

Interplay between canopy structure and topography and its impacts on seasonal variations in surface reflectance in the boreal region of Alaska – implication for surface radiation budget

Bibhash Nath^{a*}, Wenge Ni-Meister^a

^a Department of Geography and Environmental Science, Hunter College of the City University of New York, NY 10021, USA

*Corresponding author: Bibhash Nath, e-mail: bibhash12@gmail.com and bibhash.nath86@myhunter.cuny.edu

Abstract

Forests are critical in regulating the world's climate and they maintain overall Earth's energy balance. The variability in forest canopy structure, topography and underneath vegetation background condition creates uncertainty in the estimation and modelling of Earth's surface radiation particularly for boreal regions in high latitude. We studied seasonal variation in surface reflectance with respect to land cover classes, canopy structures, and topography in a boreal region of Alaska by fusing together Landsat 8 surface reflectance and LiDAR-derived canopy matrices. Our study shows that canopy structure and topography interplay and influence surface reflectance in a complex way particularly during the snow season. Topographic aspect and elevation control vegetation growth, type and structure. The southern slope is featured with more deciduous and taller trees having greater rugosity than the northern slope. Higher elevation is associated with taller trees for both vegetation types, particularly in the southern slope. In general, surface reflectance shows similar relationships with canopy cover, height and rugosity, mainly due to close relationships between these parameters. Surface reflectance decreases with canopy cover, tree height, and rugosity especially for evergreen forest. Deciduous forest shows larger variability of surface reflectance, particularly in March, mainly due to the mixing effect of snow and vegetation. The relationship between vegetation structure and surface reflectance is greatly impacted by topography. The negative relationship between elevation and surface reflectance may be due to taller and denser vegetation distribution in higher elevation. Surface reflectance in the southern slope is slightly larger than the northern slope for both deciduous and evergreen forest. The shadow effect from topography and tree crowns on surface reflectance play a different role for deciduous and evergreen forests. For deciduous forest, topographic shadow effect on surface reflectance is stronger than from tree shadowing in all seasons. For evergreen forest, shadow effects from

topography and tree crowns on surface reflectance are both equally dominant, however tree shadow effect is more significant in March than in May and August. The generalized additive models (GAM) based on non-linear relationships between response (surface reflectance) and predictor (canopy structures and topography) variables confirms such observations. Our study not only provides accurate quantification of surface radiation budget but also helps in parametrization of climate change models.

Keywords: Boreal forest, LiDAR, Landsat 8, Surface Reflectance, Alaska.

1. Introduction

Forests are critical in regulating the world's climate and they maintain overall Earth's energy balance ([Alibakhshi et al., 2020](#)). The solar radiation that enters Earth, either reflected or absorbed, and emitted from the surface are the major components of the Earth's radiation budget. The forest canopy creates uncertainty in the estimation and modelling of Earth's radiation budget and canopy radiative processes ([Mynemi et al., 1997](#)), because, incoming solar radiation interacts with vegetation canopies through complex canopy radiative transfer theory ([Ogunjemiyo et al., 2005](#)). Such an interaction occurs at both foliage and canopy levels, resulting in varied absorption, reflection and emission of solar radiation at different spectrum, vegetation structure and background condition ([Kötz et al., 2004](#); [Ogunjemiyo et al., 2005](#)).

The forest canopies are often characterized by high structural complexity (known as “rugosity”, as defined by [Hardiman et al., 2011](#)). In particular, conifer forests exhibit a complex canopy structure ([Kötz et al., 2004](#)), and tree shadowing effects which reduces surface reflectance at snow surface, resulting in high air temperature. Thus ignoring tree structure effect on surface

reflectance in high latitude boreal regions results in under-prediction of air temperature in climate models. Therefore, understanding of Earth's radiation budget, especially surface reflectance in forested landscapes with respect to seasons (depicting snow energetics), land cover (LC) classes (e.g., deciduous versus evergreen forests), canopy structures, and topography would be useful in parameterization of climate models.

