The Spectral Albedo/Reflectance of Littered Forest Snow

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ABSTRACT:

Despite the importance of litter on forest floor albedo and brightness, previous studies have not documented forest floor albedo or litter cover in any detail. Our objective was to describe the seasonal influence of litter on spectral albedos and nadir reflectances of a forest snowpack in a mixed-hardwood forest stand in the Sleepers River Research Watershed (SRRW) in Danville, Vermont (37°39′ N, 119°2′ W). Experimental simulations in a nearby open area at the Snow Research Station of the SRRW duplicated the spectral trend observed in the forest. Plots of spectral reflectance and albedo measurements in the visible/near-infrared (350–1000 nm at 3-nm resolution) and shortwave infrared (900–2500 nm at 10- to 11-nm resolution) transitioned from a gently curved shape through the visible range with a mild maximum in visible green, near 575 nm (for fine-grained, lightly littered snow), to one having a peak in the red/NIR as the snowmelt season progressed. Since increased grain size and shallow snow depth also lower the visible albedo, the addition of litter will cause the expected decrease in visible albedo to occur earlier in the snowmelt season, at deeper snow depths, and will tend to shift the peak to the 760-nm range as the melt season progresses.

Keywords: Spectral albedo, spectral reflectance, littered snow, forest snowpack

INTRODUCTION

Forest snow albedo is important in determining snowmelt rates and influencing seasonal climate in forested regions, particularly for less dense forests that permit direct shortwave radiation through canopy gaps. The effective albedo of a snow-covered forest floor depends on snow properties, especially snow grain size, but also depends on forest litter lying on and within the snowpack. Forest debris has a lower albedo than snow and heats more readily in response to absorption of solar radiation. The debris then heats the snow through conduction and longwave radiation, and this increases snowmelt. Thick layers of debris can insulate the snow and reduce melt rates (Adhikary et al. 1997); however, forest litter on and within snow is typically thin and discontinuous. Davis et al. (1997) showed that solar radiation dominates the energy exchange near the forest floor in boreal conifer canopies of <60% cover. At higher canopy densities, longwave radiation becomes important, in which case net radiation at the snow surface becomes increasingly insensitive to litter cover. Albedos from above a forest canopy can vary dramatically when a snow cover is present beneath the canopy for tree coverage <70% (Ni and Woodcock 1997); therefore, the reduced effective albedo of littered snow can affect inversion of snow-covered area information from remotely sensed scenes. Despite the importance of litter on forest floor albedo, ablation rates (Hardy et al. 1998), and inversion of snowcover information, previous studies have not documented littered snow albedo in any detail.

Our objective was to describe the change in spectral albedo/nadir reflectance of a mixed-forest snowpack over a melt season as litter accumulated on and within the snowpack. We duplicated the effect of seasonal litter accumulation on snowpack spectral albedo in an experiment conducted in an open field. Spectra of litter materials were measured to help explain the littered snow spectra.

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Background

A forest snowpack in the melt season is composed of ice, air, and unless there is ponding, usually no more than 5% liquid water. It is contaminated by forest debris, dust, and aerosols, and underlain by a forest floor. The arrangement of these constituents, along with illumination geometry, determines the forest floor albedo. Snow grain size is the property most important to snow albedo in the near-infrared wavelengths (Warren 1982) where ice is moderately absorptive. Bohren and Beschta (1979) showed that albedo did not change when a snowpack was physically compacted, thus it is believed to be the size and number of snow grains that act as scatterers that reduce the near-infrared albedo. The refractive index between water and ice is small, and the decreased albedo associated with liquid water can be thought of as an effective increase in grain size (Warren 1982). Furthermore, as water refreezes in the snowpack, the albedo remains reduced (Berger 1979).

