenland, and in the laboratory using samples collected during those campaigns, are discussed to evaluate the spectral signature of lichens. Given the diversity in lichen species, colors, and appearance — ranging from crust-like (crustose) to almost like mini shrubs (fructicose) — it is not surprising that no single signature was found. Some of the brighter fructicose lichens have reflectance characteristics very similar to those of green vegetation, with a pronounced rise in reflectivity around 750 nm. However, the most abundant lichen species covering rocks in the ice-marginal zone of west Greenland are dark grey to black crustose and foliose ephilithic (rock-growing) lichens and the shape of the reflectance spectrum for these lichens is generally very different from that of other surface types and landcovers, with near-zero reflectance at visible wavelengths, and a maximum around 1 600 nm. This characteristic allows rock-covered lichen to be identified on multispectral satellite imagery.

RÉSUMÉ *Signatures spectrales des lichens du Groenland.* L'évaluation de la signature spectrale des lichens est effectuée à partir de mesures prises en laboratoire et sur le terrain, au Groenland occidental. Aucune signature spécifique ne peut être identifiée, en raison de la diversité des espèces quant à leur couleur et à leur port, allant de la croûte à l'arbuste nain. Les lichens arbustifs les plus brillants montrent une signature spectrale semblable à celle des plantes vertes, avec un pic très prononcé autour de 750 nm. Toutefois, les lichens les plus abondants sur les roches à proximité des glaces sont gris foncés à noirs et du type crustacé ou foliacé; leur spectre de réflectance montre une allure très différente de celle des autres types de surface et de couverture, et se rapproche de zéro dans le spectre visible avec un pic autour de 1 600 nm. Cette caractéristique permet l'identification des roches recouvertes de lichens par l'imagerie satellitaire multispectrale.

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INTRODUCTION

Lichens are "an association of a fungus and a photosynthetic symbiont resulting in a stable thallus of specific structure" (Hawksworth and Hill, 1984). The symbiont, or algae, provides organic matter (carbohydrates) through photosynthesis to the fungus which, in return, provides water and nutrient salts to the algae. This symbiosis allows lichens to live in places where few other plants can survive, such as on bare rock, and lichens are often among the first organisms to establish themselves on new soil and exposed rock faces (Hansen and Anderson, 1995: p. 5-6). Thus, in a recently deglaciated ice-marginal environment one may find a distinct zone where boulders and exposed bedrock are covered with epilithic lichens with vegetation otherwise mostly absent, adjacent to vegetated surfaces exposed at an earlier time and where soil has formed, allowing rooted plants, mosses, and fructicose lichen to become established. The boundary separating vegetated surfaces from bare or lichens-covered bedrock and debris is called the trimline. Provided a clear spectral signature of lichen-covered rocks can be established, it is possible to identify these surfaces on multispectral satellite images such as Landsat or ASTER, thereby allowing recent histories of glacier change to be established over larger areas (Csatho *et al.,* this issue).

A number of studies have investigated the effect of lichens on the reflectance spectrum of the underlying land or rock surface. Earlier studies (Gates *et al.,* 1965, 1966; Hoffman, 1970; Gauslaa, 1984) failed to observe significant spectral differences between lichens and leaves of vascular plants. However, Ager and Milton (1987) found that the reflectance curves of lichen-covered rocks are distinctly different from those of green, leafy plants. For wavelengths in the range 700-1 350 nm, lichen reflectance increases steadily and remains high at greater wavelengths. This steady increase is distinctly different from the reflectance curve of vascular plants, which tends to rise almost vertically from the visible to the near infrared and decreases slowly from 800 to 1 300 nm (Ager and Milton, 1987).

In this study, we present measurements of lichen reflectance spectra conducted both in the field and under more controlled laboratory conditions. The objective of this study was to provide independent validation of surface classification using multispectral Landsat imagery (Csatho *et al.*, this issue). Given the comparatively scarcity of previous studies, a discussion of prior results is given below that summarizes the most relevant earlier findings, followed by presentation of field and laboratory measurements on a range of lichen types.

PRIOR STUDIES ON LICHEN REFLECTANCE

Gates *et al.* (1965) studied spectral properties of plant leaves and stems and of selected lichens for wavelengths ranging from 400 to 1 100 nm. Two instruments were used in a laboratory setting, namely an integrating sphere attachment to the Hardy (General Electric) recording spectrophotometer (Gibson and Keegan, 1938) and a Cary 14 spectrophotometer with a Cary 1411 reflectance attachment (Keegan *et al.*, 1962). Calibration of wavelengths and photometric scales was done using filters and standard test surfaces (Keegan *et al.*, 1964). Samples were illuminated by monochromatic dispersed radiation incident at a 6° angle in the GE spectrophotometer, and specular and diffuse reflected radiation was detected in the integrating sphere. For the Cary 14 measurements, intense, undispersed radiation was incident on the sample by diffuse reflectance from the wall of the integrating sphere. Samples were viewed at ~60° (Gates *et al.,* 1965). Comparison with reflectance curves of plants and leaves led Gates *et al.* (1965) to conclude that "within the wavelength region for which the measurements were made, there would appear to be no prominent features of the spectral reflectance of lichens distinguishing them from higher plants. One possible exception is the absence with the lichens of a strong green peak of spectral reflectance around 500 nm which occurs for the higher plants".

In a subsequent study, Gates *et al.* (1966) note that pigments present in the fungus which forms the main body of the lichen, may contribute the primary color appearance of the lichen, but some of the chlorophyll contained in the encased algae may show through in the reflectance spectra. The reflectance curve for *Parmelia isidiata* shown in Figure 1 is characterized by a sharp absorption edge at 700 nm, due to strong absorption (low reflectance) of blue and red wavelengths by chlorophyll, although the increase in reflectance at this edge is not nearly as much as for the moss. Gates *et al.* (1966) argue that only in unusual situations will the pigment in the fungus completely hide the chlorophyll pigment, resulting in a reflectance curve without the sharp absorption edge.

Hoffman (1970) used a Beckman DK-2A ratio-recording spectrophotometer to measure spectral properties of plant leaves and moistened thalli of lichens and bryophytes. Reflectance curves for *Parmelia hyperopta* and *Cladonia* lichen are similar to those of vascular plants with a strong increase in reflectance around 700 nm, and show a reflectance peak at 550 nm which was not reported for other lichen species by Gates *et al.* (1965, 1966).

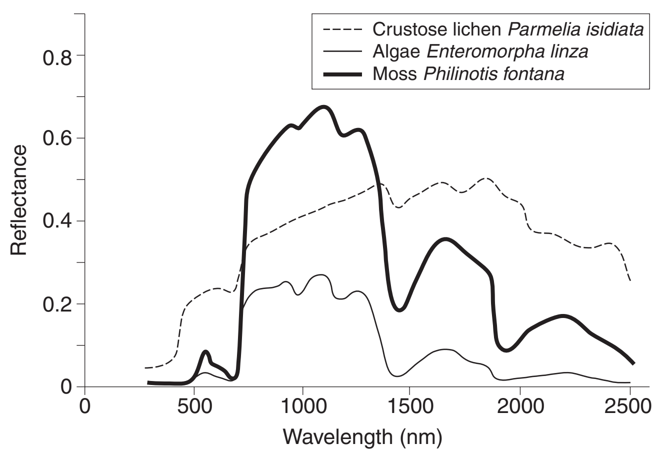

FIGURE 1. Spectral reflectance of a crustose lichen, algae, and moss as a function of wavelength. This material is reprinted from Gates *et al.* (1966) with permission of the American Astronautical Society.