Forest canopy reflectance is a function of variety of factors including leaf optical properties, canopy structures, background reflectance, solar illumination geometries, and the viewing angles as well as the topography, e.g., elevation (Goel, 1988; Williams, 1991; Ni et al., 1999; Chen et al., 2000; Kötz et al., 2004; Grabska and Socha, 2021). The presence of snow on the ground or on the leaves and branches adds complexity to forest canopy reflectance because snow has very high reflective characteristics of incoming solar radiation, especially in the visible and near infrared wavelengths (Ni and Woodcock, 1999; Heinilä et al., 2019). The forest canopy structures interact in the processes associated with snow accumulation and its disappearance because trees and canopy structure intercept and attenuate solar radiation (Schneider et al., 2019; Jost et al., 2007; Varhola et al., 2010). Schneider et al. (2019) demonstrated that spatial and vertical variation within the forest canopy induces spatial heterogeneity in snow accumulation and its persistence. The highly reflective snow makes a heterogeneous surface when mixed with absorbent forest canopies. Under these circumstances, the overall reflectivity of the surface reduces considerably compared with forest-free snow covered surfaces (Webster and Jonas, 2018). Such a behavior also contributes to the greater spatial heterogeneity in the snow melting processes because varying melt rates is driven by forest canopy density (Heinilä et al., 2019). Topography presents a further challenge in the accurate quantification of surface radiative forcing at both small (in meters) and

large (in kilometers) spatial scales (Cherubini et al., 2017). Rugged terrain and solar zenith angle (SZA) controls in part the surface albedo (Hao et al., 2019).

The knowledge of vertical and horizontal forest-structures is essential in understanding the surface radiative-processes of incoming solar radiation that also interacts with vegetation and forest floor (Wang and Ni-Meister, 2019). However, large variability in forest-structures can modulate the generation of shades and exert variation in snow accumulation and snowmelt conditions (Schneider et al., 2019). The accurate assessment of the relationship between vertical or horizontal forest-structure and surface reflectance is essential for the quantitative measurement and modelling of the solar radiation budget. Because the radiative transfer models can simulate the physics of radiative processes, however, detailed specifics of canopy structural input are necessary for accurate modelling and quantification (Ni et al., 1997). Combining optical data from the moderate resolution and larger geographic coverage Landsat satellites with high resolution 3D vegetation-structure parameters from LiDAR (light detection and ranging) would not only address spatio-temporal heterogeneities of surface radiative processes associated with gaps and edges within a forest stand, but also allows us to identify direct relationships between vegetation structure measurements by LiDAR with the seasonal multispectral surface reflectance measured by Landsat. The quantitative information will provide us guidance on how best to fuse the global vegetation structure measurements from the Global Ecosystem Dynamics Investigation (GEDI) mission with climate prediction models through a coupled canopy radiative transfer model embedded in climate models to simulate impact of vegetation structure on land surface reflectance and albedo patterns at continental and global scales (Ni-Meister et al., 2010).

In boreal forests, the canopy reflectance can be affected by forest floor conditions because it constitutes heterogeneous and clumped forest canopies (Ni-Meister and Gao, 2011; Markiet and

Möttus, 2020). The seasonal snow that overlaps a significant portion of the boreal forests in the northern hemisphere creates large variations in snow accumulation and snowmelt conditions (Ni-Meister and Gao, 2011; Webster and Jonas, 2018). This makes a serious challenge in these areas to accurately quantify solar radiation balance and canopy radiative transfer processes in different forest types. The availability of satellite-derived optical data forms a cost-effective option to obtain information of the Earth's radiation budget and find relationships between these variables. Additionally, the interaction between vegetation and incoming solar radiation in a continuous spatial and temporal scale can be achieved seamlessly because remote sensing data provide less limitations and uncertainties compared to modeled parameters.

Therefore, the aim of this study is to examine the relationship between canopy structures, topography and surface reflectance during different seasons in a boreal forest near Fairbanks, Alaska using Landsat 8 satellite images and LiDAR-derived canopy metrics. We explored the causes of variations in surface reflectance during different seasons in relation to LiDAR-derived canopy metrics, such as tree heights, rugosity (i.e., structural complexity) and canopy cover and topography (slope, elevation and aspect). The accurate understanding of the effect of forest structural complexity on the spatial heterogeneity of surface reflectance in snow-dominated areas would help reduce uncertainty in climate predictions and model parametrization.