In the visible wavelengths, pure ice is weakly absorptive (Grenfell and Perovich 1981), and snow albedo is relatively insensitive to grain size, allowing impurities in snow to become important determiners of snow albedo (Warren 1982). Warren and Wiscombe (1980) proposed that the presence of small concentrations of carbon soot aerosol, a gray absorber in that its imaginary refractive index is nearly constant across the visible spectrum, could lower snow albedo. Moreover, they speculated that large variations in reported albedos across polar and mid-latitude snowfields might be explained by variations in absorbing particle concentrations. Conway et al. (1996) treated snow surfaces with soot and ash, finding that submicron-sized soot particles flushed through the snowpack with meltwater, limiting the amount of albedo reduction after a few days of application, while volcanic ash particles larger than 5 microns remained on the surface and continued to reduce albedo. They theorized that the thin water films present in partially saturated melting snow could not transport the larger particles. Dunne and Leopold (1978) state that only when dust and vegetation debris become concentrated on the surface of the pack does snow albedo fall to the 0.50–0.60 range. Barry et al. (1990), in a study of a balsam fir forest in the Lac Laflamme basin north of Quebec City, Quebec, Canada, commented that forest dust and debris reduced forest floor albedos to 0.7 to 0.3, for new and aged snow, respectively. The U.S. Army Corps of Engineers (1956) suggest a 15- to 20-day-old snow surface in the forest would approach a mean daily albedo near 0.40 during the melt season. The effect of shallow snow depth is greatest in the visible wavelengths, causing a flattening of the spectral albedo plot (Marshall and Warren, 1987).

Site Description

The study sites consist of an opening in the forest at the Snow Research Station of the Sleepers River Research Watershed near Danville, Vermont (37°39′ N, 119°2′ W), and a mixed forest plot adjacent to the opening. The mixed forest is a balsam fir and white birch forest at 550-m elevation, which lies between the spruce–fir forest (*Picea rubens–Abies balsamea*) of the colder regions of Vermont and the northern hardwood forest (*Acer saccharum–Fagus grandifolia–Betula allegheniensis*) that covers much of the rest of the state (Thompson and Sorenson 2000). Balsam fir (*Abies balsamea*) and white birch (*Betula papyrifera*) are the dominant species at 52.3% and 42.8%, respectively. The minority species are striped maple (*Acer pensylvanicum),* mountain maple (*Acer spicatum*), sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), yellow birch (*Betula allegheniensis*), red spruce (*Picea rubra*), black cherry (*Prunus serotina*), and beaked hazelnut (*Corylus conuta*). The total DBH (diameter at breast height) for trees taller than 2 m was 237 m ha^{-1}. Excluding all dead standing the DBH was 225.9 m ha^{-1}. The shrub–sapling layer species are 57% mountain maple (*Acer spicatum*), 30% striped maple (*Acer pensylvanicum*), 6% balsam fir (*Abies balsamea*), and the remaining fraction sugar maple (*Acer saccharum*) and American beech (*Fagus grandifolia*).

METHODS AND RESULTS

Seasonal Spectral Albedos in the Mixed Forest and in the Open

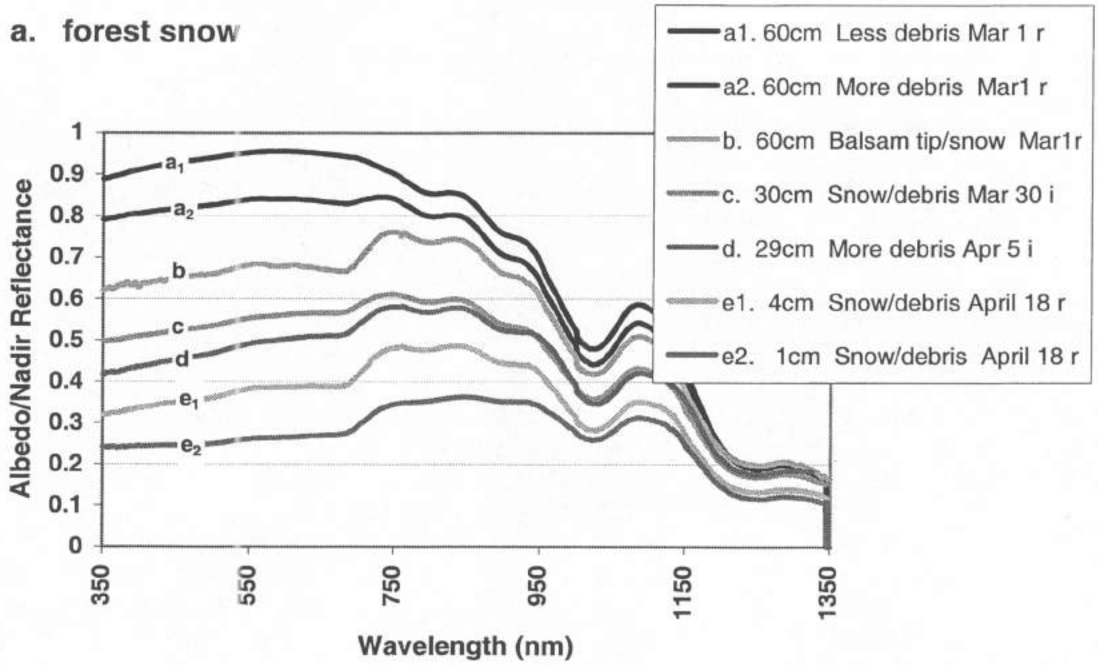
Spectra of the snow, and sky in the visible and near-infrared (350–1000 nm at 3-nm resolution) and shortwave infrared (900–2500 nm at 10- to 11-nm resolution) wavelengths were measured with an Analytical Spectral Devices FieldSpec-FR in the open, and in the adjacent mixed-forest plot. The instrument measures shortwave radiation in the visible and near-infrared range with a silicon photodiode and in the near-infrared (NIR) with two scanning spectrometers consisting of concave holographic gratings and thermoelectrically cooled Indium–Gallium–Arsenide detectors (Analytical Spectral Devices, Inc. 1995).