Signatures spectrales d'un lichen crustacé, d'une algue et d'une mousse en fonction de la longueur d'onde. Cette figure est reproduite d'après Gates et al. *(1966) avec la permission de l'*American Astronautical Society.

As part of a study on the energy budget of Scandinavian plants, Gauslaa (1984) measured reflectances in the wavelength interval 400-1 400 nm of 24 lichen species including alpine and lowland species as well as different ecological groups such as chionophilous (“snow loving”) and chionophobous lichens among the alpine species, and shade-tolerant and photophylous (“sun loving”) lichens among the lowland species. Reflectance was measured on samples consisting of several layers with lobes or podetia (“fingers”) carefully arranged in order to minimize spaces between individual lobes, and to make the upper surface of the sample as smooth as possible. A Beckman DU spectrophotometer was used with a reflectance attachment that measured the diffuse reflectance relative to a magnesium carbonate standard. Light emerging from the monochromator was directed perpendicular to the sample (2.5 cm diameter) from where diffuse light was reflected upwards at angles between 35 and 55° on an ellipsoidal mirror, and recorded by a phototube. As in earlier studies, no obvious differences between lichen and various alpine vascular plants were found by Gauslaa (1984) that could be used to differentiate lichen cover from other vegetation.

Satterwhite *et al.* (1985) collected rock and lichen samples from bedrock exposures and talus slopes from the East Pioneer Mountains, near Melrose, Montana, to determine the effect of lichen cover on the visible and infrared reflectance spectra of granitic rocks. Samples were measured in the laboratory over the 400-1 100 nm region in 10 nm increments using an EG&G Model 550/555 spectroradiometer with illumination provided by a 300 W Xenon lamp (Oriel Corporation, Model 81100) operated at 296 W. Reflectance spectra for samples were calculated as a percentage of the spectral reflectance of a polytetrafluoroethylene (Halon) standard reference target. In all, 48 reflectance spectra were measure from 13 rock and 35 lichen samples, and grouped according to the shape and amplitude of reflectance curves to yield the average reflectance curve for each group. Satterwhite *et al.* (1985) did not identify the lichen species other than by color, but presumably the measurements refer to crustose lichen. From comparison of the various spectra obtained, Satterwhite *et al.* (1985) conclude that the spectrum of a lichen-covered rock surface can be significantly different from the spectrum of the bare rock; depending on the spectral contrast between the lichen and the rock substrate, the presence of lichens can increase, decrease, or have little effect on the spectral reflectance of the rock surface. For example, orange lichens on a quartz-diorite substrate will significantly increase the reflectance (except at small wavelengths, <500 nm), while on a granodiorite substrate, these lichens will significantly reduce reflectance at wavelengths smaller than ~800 nm, and moderately increase reflectance at higher wavelengths.

Samples of lichen and their granite, slate, and hornfels substrates from the Extremadura region, Spain, were measured by Ager and Milton (1987), using a Beckman 5240 spectrophotometer with an integrating sphere and a barium sulfate standard, at a resolution of 1 nm from 400 to 800 nm, and at 4 nm from 800 to 2 500 nm. Lichen species most commonly occurring on each rock type were collected and average reflectance curves established for three color groups based on 54 spectra measured from 27 lichen samples. Spectra for the three rock substrates were based on 50 spectra from 25 rock samples on which lichens were found to be growing. For the three most common lichen groups, spectral differences in the range 400-700 nm are primarily associated with pigmentation. The reflectance increase over the 700 to 1 350 nm range is less pronounced than for green leafy vegetation, and the chlorophyll edge is more subdued, in particular for the group of brown lichens. For all three lichen groups, reflectance is greatest between 1 300 and 1 850 nm, except for a minimum around 1 400 nm where the hydroxyl overtone increases absorption. At wavelengths greater than 1 400 nm, reflectance of all lichens differ by less than 5% and the spectra are almost identical in shape, with similar locations and shapes of absorption features (Ager and Milton, 1987).

To assess how lichens affect rock spectra, Ager and Milton (1987) used a linear mixing model to compute spectra of rock substrates partially covered with lichen. Linear mixing involves averaging of the spectrum of the rock type and the spectrum derived from a combination of all lichens found on that substrate. The assumption is made that incident energy is scattered only once (from the surface to the sensor) and does not undergo multiple scattering among foliage components or between the vegetation canopy and soil or rock surface. Some of the mixed spectral curves are shown in Figure 2, corresponding to slate, hornfels, and granite substrates with 0% (bare rock), 50%, and 100% (full) lichen cover. The only absorption bands visible in the slate reflectance curve are at 1 400 and 2 200 nm, but because these bands are very shallow, they are obscured by as little as 10-20% lichen cover. As the lichen cover increases, the water-absorption band at 1 930 nm deepens, as well as the hydroxyl band at 1 400 nm. Note also the appearance and sharpening of the chlorophyll edge at 680 nm. Similarly, the rather featureless spectrum of hornfels is strongly affected by relatively modest lichen cover. Because of the greater overall reflectance of lichens throughout the near infrared, lichen cover increases the reflectance of both the slate and hornfels substrate. Granite, however, is generally more reflective than lichens over the spectral range considered and lichen cover reduces the overall reflectance. The strong absorption bands at 1 400 nm and 2 200 nm remain visible although becoming more shallow and broad as the lichen cover increases. Ager and Milton (1987) conclude that the sharper and deeper absorption bands in the rock spectra are less affected by lichen cover while a level or gently sloping part of the rock spectrum will permit any strong feature in the lichen spectrum to become noticeable at low lichen cover. The absorption features of granite are sharper and stronger than the much weaker absorption bands in the slate and hornfels spectra. Consequently, lichens begin to dominate the spectra of slate and hornfels at 40 to 50% cover, but not until 80% cover for the granite.