2. Materials and Methods

2.1 Study area

The study area falls within the Level-III ecoregion of Alaska, bordering Interior Highlands and Interior Bottomlands ecoregions and is located in a mountainous area near Harding-Birch lakes region in Fairbanks, Alaska (Fig. 1). The study area is approximately 400 m wide and 8,000 m

long and the shape is elongated in NE-SW direction. The topography is highly variable and located in the central Tanana valley. The elevation is ranging between 350 and 600 meters above mean sea level with slopes ranging between 0 and 30 degrees. The vegetation communities include spruces, firs, and conifers, and deciduous trees along waterways (Gallant et al., 1995). The study area is primarily dominated by evergreen (white and black spruce species) and deciduous (e.g., paper birch species) forests land cover class.

The study area experiences a continental subarctic climate with mild summers and icy winters. It has four seasons that includes short summer (average high temperature of 22.8°C with a high in July) and dominant winter season (average low temperature of -27.2°C with a low in January). The average annual snowfall is 1,651 mm, which lasts from October to May and peaks in January.

2.2 Data

Landsat 8 OLI/TIRS (Operational Land Imager/Thermal Infrared Sensor) surface reflectance of 30-m spatial resolution was used in this study. The images were downloaded from U.S. Geological Survey (USGS) Earth Explorer data portal. The detailed product information can be downloaded from the USGS website (USGS, 2020). Satellite images from three time-periods, March 26, May 29 and August 8, 2014, were selected for this study. The date of scenes were selected on the basis of cloud free conditions and to reflect three different seasonal patterns.

LiDAR data were downloaded from NASA's G-LiHT program (Cook et al., 2013). LiDAR data were acquired on August 6, 2014, which overlapped with one of the Landsat 8 scenes that we chose to study. Several LiDAR metrics, such as mean tree return heights (tree_mean), quadratic mean tree return heights (tree_qmean), standard deviation of tree return heights (tree_stdev), standard deviation of gridded canopy height model (tree_rugosity), fraction of first returns

intercepted by tree (*tree_fcover*), fraction of all returns classified as tree (*tree_fract_all*) at 13-m spatial resolution were used in this study. In addition to that, slope, aspect and elevation derived from the gridded digital terrain model were used.

National Land Cover Database 2011 ([NLCD 2011](#)) at 30-m spatial resolution was used to identify the dominant land cover classes in the study area. Two main land cover classes (i.e., deciduous and evergreen forests) were identified in the study area. These land cover classes were determined on the basis of an assumption that the trees in each class were taller than 5 meters and consisted of more than 20% of total canopy cover. In addition to that, more than 75% of the tree species in deciduous forest lose foliage in response to seasonal changes, whereas more than 75% of the tree species in evergreen forest class maintain foliage all year.

2.3 Methodology

Landsat 8 surface reflectance from visible (VIS), near infrared (NIR) and shortwave infrared (SWIR) bands from three time-periods were co-registered with LiDAR-derived vegetation metrics and NCLD 2011 land cover datasets. Landsat surface reflectance and NCLD land cover classes were resampled at 13-m spatial resolution to correspond with LiDAR metrics. Pixel-level ($n = 4,574$) information was extracted in ArcGIS Pro for detailed statistical analysis in RStudio 4.0.4 software.

We compared seasonal variation of Landsat 8 surface reflectance for two NCLD 2011 land cover classes (i.e., deciduous and evergreen forests). Bivariate relationships between LiDAR metrics, such as canopy cover (*tree_fract_all*), tree heights (*tree_mean*) and rugosity (*tree_rugosity*), and surface reflectance were studied. Bivariate relationships between topography (such as elevation as well as slopes, and aspects) and surface reflectance were also studied.

The coefficient of variation (*CV*) was calculated to evaluate the effects of land cover classes on surface reflectance in different wavelength regions in the study area.

$$CV = \frac{\sigma}{|\mu|} \times 100 \%$$

where σ and μ are the standard deviation and the mean of the surface reflectance corresponding to different wavelengths and land cover classes. Greater *CV* indicates larger variability and thus shows stronger effects.

Ordinary least square (OLS) regression analysis using multiple independent variables was carried out to quantify the relationship of canopy metrics and topography variables with surface reflectance in winter and summer scenes for visible and near infrared bands.

$$y = \beta_0 + \beta_1 X_i + \beta_2 X_j + \dots + \beta_n X_n + \varepsilon$$

where Y is the predicted variable, X_{i-n} is the explanatory variable, β_0 is the intercept, β_{1-n} is the slope of the relationship between X_{i-n} (multiple independent variables) and Y , and ε is the error.