Individual spectral measurements consisted of averages of 100 samples, and the spectral albedos were computed from one or more series of sky and snow measurements during which sky conditions were demonstrably constant before and after the snow spectra were collected. On overcast days with canopy shading not visually apparent on the snow surface, we measured spectral irradiances of snow and sky with a remote cosine receptor over a 180° field of view (FOV). When the target of interest required a limited field of view, such as patches of thin snow, we collected spectral radiances at nadir over 21° FOV. Radiances were collected with the bare fiber optics cable in a leveled pistol grip, pointing perpendicularly to a level snow surface, or a leveled white spectralon reference target representing sky illumination. We found that our forest reflectance measurements taken under diffuse sky conditions over 21° FOV closely approximated the spectral curve shape of forest albedos measured with the cosine receptor (180° FOV), and have taken the liberty of plotting them together on Figure 1. The data collected from late winter until the end of ablation describe a seasonal trend in the shape of the spectral curve as litter accumulates and the snow ages (Fig. 1).

Spectra measured over the spring in the forest transitioned from a gently curved shape with a mild maximum near 575 nm in the visible green range, to one that peaked in the red/NIR near the 760-nm wavelength (Fig. 1). The initial snowpack of March 1 was a fine-grained (0.025–0.05 mm diameter), lightly littered snow 60 cm deep. Spectral curve b in Fig. 1 is the same snow but with the fiber optics cable pointed at a balsam fir tip (Fig. 2b). The decrease in visible relative to the red/NIR in curve b, due to the balsam fir tip, mimics the seasonal change seen in the curves of later dates with more surface litter. Spectral curves c and d (Fig. 1) were measured at the same location in the forest, each at approximately 30-cm snowdepth, but with an increase in litter over a seven-day interval (Fig. 2c–d). Late-season spectra of littered and optically thin snow 1 to 4 cm deep (curves e_1 and e_2) continued to show red/NIR maxima (Fig. 1). The surface litter cover increased from <1% to approximately 30% from March 1 to April 18. A pronounced spectral peak in the red/NIR did not occur for optically thin snow without litter on the surface (Fig. 1b).

Litter Absorptance Spectra

Litter samples were obtained by collecting snow in large bags sewn from polyester filter fabric with a nominal particle retention rating of 50 microns. Warm tap water was poured over the bags to melt the snow and the litter was laid out to air-dry overnight. By the next day the litter was still moist, but dry enough to be strewn without clumping together. The litter (Fig. 3) was separated into fine materials consisting predominantly of 1) brown and green balsam fir needles, also resin balls and fine twigs, 2) medium-sized litter that was predominantly conifer tips (needled twigs), and 3) a larger fraction that was predominantly deciduous bark, leaves, and large twigs. Spectra of optically thick samples of the litter were measured using a bare fiber optics cable (21° FOV) under clear sky illumination (April 1, 2000). The absorptance spectra (absorptance = 1- reflectance) show that though the litters absorbed highly across the visible spectra compared to snow, litter absorptance decreased in the red/NIR, and at wavelengths longer than 1000 nm, absorptance was less than that of snow (Fig. 3). The large litter fraction included light-toned birch bark, thus was the least absorptive in the visible range.