Measurements of lichen transmittance conducted by Bechtel *et al.* (2002) indicate that lichens prevent transmission of light to the underlying rock substrate. Thus, the linear mixing model employed by Ager and Milton (1987) is appropriate to evaluate the effect of lichen cover on bedrock surfaces, or to assess the sub-pixel influence of lichen and rock within a multispectral satellite scene. Bechtel *et al.* (2002) used a FieldSpec FR spectroradiometer from Analytical Spectral

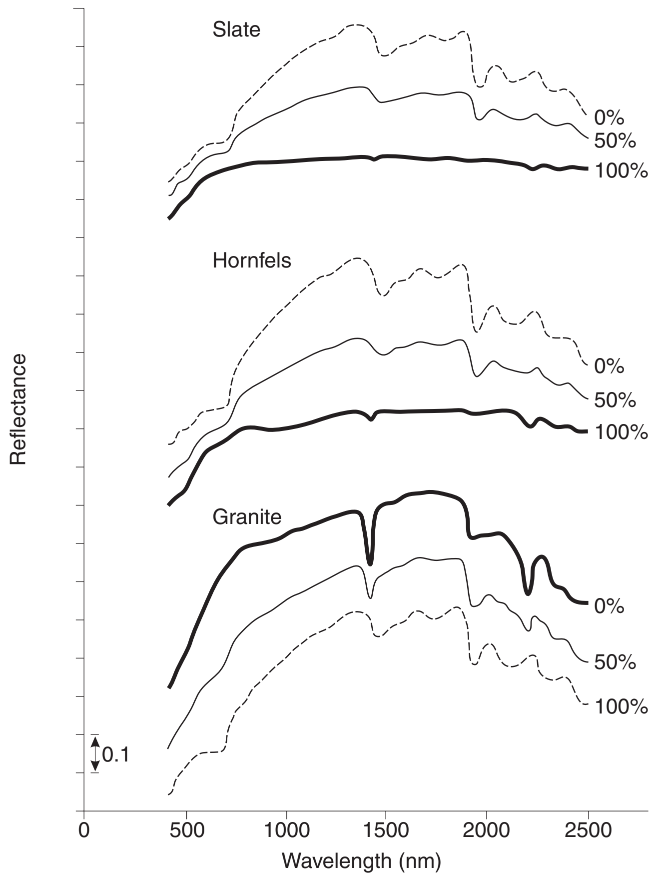

FIGURE 2. Mixed spectral curves for selected rock substrates with varying amounts of lichen cover, ranging from bare rock (0%) to complete lichen cover (100%). This material is reprinted from Ager and Milton (1987).

Signatures spectrales de différents substrats rocheux avec une couverture de lichen variable, allant de la roche nue (0%) à entièrement recouverte de lichen (100%). Cette figure est reproduite d'après Ager et Milton (1987).

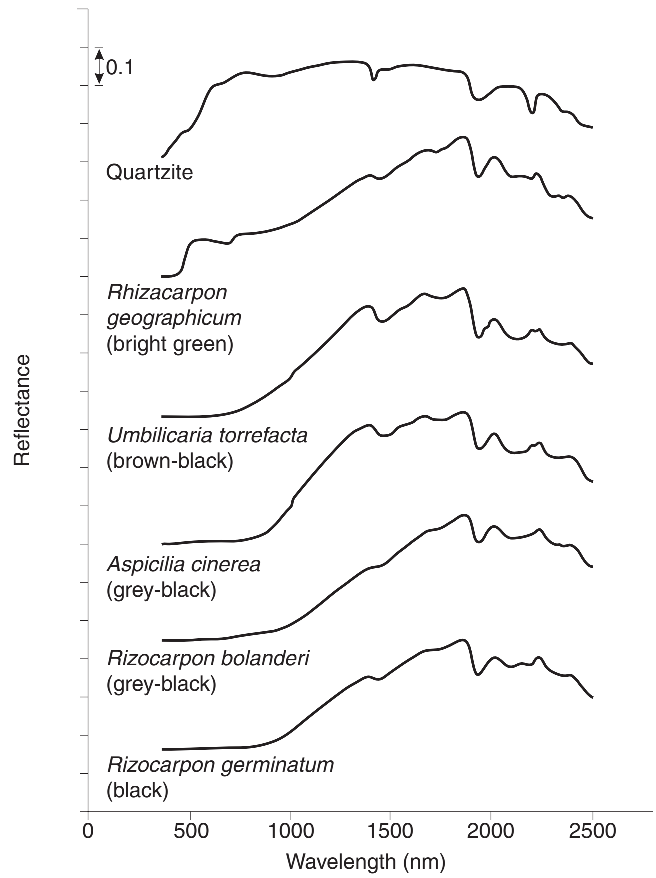

FIGURE 3. Spectral characteristics of five lichen species and quartzite. Each spectrum represent the average of five locations. Percent reflectance for the vertical axis is offset for clarity. This material is reprinted from Bechtel *et al.* (2002) with permission of Elsevier.

Signatures spectrales de cinq espèces de lichens et de la quartzite. Chaque spectre représente une moyenne de cinq mesures. L'axe vertical a été décalé pour améliorer la lecture du graphique. Cette figure est reproduite d'après Bechtel et al. *(2002) avec la permission d'Elsevier.*

Devices to measure reflectance and transmittance of lichen-bearing rock samples collected from the Gog Quartzite Formation in Jasper, Alberta. Transmittance was determined by placing a sample of the foliose *Umbilicaria torrefacta* first on a white Spectralon panel (99% reflectance) and next on a black Spectralon panel (2% reflectance). Both reflectance spectra showed only small differences ranging from 0% to 3%, indicating that this lichen transmits little or no light.

Reflectance spectra measured in five lichen species obtained by Bechtel *et al.* (2002) are shown in Figure 3. With the exception of the foliose *Umbilicaria torrefacta*, all species are crustose. Dark colored lichen have low reflectance in the visible part of the spectrum (3% to 7%), and show a gradual increase in reflectance at greater wavelengths, reaching a maximum around 1 860 nm. The absorption feature near 1 445 nm is caused by water in the lichens. The spectrum of the bright green *Rhizocarpon geographicum* is different in that reflectance rises quickly from 4-5% at 400 nm to 11-17% at 520 nm, followed by a chlorophyll edge at approximately 685 nm (Bechtel *et al.,* 2002).

The studies discussed so far involved laboratory measurements on field-collected samples. Rivard and Arvidson (1992) conducted field observations to obtain *in situ* spectra of different surfaces on the island of Qilangarssuit, about 30 km south of Nuuk on the west coast of Greenland. Exposed lithologic units included gneiss, granite, anorthosite, and amphibolite rocks. On outcrops, the areal extent of lichen cover was ~80%. Field measurements were carried out over the range 450 to 2 400 nm with band spacing ranging from 9 nm at 450 nm to 40 nm at 1 300 nm. The sensor of the Daedalus AA440 Spectrafax spectrometer was placed ~1 m above the imaged surface, giving a field of view area of ~5 cm^2 at an observation angle of a few degrees. Raw data were smoothed using a five-band arithmetic moving average, and converted to radiance coefficients by dividing the radiance of the measured surface by the radiance of a unit lightness Lambertian

Spectrahalon standard surface identically illuminated. Reflectance spectra for common surface types in the region studied by Rivard and Arvidson (1992) are shown in Figure 4. The upper panel displays spectra of snow, tundra vegetation, and of clear, deep water. The clear water spectrum has the highest reflectance values in the blue-green wavelength range, while snow displays a peak near 1 000 nm; and both surface types have low reflectance in the near infrared. The sample of tundra vegetation consisted of mosses and pieces of leafy bushes and the spectrum is typical of that of green plants, characterized by water absorption features at 1 400 and 1 900 nm, and a broad, high plateau in the 900 to 1 300 nm range associated with scattering from leaves (Rivard and Arvidson, 1992).