The OLS regression is well known for its simplicity and has good predictive power (Freese, 1964). The analysis was conducted in R environments using *olsrr* package (Hebbali, 2018). The best model was chosen by running *ols_step_best_subset* function of *olsrr* package having the largest adjusted R-squared values and/or the smallest Akaike information criterion (AIC) (Akaike, 1974).

Since, the relationship between response (surface reflectance) and predictor (LiDAR-derived canopy metrics and topography parameters) variables exhibited a complex non-linear pattern, mainly due to the heterogeneity in environmental parameters, a non-linear model of the relationship of canopy metrics and topography variables with surface reflectance was constructed using the Generalized Additive Models (GAM). The GAM is a widely used model in

environmental studies and has the ability to fit complex, non-linear relationships between independent and response variables (Maack et al., 2016; Ravindra et al., 2019).

$$z = \beta_0 + \sum_{i=1}^N s_i(X_i)$$

where β_0 is the intercept, $s_i(X_i)$ is the smooth function of the predictor variables X_i , Z is the predicted variable.

We used mgcv's gam package, which offers several different methods for selecting smoothing parameters and basis functions. The mgcv's "Restricted Maximum Likelihood" method was used in this analysis. The method offers default smooth and basis functions and provides reliable and stable results. The final GAM model was selected on the basis of the significance of influential predictors together with the lowest AIC value and the highest adjusted R-square. The model was evaluated by looking at Q-Q plot and histogram of residuals as well as response versus fitted values which follow a pattern that clustered around the 1-to-1 line. The analysis was also conducted in R environments using *mgcv* package (Wood, 2017).

3. Results

3.1 Relationship between canopy structure, topography and land cover types

In our study area, the canopy cover ranges between 0.01 and 0.90 (fraction). Deciduous forests during leaf-on season have significantly higher mean canopy cover than the evergreen forests (0.54 and 0.21, respectively). Likewise, trees were much taller in deciduous forests than in evergreen forests (7.2 m and 3.2 m, respectively). Rugosity (the height variability) was also greater in deciduous forests than in evergreen forests (4.6 m and 1.9 m, respectively). Deciduous forests were dominantly in the southern aspect, trees tend to be taller with more height variability and more canopy cover than evergreen forests. On the other hand, evergreen forests were evenly distributed

in both southern and northern aspects. However, evergreen forests in the southern aspect tend to be taller with more height variability.

The relationship between canopy cover and tree heights are non-linear for both deciduous and evergreen forests (Fig. 2). In deciduous forests, the locally weighted scatterplot smoothing (LOWESS) regression line shows different intercepts for trees in northern and southern aspects, suggesting different minimum tree heights (Fig. 2a). In evergreen forests, the LOWESS regression lines show similar intercepts, however with increasing canopy cover the rate of increase in tree heights is much greater in southern aspects than in northern aspects (Fig. 2d). The correlation between canopy cover and rugosity is also non-linear for both deciduous and evergreen forests (Figs. 2b,e). Likewise, the correlation between tree heights and rugosity is non-linear (Figs. 2c,f). The trend in the LOWESS regression line is different for deciduous trees in northern and southern aspects. However, for trees <5 m and canopy cover <0.45, the LOWESS regression line follows the same path for trees in both aspects in evergreen forests.

We further looked into the relationship between canopy structures and topography (such as slopes, elevation and aspect) (Fig. 3). Evergreen forests are primarily located in low slopes (mean slope is 5.7 °), whereas deciduous forests are primarily located in high slopes (mean slope is 14 °). There is a general increase in tree height, rugosity and canopy cover with increase in slopes (Fig. 3). However, such an increase is mainly observable in the southern aspect than in the northern aspect for both land cover classes (i.e., tree height remains fairly unchanged with increase in slopes in northern aspects). Taller trees with higher rugosity and greater canopy cover are mostly dominated in southern aspects.

The relationship between canopy structures and elevation shows that with increase in elevation the tree height, rugosity and canopy cover are increasing but with greater rate of change in southern

aspects than in northern aspects (Fig. 4). In deciduous forests, trees are clustered into two groups, one in low elevation and the other in high elevation, but these trees do show a positive change in heights, rugosity and canopy cover with elevation. For deciduous forests, tree height, rugosity and canopy cover increase with elevation (Figs. 4a-c). For evergreen forests, this trend works for trees in the southern aspect only (Figs. 4d-f). Evergreen forest canopy structure metrics in the northern slope do not show any relationship with elevation.