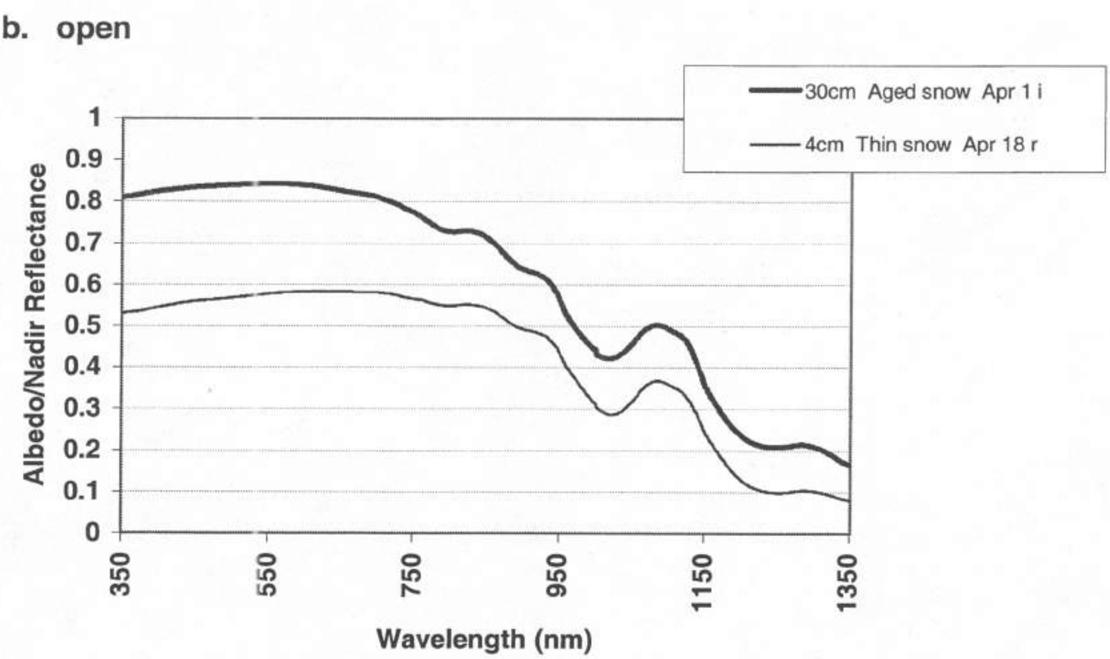


Figure 1. Seasonal spectral albedos and nadir reflectances in a) mixed-forest and b) open site. Spectra dates followed by i's are albedos measured with a cosine receptor foreoptic attachment, and r's indicate the spectra are reflectances measured at nadir over a 21° FOV with the bare fiber optics cable. All measurements were taken under diffuse sky conditions except for April 1.