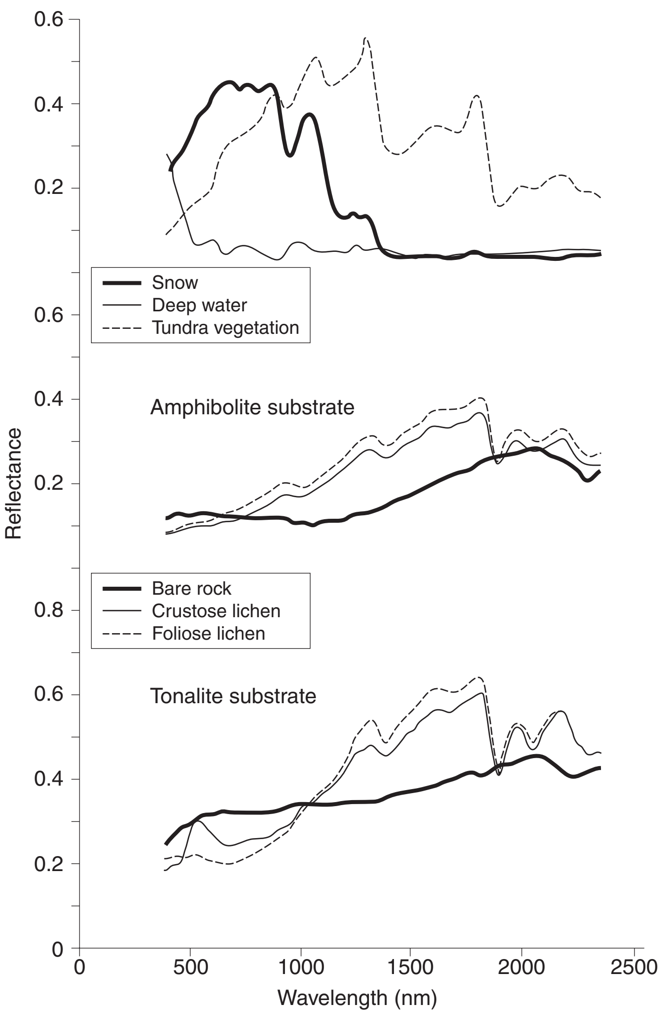

FIGURE 4. Reflectance spectra acquired in the field for snow, water, and tundra vegetation (top panel), and for amphibolite and tonalite substrates with and without lichen cover (middle and bottom panels). This material is reprinted from Rivard and Arvidson (1992) with permission of the American Society for Photogrammetry and Remote Sensing.

*Signatures spectrales acquises sur le terrain pour la neige, l'eau et la végétation de toundra (en haut), et pour les substrats rocheux d'amphibole et de tonalite avec ou sans couverture de lichen (au milieu et en bas). Cette figure est reproduite d'après Rivard et Arvidson (1992) avec la permission de l'*American Society for Photogrammetry and Remote Sensing.

The spectra of bare amphibolite and tonalite substrates are rather flat and featureless and significantly altered by lichen cover. Most importantly, at intermediate wavelengths, 1 200-2 000 nm, the reflectance is increased by lichen cover compared to bare rock. In part this is because amphibolite is comprised of hornblende, usually dark green to black in color, and plagioclase, whereas in external appearance, tonalites are similar to granite but usually darker in color. Thus, the field observations of Rivard and Arvidson (1992) confirm the most important features of the computer-generated mixed spectra predicted by Ager and Milton (1987).

In a more recent study, Tukiainen *et al*. (2003) present field and laboratory reflectance spectra of mafic and felsic rocks covered by orange lichen (species not identified, but probably *Xanthoria borealis*). Most lichen spectra are similar to that of green vegetation, with a rapid increase in reflectivity around 700 nm, and strong absorption peaks around 1 450 and 1 950 nm.

FIELD MEASUREMENTS OF LICHEN REFLECTANCE SPECTRA

Reflectance spectra were collected during a field campaign in July, 2003, in the ice-marginal region north of Jakobshavn Isfjord, and in June, 2004, near Kangerlussuaq (formerly known as Søndre Strømfjord), west Greenland (Fig. 5). For these measurements, a Fieldspec® PRO spectroradiometer from Analytical Spectral Devices, Inc. was used. During the 2003 field season, an instrument rented from ASD was used, while for the 2004 field and subsequent laboratory measurements, an instrument purchased with funds from the National Science Foundation was used. The instrument covers the spectral range from 350 to 2 500 nm with a sampling interval of 1.4 nm for the region 350-1 000 nm, and 2 nm for the region 1 000-2 500 nm, giving a spectral resolution (defined as the full-width half-maximum of the instrument response to a monochromatic light source) of 3 nm for the interval 350-1 000 nm, and 10 nm for the interval 1 000-2 500 nm (ASD, 2002). The reflectance of a target surface is computed by dividing the measured signal from the target by the measured signal from a Lambertian white reference surface illuminated under the same lighting conditions. All field measurements were taken using solar illumination under clear-sky to slight cloud cover conditions. Because of absorption of solar radiation by atmospheric water vapor in the spectral bands around 1 400 nm and 1 900 nm, at these wavelengths essentially no solar energy reaches the Earth's surface and the measured signal from both the target and white reference should be zero. In practice, however, the measured signals contain small but non-zero random noise generated by the instrument. Consequently, at these wavelengths, the target reflectance spectrum exhibits large noise peaks resulting from division of two random numbers. For ease of interpreting the field measurements, data corresponding to the atmospheric water absorption bands are omitted from the spectral curves shown below. For each target measurement, ten consecutive spectra were collected, and averaged to further minimize noise and random error. Differences between each of these ten spectra turned out to be minimal, however.

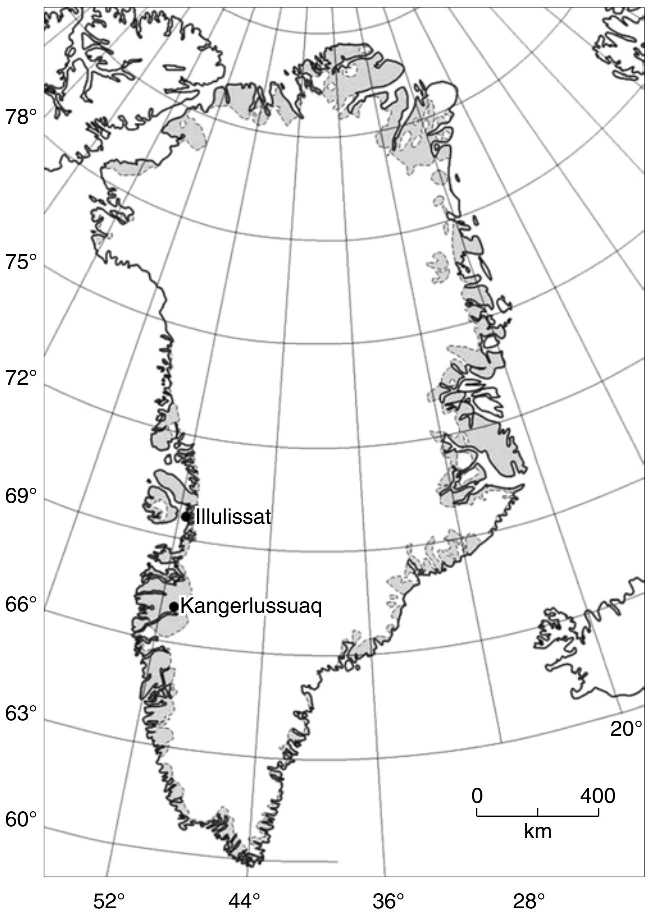

FIGURE 5. Location map showing sites of field campaigns. In 2003, measurements were conducted at the head of Jakobshavn Isfjord, ~60 km east of the town of Ilulissat, while measurements were conducted in 2004 in the ice-marginal region near Kangerlussuaq.

Carte de localisation des deux campagnes d'échantillonnage sur le terrain. En 2003, les mesures ont été faites au sommet du fjord de Jakobshavn, à 60 km à l'est de la ville de Ilulissat, tandis que les mesures de 2004 ont été faites dans la région glaciaire en marge de Kangerlussuaq.

All measurements of rock and vegetation reflectance were conducted on approximately horizontal surfaces with the optical sensor enclosed in a pistol grip mounted on a tripod and looking vertically downward through a 1 degree foreoptic. The nominal distance between the target surface and the foreoptic ranged from ~20 cm to ~80 cm, corresponding to a circular viewing area with a radius of 0.3-1.4 cm. The pistol grip was placed above the target as best as possible using a plumbing string. Further, where possible, only relatively large areas (~5 × 5 cm or greater) with uniform surface characteristics were selected for spectral measurements. Reflectance of the Lambertian white reference surface was measured regularly to ensure comparability between reflectance measurements collected at different times and under different solar illumination conditions. Nevertheless, it should be kept in mind that, as noted by Gates *et al.* (1966), "spectral reflectance measurements may be considered as qualitatively accurate as a function of frequency or wavelength. The shapes of the curves and character of the features are valid, but the photometric value of reflectance can not be considered as representative. The value of reflectance is correct for the particular measurement, but represents the nature of the sample used and the conditions under which the measurement was made. The reflectance will change for different angles of illumination, whether a point source or extended source is used, and other measurement conditions".

Similarly, Ager and Milton (1987) state that, "in this study, we focus on locations and intensities of absorption features of rocks and lichen. Differences in the amplitudes of reflectances are not reliable because of the variability between samples within the same rock or lichen type, and even between two measurements of the same sample when field of view or moisture content varies".

The dominant bedrock type in the study region is gneiss ranging in color from light grey to dark charcoal grey. Locally, there are segregations of pink orthoclase and grey to white quartz. It should be noted that often the surface is covered with different types of boulders of foreign origin, transported and deposited by the glacier. These various rock surfaces have clearly different spectral reflectance due to their different mineral compositions, as illustrated by the bare-rock spectra shown in Figure 6. Most outstanding is the spectrum of bright white quartz in veins, which has a high reflectance in the visible range of the spectrum.

Above the trimline separating the vegetated region from bare or lichen-covered rock surfaces, few of the boulders and exposed bedrock surfaces are free from lichen. Indeed, most of the rock substrates have a grey to black appearance as a result of being covered with various types of mostly black epilithic lichen (including *Pseudophebe minuscule* and *Pseudophebe pubescens*). Lichens of other colors are present (*e.g.* the yellow-green *Rhizocarpon geographicum*, orange *Xanthoria elegans*, and light grey *Physcia caesia*), but these cover a significantly smaller surface area. The effect of dark crustose lichen cover on the reflectance of rock surfaces is obvious from the panels in Figure 6. For all rock types, reflectance at visible wavelengths decreases to near zero, while in the near infrared, reflectance remains high. This effect is most pronounced for the quartz substrate, which has a high reflectance at small wavelengths. For the altered gneiss surface, the effect of lichen cover is rather muted as the reflectivity of the bare substrate is low at visible wavelengths.

The land surface above the trimline is composed of lichen-covered bedrock and boulders, mixed with typical tundra vegetation consisting of differently-colored mosses and fructicose lichen with a moss-like appearance such as the dark brown to black *Cetraria nigrican*, and the almost white *Stereocaulon rivulorum*. Where a sufficiently-thick layer of soil has been formed since the last deglaciation, low, shrub-like vegetation, mostly Arctic willow, is abundant. Typical vegetation spectra are shown in Figures 7 and 8.

Fructicose lichens generally grow on soil and have more of a moss-like appearance, with thalli up to several cm in height. Depending on the dominant color, reflectance spectra are similar to those of green vegetation (Fig. 7). For example, the white

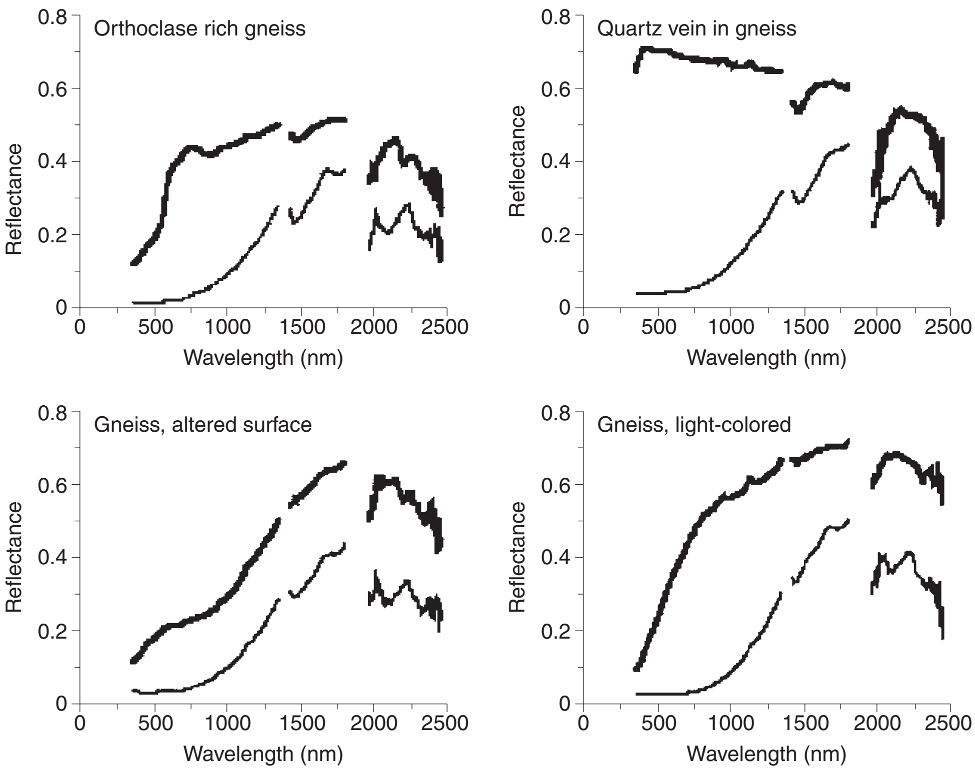

FIGURE 6. Field measurements of the effect of black crustose lichen on reflectance of various rock substrates. The heavy curves correspond to bare rock and the light curves to lichen on the same substrate. Gaps in the curves correspond to the atmospheric water vapor absorption bands, as explained in the text.