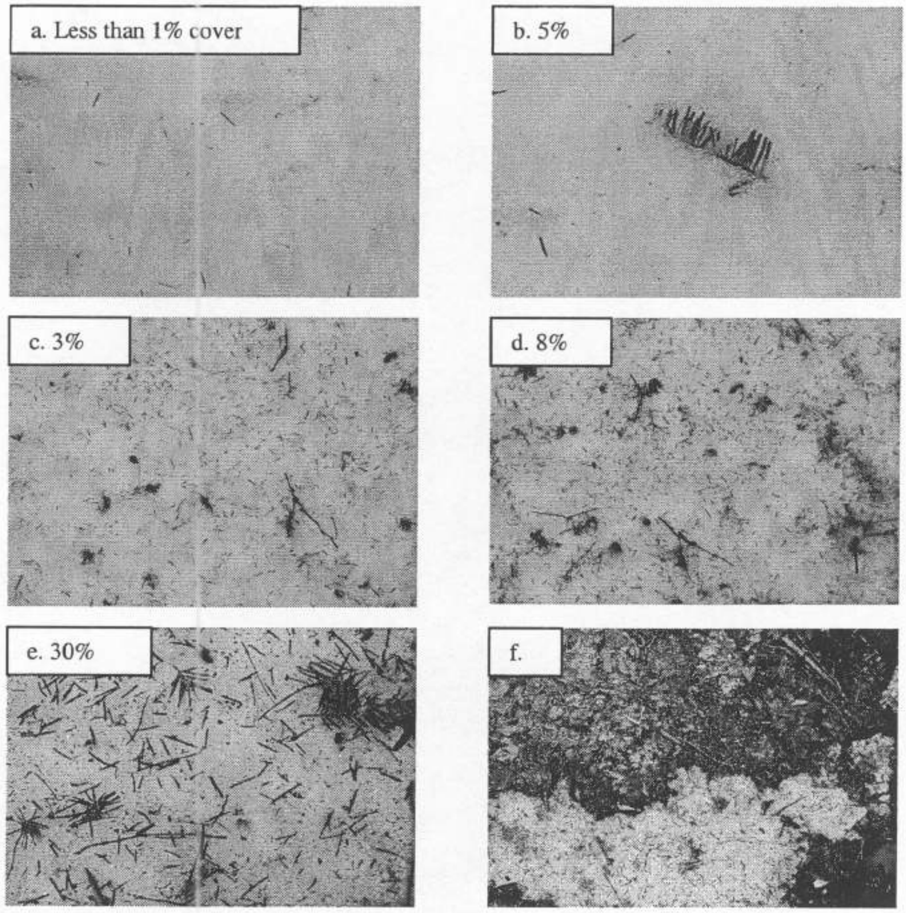


Figure 2. Photographs of surface snow corresponding to spectral albedos and nadir reflectances (Fig. 1a). a) March 1, fine-grained snow (<0.05 mm) with sparse litter. b) March 1, the fiber optics FOV included this balsam fir tip. c) March 30 coarse-grained snow (>1 mm) with litter. d) April 5, the same coarse-grained snow with increased litter. e) April 18, close-up of patch of thin snow at end of melt season. f) The same patch from a distance, showing the exposed forest floor surrounding the patch.

Spectra of Artificially Littered Snow

Spectra were collected using a 180° remote cosine foreoptic attachment, as litter was introduced to the aged snow surface in the open (Fig. 4) on April 1, 2000, under clear sky conditions. This experiment allowed us to begin with an aged snow surface, relatively free of litter, and had the advantage of simplified illumination compared to constantly changing overcast conditions. The cosine foreoptic attachment was extended approximately six feet from a tripod and 70 cm above the snow surface. Integrated albedos of snow without added litter, measured with Eppley pyranometers (350 to 2850 nm) at a spot nearby in the same open area, provided a separate measure of the untreated snow albedo over time, due primarily to the change in sun zenith angle during the day (Fig. 5). Integrated spectrometer measurements of untreated snow obtained at the beginning and near the end of our measurement series agreed well with the pyranometer measurements. The snowpack depth decreased 3 cm during the experiment, ending at 29 cm in depth (12.3-cm water equivalent). The snowpack was composed of clustered rounded grains (>1 mm) and water was present in the snow matrix. Using the two-stream approximation of Choudhury and Chang (1979), imaginary parts of the index of refraction from Perovich and

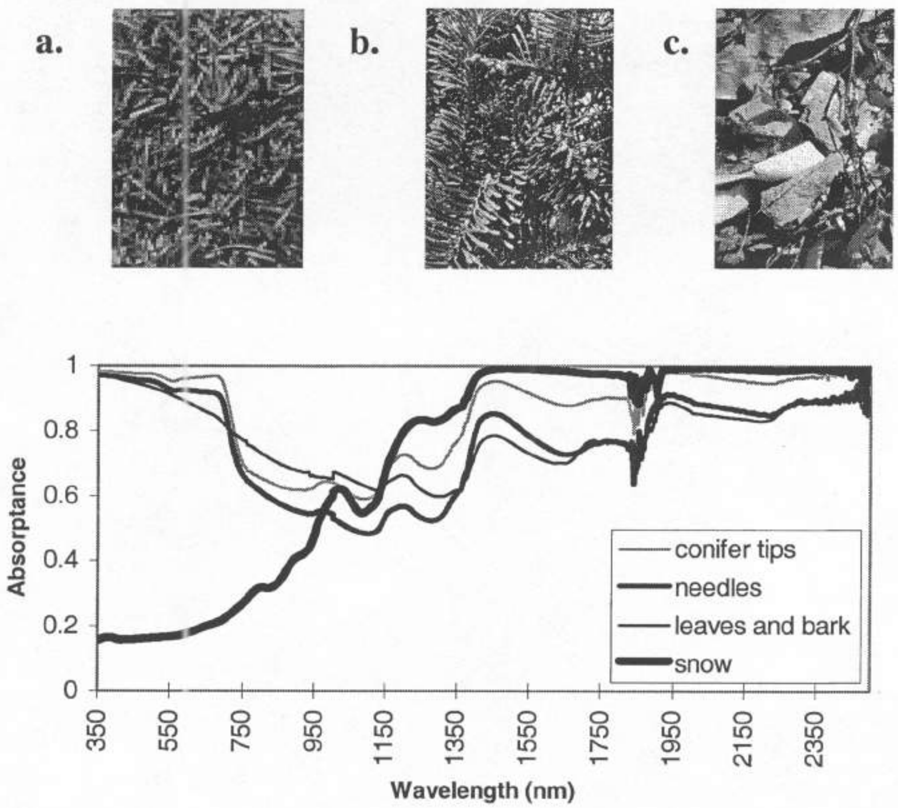


Figure 3. Absorptance spectra of three litter samples collected in the mixed-forest site. Photographs are a.) fine twigs and needles, b.) conifer tips, and c.) deciduous leaves and bark.