Mesures de terrain de l'effet du lichen noir crustacé sur la réflectance de différents substrats rocheux. Les courbes épaisses correspondent aux roches nues tandis que les courbes fines réfèrent aux mêmes substrats recouverts de lichens. Les parties manquantes correspondent aux bandes d'absorption de la vapeur d'eau atmosphérique tel qu'expliqué dans le texte.

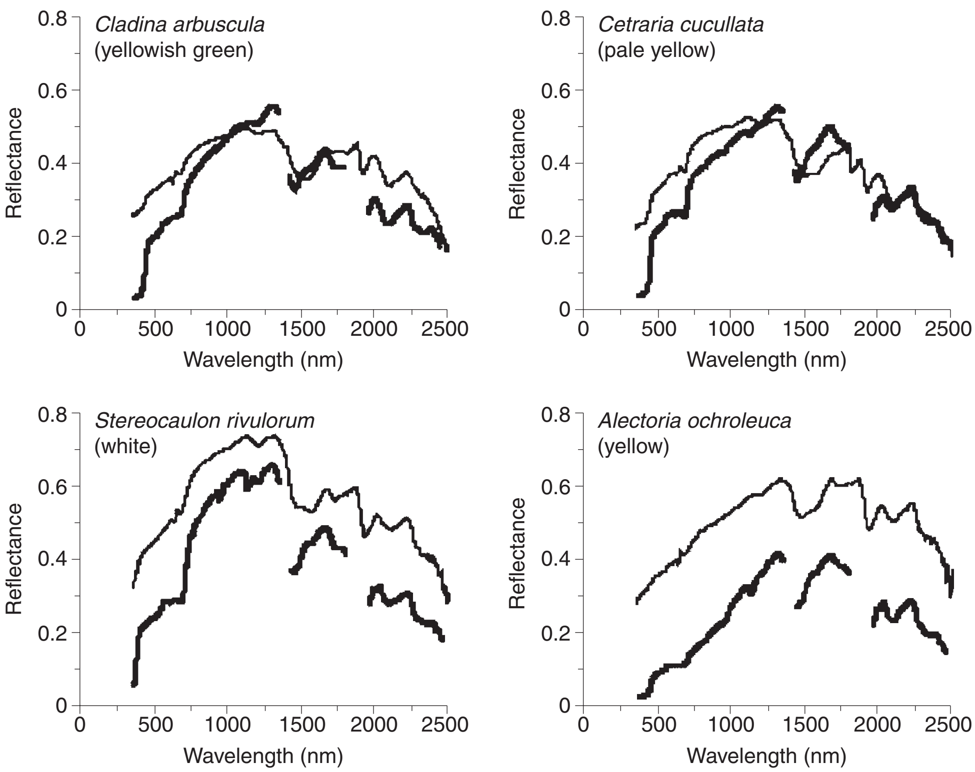

FIGURE 7. Reflectance spectra of various fructicose lichens as measured in the field (heavy curves) and in the laboratory (light curves) using the same samples.

Signatures spectrales de différents lichens arbustifs telles que mesurées sur le terrain (courbes épaisses) et en laboratoire (courbes fines) en utilisant les mêmes échantillons.

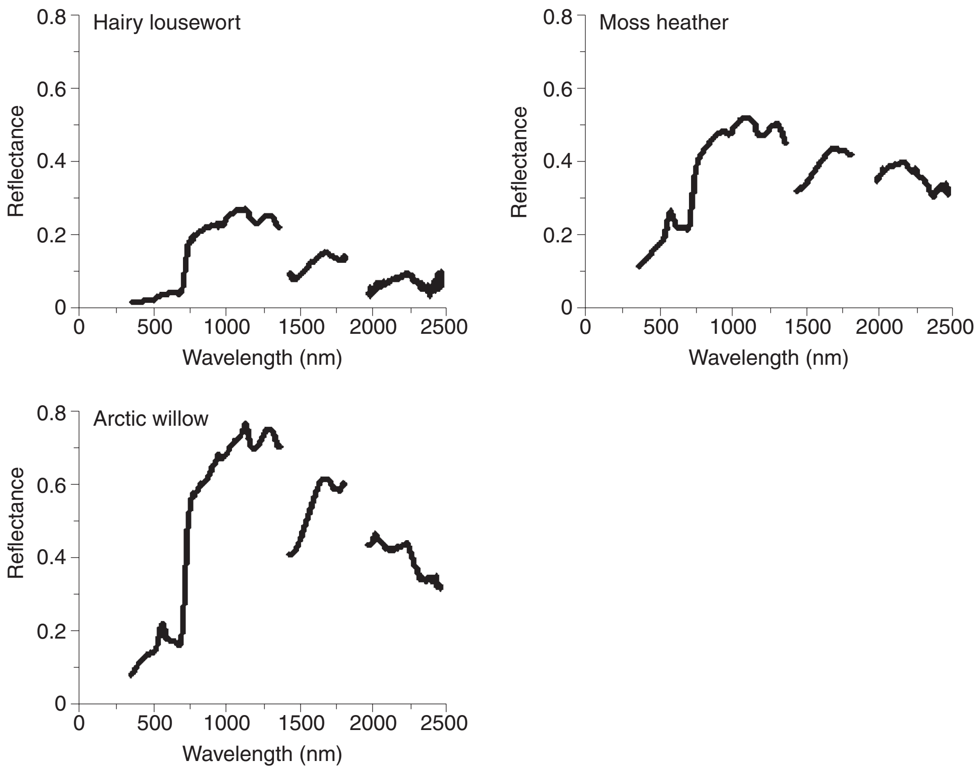

FIGURE 8. Reflectance spectra of typical west Greenland tundra vegetation, measured in the field.

Signatures spectrales de la végétation de toundra typique du Groenland occidental mesurées sur le terrain.

Stereocaulon rivulorum has a pronounced increase in reflectance at ~750 nm, similar to the chlorophyll edge in leafy vegetation, while the pale yellow *Cetraria cucullata* has a somewhat smaller edge around 750 nm. In the spectra for the darker yellow *Alectoria ochroleuca* and the brownish black *Bryoria chalybeiformis*, reflectance increases more gradually from near zero at small wavelengths to a maximum in the 1 250-1 750 nm range, with a minimum around 1 400 nm where the hydroxyl overtone increases absorption (Ager and Milton, 1987). Reflectance decreases for greater wavelengths and, in this part of the spectrum, there is little difference between the various lichen species. For comparison, also shown in this figure (continuous thin curves) are reflectance curves measured on the same samples under laboratory conditions using the set up described below. While there are some differences between the field and laboratory measurements, the general characteristics and shapes of corresponding spectral curves are very similar, lending credence to the field measurements that were not always conducted under optimal lighting conditions.

The spectrum of leafy plants shows the characteristics of a typical vegetation spectrum (Fig. 8). In the visible part of the spectrum (400-700 nm) reflectance is low as a result of high absorption of radiative energy by leaf pigments such as chlorophyll, carotene, lutein, and anthocyanine. Absorption bands of these pigments are broadened and intensified because multiple scattering of light within a leaf increases the length of path traveled (Gates, 1980: p. 221). A small peak in reflectivity at ~550 nm accounts for the green color of plants and is caused by chlorophyll content of the leaves, as in the photosynthesis process chlorophyll absorbs the incident blue and red wavelengths, while green wavelengths are partially reflected (Sabin, 1997: p. 57). Reflectance in the near infrared (700-1 300 nm) is high, because the longer wavelengths penetrate into deeper layers, where they are strongly scattered and reflected by the boundaries between cell walls and air spaces (Sabin, 1997). The absorption bands of liquid water start affecting the reflectance spectrum in the infrared region (>1 300 nm) and at higher wavelengths the spectral reflectance of a vascular leaf is the same as that of an equivalent thickness of water (Knipling, 1970; Raines and Canney, 1980). As a result of the water absorption, the reflectance of vascular leaves decreases rapidly in the infrared region, with nearly complete absorption occurring at wavelengths greater than 2 000 nm (Gates, 1980: p. 223).

Perhaps the most striking feature of the vegetation reflectance spectra is the abrupt increase of reflectance at 700 nm, sometimes referred to as the chlorophyll edge. The position of this edge depends on the nature of the pigments in the plant leaves. In green leaves, this edge is largely determined by chlorophyll and is located at 700 nm. For plants that lack chlorophyll, or where other colors are more dominant, the edge may be displayed towards smaller wavelengths (Gates, 1980).

LABORATORY MEASUREMENTS OF LICHEN REFLECTANCE

During the 2003 field season, samples of rocks partially covered with lichens, and samples of fructicose lichen were collected for lichen identification and for reflectance measurements in a controlled laboratory setting. The same type of spectroradiometer was used for these measurements, with illumination provided by a Halogen Lowell Pro lamp. Samples were placed on a small table and illuminated at an angle of approximately 45°. The optical sensor was enclosed in a pistol grip mounted on a tripod placed opposite of the light source, and aimed at ~45° angle towards the sample. Again, for each measurement, ten spectra were collected automatically in short order, and these were averaged to obtain the reflectance curves shown here.

Results for the fructicose lichen are shown in Figure 7, discussed above. As noted, the laboratory and field measurements yield very comparable reflectance spectra. Differences exist, but these are most likely associated with imaging the samples. Fructicose lichens have thalli up to a few cm in height, with a moss-like, or "mini shrub" appearance. Consequently, samples are very irregular, and reflectance may be expected to depend on what part of the lichen is measured. Moreover, these samples were not measured in the laboratory until after the 2004 field season when we had access to our own spectroradiometer. For some of the reflectance curves, absolute values are significantly different (*e.g. Alectoria ochroleuca* and *Bryoria chalybeiformis*), but these differences may well be associated with the different lighting conditions and other factors (Gates *et al.,* 1966; Ager and Milton, 1987). Thus, it appears that the reflectance spectra are fairly robust and not overly sensitive to the conditions under which these spectra are collected.

Common bedrock type in west Greenland is granitic to granodioritic gneiss, mostly with a greyish appearance, and the darker amphibolite. How lichen cover affects these substrates is illustrated in Figures 9 and 10. The heavy curves in these graphs correspond to the bare rock samples, and the light curves to lichen on the same samples. Unless indicated, lichens measured were crustose. Dark-colored lichens reduce the reflectance in the visible part of the spectrum but have little effect on the reflectance curve at higher wavelengths. The major absorption band at ~1 900 nm observed in granitic gneiss is not masked by the lichens, suggesting that both the

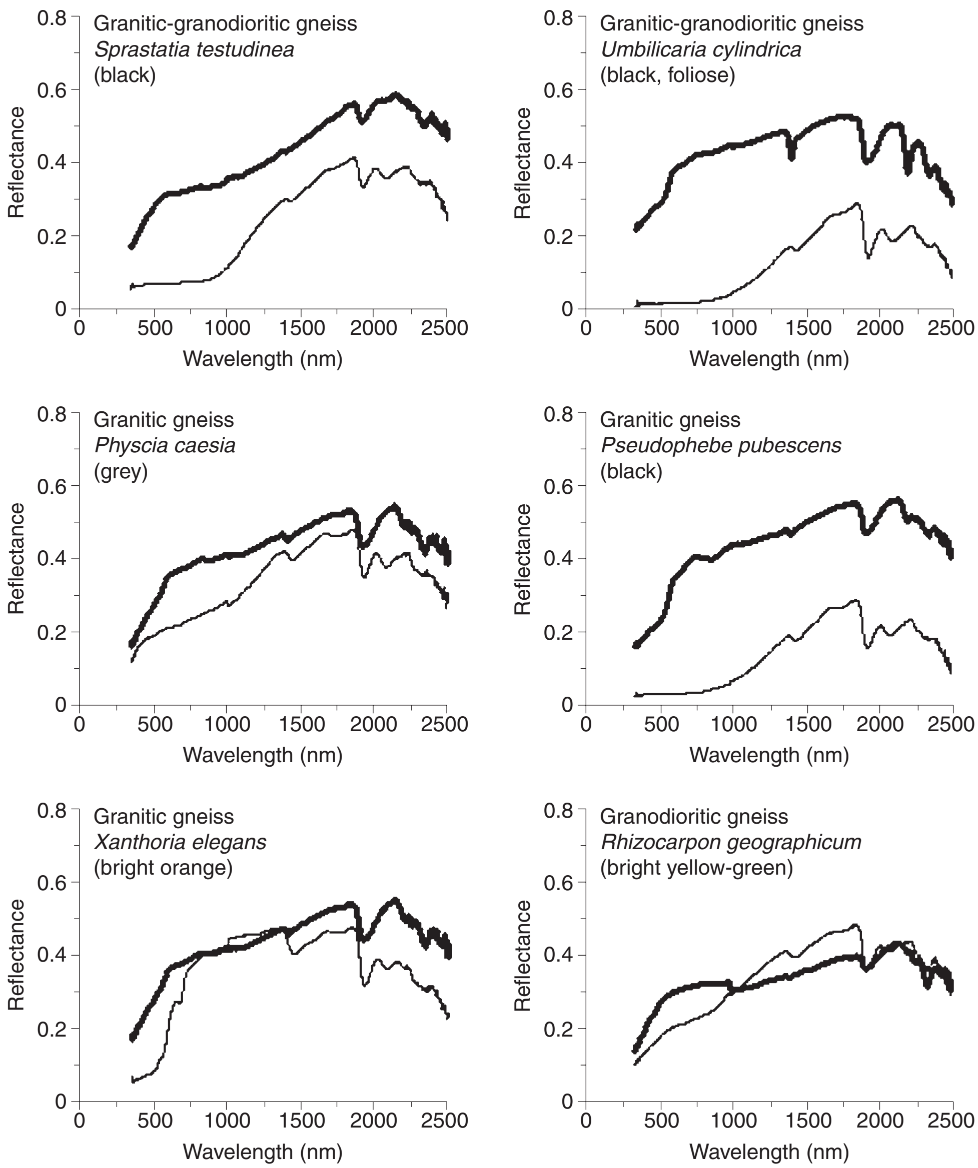

FIGURE 9. Effect of crustose (unless otherwise noted) lichens on various rock substrates as measured in the laboratory using samples collected in west Greenland. Heavy curves refer to bare rock and light curves to lichen on the same rock sample.