Govoni (1991) and Grenfell and Perovich (1981), and our measurements of the spectral reflectance of the ground beneath the snow, we show that the ground had very limited influence on the measurements (Fig. 6).

There was a spectral shift in albedo from a maximum in the visible to a maximum in the red/NIR wavelengths as the litter cover was increased from 0% to approximately 20%, between spectra 1 and 8 (Fig. 4). Integrated visible wavelength spectra (400 to 700 nm) serve as indicators of contamination, and decreased as litter was introduced (Fig. 5). The near-infrared 1040-nm wavelength serves as an indicator of grain growth (Nolin and Dozier 1993), and though it varied through the day because of incidence angle, it showed no obvious indication of grain growth.

Measurements resumed after 2 p.m. as integrated albedos began a mild upward climb because of sun incidence angle (Fig. 5). At this time, the litter already on the surface had melted snow bordering the litter particles, imparting a surface texture. The full range of litter additions compared to clean snow, shown on the right side of Figure 4, occurred over a short time period when the infrared wavelengths were stable. Bark dust was cast on, producing spectral curve 9 (Fig. 4b). The bark dust was obtained by scraping the outer surface of trees and crushing pieces of bark. Spectral curve 9 came closest to matching littered forest snow spectra collected on March 30, showing a pronounced shift in peak toward the NIR as visible wavelength reflectance decreased. Finally, we moved to a new site of untreated snow and repeated the first few steps of the experiment (curves 10 and 11). The afternoon untreated snow albedo (curves 10 and 11) was much like that measured in the morning, having a mild maximum in the visible green range. Finally, balsam needles were sprinkled onto the new snow surface, resulting in diminished visible spectra (curve 12).

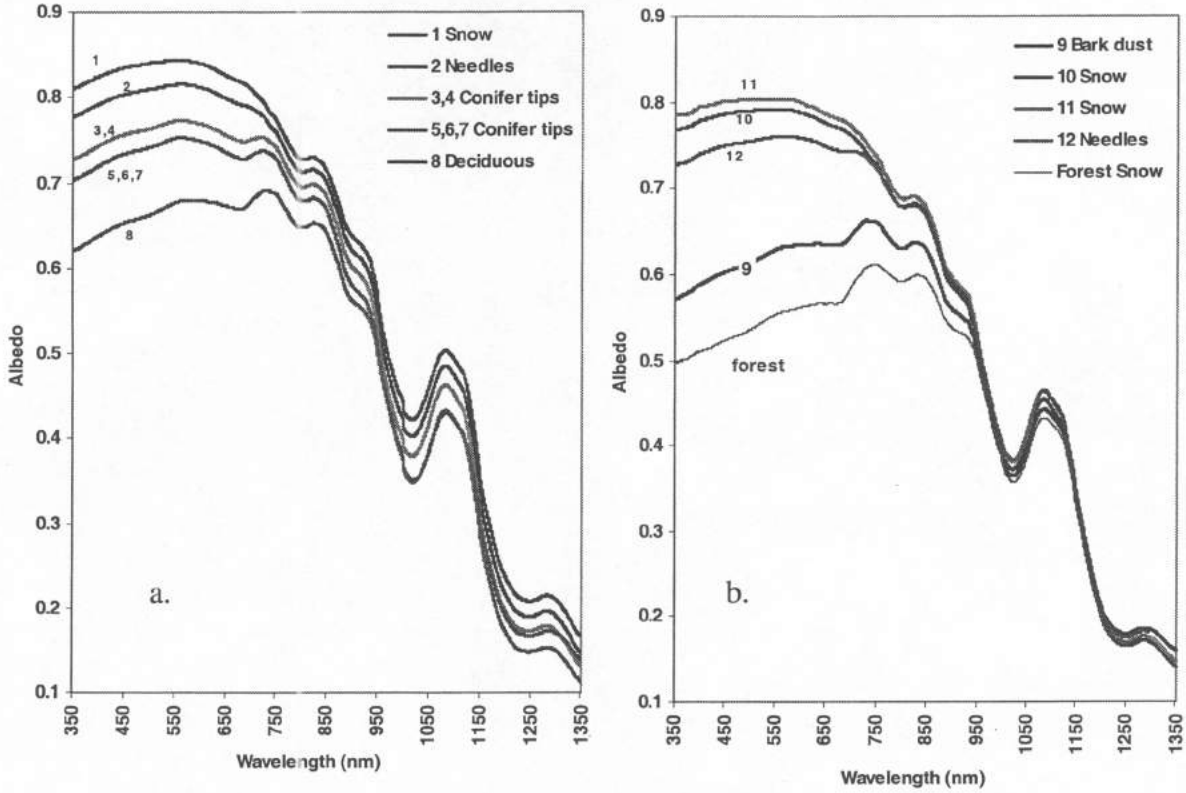


Figure 4 . Spectral albedos measured in the open as litter was cast onto an aged snow surface. a) Before 1 p.m. b) After 2 p.m. The legends indicate what was cumulatively added to the snow surface for specific spectra and times given in Figure 5.

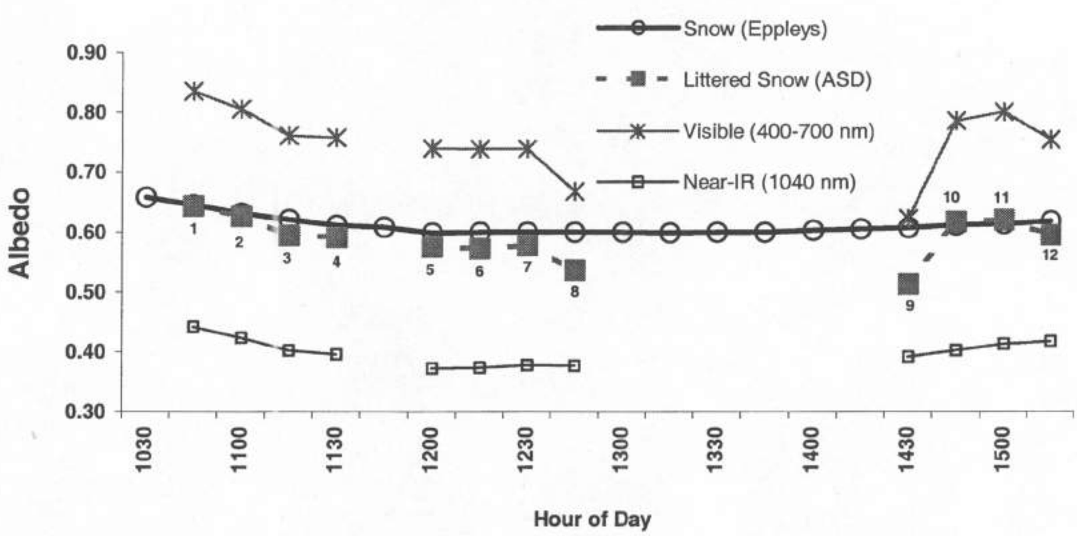


Figure 5. Albedos measured in the open as litter was cast onto an aged snow surface. The visible (400–700 nm) and an infrared wavelength highly sensitive to grain size (1040 nm) were extracted from the spectral data and plotted for comparison with the integrated measurement (Eppleys). Numbers 1–12 correspond to the materials listed in the legend of Figure 4.

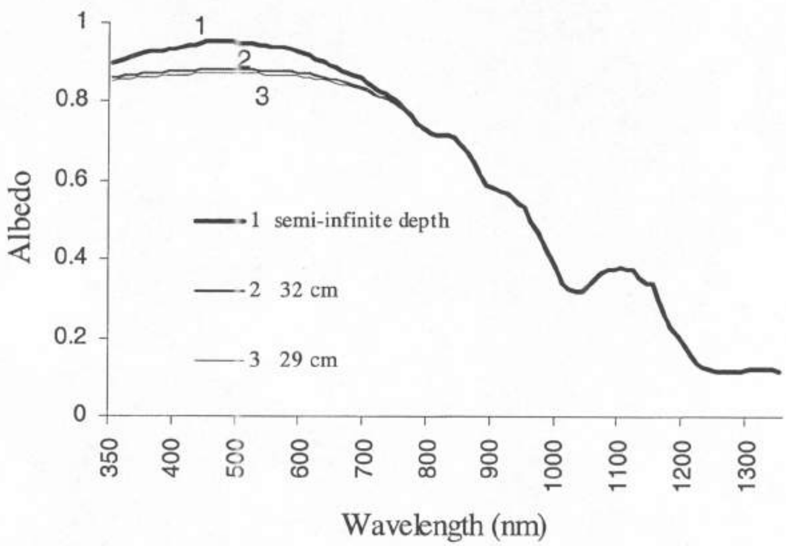


Figure 6. A two-stream approximation of snow albedo showing the insignificant change in effect of the ground surface albedo on the surface albedo for starting and ending snow depths (32 and 29 cm).