Effet des lichens crustacés (sauf indication contraire) sur différents substrats rocheux tel que mesuré en laboratoire sur les échantillons prélevés sur le terrain au Groenland occidental. Les courbes épaisses correspondent aux roches nues tandis que les courbes fines réfèrent aux mêmes substrats rocheux recouverts de lichens.

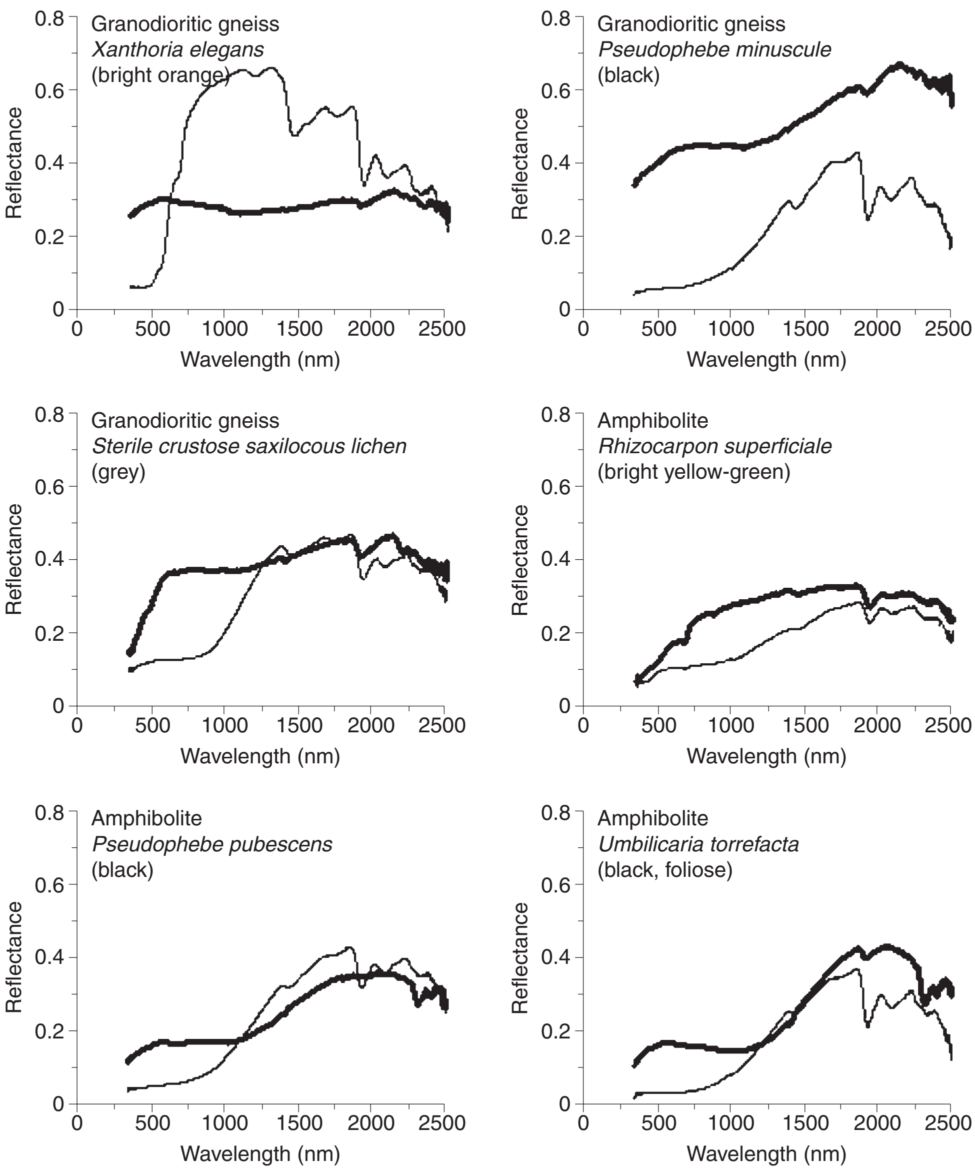

FIGURE 10. Effect of crustose (unless otherwise noted) lichens on various rock substrates as measured in the laboratory using samples collected in west Greenland. Heavy curves refer to bare rock and light curves to lichen on the same rock sample.

Effet des lichens crustacés (sauf indication contraire) sur différents substrats rocheux tel que mesuré en laboratoire sur les échantillons prélevés sur le terrain au Groenland occidental. Les courbes épaisses correspondent aux roches nues tandis que les courbes fines réfèrent aux mêmes substrats rocheux recouverts de lichens.

gneiss and the lichens have strong absorption bands at this wavelength. Indeed, this absorption band is apparent also in the spectra of lichen on granodioritic gneiss and amphibolite, both of which show only a small absorption band at this wavelength. The only lichen that has a remarkably different effect on the reflectance is the bright orange *Xanthoria elegans*, which has a high reflectance at smaller wavelengths, associated with its bright-colored pigments.

Spectra for the darker lichen are similar to those reported by Bechtel *et al.* (2002), but the spectrum for *Rhizocarpon geographicum* does not exhibit the rapid increase in reflectance around 500 nm as found by Bechtel *et al.* (2002) and shown in Figure 3. The reason why our measurements lack this rise is not clear but it may be noted that the other bright lichen species, *Xanthoria elegans*, possesses a reflectance spectrum similar to that of *Rhizocarpon geographicum* obtained by Bechtel *et al.* (2002).

DISCUSSION

Lichen come in a wide variety of shapes, sizes, and colors, ranging from small individual spots adhering to rock substrates such as the yellow-green *Rizocarpon geographicum*, to more ornate fructicose lichen that grow were soil has developed. It is not surprising, therefore, that there is no single spectral feature characterizing lichens and that can be used to identify lichens on multispectral imagery. For some of the lichen varieties studied here, reflectance is not much different from that of green vegetation, with a rapid increase in reflectivity around 700 nm, corresponding to the chlorophyll edge in green leaves. Nevertheless, the unique spectral properties of the most abundant epilithic lichen near the trimline in west Greenland allow for mapping of the trimline using multispectral satellite imagery, as demonstrated by Csatho *et al.* (this issue).

Dark grey to black crustose and foliose lichen cover most of the rocks and outcrops near the trimline, where vegetation is otherwise mostly absent due to lack of soil. As shown in Figure 6, these lichen species have near zero reflectance in the visible part of the spectrum, and reflectance increases gradually to a maximum in the 1 250-1 750 nm range, decreasing again for greater wavelengths. This spectral signature is markedly different from other surface types and landcovers in the region as classified on multispectral Landsat imagery (Csatho *et al.*, this issue). Thus, the spectral measurements presented in this study support the conclusion by Csatho *et al.* (this issue) that glacier trimlines can be mapped reliably over different rock substrates using images that cover the broad spectral range up to 2 400 nm, because of the distinct reflectance properties of the most abundant epilithic lichen species.

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