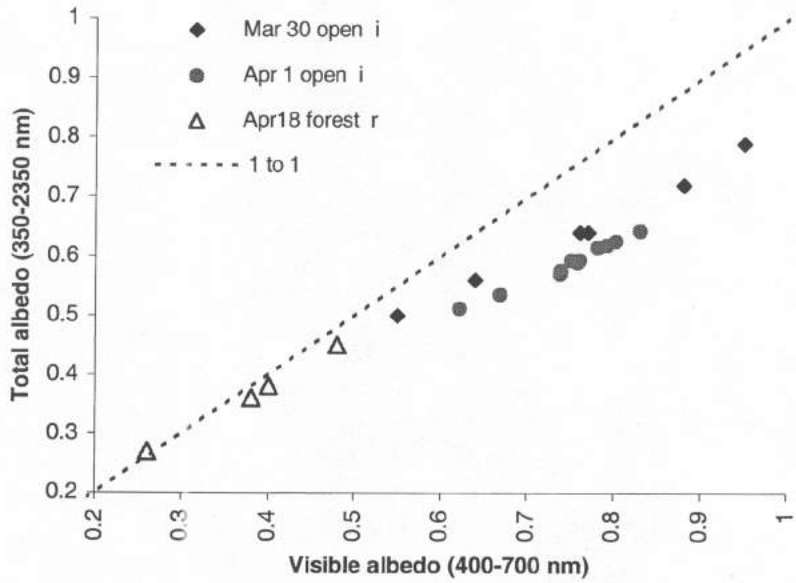


Figure 7. Total and visible albedo comparisons for days with multiple spectral albedo measurements of varying amounts of surface litter. Legend dates followed by i's are irradiance spectra measured with a cosine receptor foreoptic attachment, and r's indicate the spectra are radiances measured over a 21° FOV with the bare fiber optics cable. All measurements were taken under diffuse sky conditions except for April 1.

DISCUSSION AND CONCLUSIONS

The plot of spectra albedos/nadir reflectances measured over the spring in the mixed-forest transitioned from a gently shaped curve with a maximum near 575 nm in the visible range, to one that had shifted to a peak in the red/NIR 760-nm wavelength as litter accumulated on the surface and grain sizes increased. Artificially littered snow in the open exhibited a similar shift in maximum albedo as litter was added to the surface. This shift occurred because the litter was relatively less reflective in the shorter wavelength visible range than it was in the 750- to 950-nm range, not because of an increase in red/NIR reflectance. Since increased grain size and shallow snow depth also lower the visible albedo, adding litter will cause the expected decrease in visible albedo to occur earlier in the snowmelt season, at deeper snow depths, and will tend to shift the peak to the 760-nm range as the melt season progresses.

Our experimental approach in the open could not include litter at depth in the snowpack as occurs in the forest, and because light penetrates into the snowpack there would also be absorption by litter at shallow depths, which would decrease the surface albedo, additionally. The experiment in the open did not account for fine dust or aerosols that caused the snow in the forest to be visibly dirtier than in the open. This contamination reduces the visible wavelength albedo additionally and the spectra of these materials were not measured here. These small particles may be what caused the particularly low nadir reflectances in the shorter visible wavelengths in the forest snowpack. Alternatively, our experiment in the open showed the same pattern after allowing litter to melt into the surface, raising the question of litter causing a melt-textured surface effect on albedo (Fig. 5).

On days when we measured albedos and nadir reflectances of snow at a number of locations with varying amounts of surface litter, there was an approximately linear relationship between visible and total albedo (Fig. 7). This infers that for near-constant grain sizes over a day, or over several days, photography in visible wavelengths can be used to extend point measurements of albedo in a forest to the stand scale, if the distribution of surface litter is known from a photographic survey, and the litter spectral content does not change significantly from location to location.

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