3.2 Surface reflectance as a function of land cover types and canopy structures

Surface reflectance in visible (Band 3), near infrared (Band 5) and shortwave infrared (Band 6) wavelengths were shown for deciduous and evergreen land cover classes during March, May and August 2014 (Fig. 5). Surface reflectance in visible wavelengths was the highest in March, followed by May and August. Near infrared reflectance was the highest in March, followed by August and May, whereas shortwave infrared reflectance was the highest in May, followed by August and March. The coefficient of variations (CVs) were the highest in March, whereas CVs were quite similar in May and August (Fig. 5). However during March, visible wavelengths (Band 3) have slightly lower surface reflectance in comparison with near infrared wavelengths (Band 5). This is perhaps the result of large-scale surface heterogeneity created by the combination of snow and vegetation reflectance. This has resulted in higher CVs for visible bands (54 to 65%) than the near infrared bands (37 to 41%).

In evergreen forests, the visible and near infrared reflectance decreases with increasing canopy cover during different months (Figs. 6b,d,f). The magnitude of this decrease is much greater in March than in other months. These results imply a significant masking effect of boreal evergreen forest on surface reflectance. However, in March, shortwave infrared reflectance increases with

increase in canopy cover. This could be due to higher absorption at these wavelengths by snow at lower canopy cover while at higher canopy cover lesser absorption due to greater masking effects. In deciduous forests, the surface reflectance is clearly divided into two significant groups, one group with higher canopy cover fractions, the other with lower canopy cover fractions (Figs. 6a,c,e). Deciduous forest shows larger variability in surface reflectance, particularly in March, mainly due to the mixing effect of snow and vegetation. Large variabilities of reflectance in visible and near infrared spectrums suggests significant masking effect by the branches on surface albedo even during leaf-off seasons. Within each group, surface reflectance does not show a particular pattern with changes in canopy cover fractions, however mean surface reflectance is slightly lower in trees with lower canopy cover than in higher canopy cover (Figs. 6a,c,e). For similar canopy cover, evergreen forest has lower surface reflectance than deciduous forest in all seasons. It is partially due to the fact that deciduous forest is a dominant vegetation type in the southern aspect. In snow season, it may also be due to stronger masking effect caused by tree shadowing in evergreen forests. Large variability in surface reflectance during different months and LC classes with respect to canopy cover is suggestive of multiple controlling factors such as tree heights and rugosity which has a non-linear relationship with canopy cover in our study area.

Surface reflectance shows similar relationships with canopy cover, height and rugosity, mainly due to close relationships between these three parameters (Fig. 2). For evergreen forests, the results show a large change in visible and near infrared reflectance with increase in tree heights from 2 to 4 m (Fig. 7b). In relatively taller trees, e.g., tree height from 4 to 8 m, evergreen forests have much lower surface reflectance for the March scene than the deciduous forests, suggesting greater masking effect by trees in evergreen forest than deciduous forest on snow surface reflectance (Figs. 7a,b). During the leaf-off season (i.e., winter), deciduous forests cast larger gaps than evergreen

forests, allowing greater impact from background snow on surface reflectance in visible and near infrared spectrum. While taller trees in evergreen forests could produce greater shade and thereby lower the reflectance in the visible and near infrared wavelengths. In shortwave infrared bands, slight increase in surface reflectance with increase in tree heights could be due to greater masking effects and lack of absorption by the snow in the presence of taller trees (Fig. 7). Whereas, higher surface reflectance in May and August than in March for shorter tree heights could be due to lack of soil moisture and leaf water content. With increasing tree heights, the effect of soil moisture is reduced, which is more pronounced during May and August than the March scene due to lesser gaps and greater masking effects by the trees.

The relationship between surface reflectance and rugosity is very similar to the relationship between surface reflectance and tree height (Fig. 8). This is because taller forests with maximum canopy heights have higher rugosity (Gough et al., 2020). We observed a general decreasing trend of surface reflectance of visible, near infrared and shortwave infrared bands with increasing rugosity during different months of the year for both LC classes (Fig. 8). Higher surface reflectance at low rugosity could be attributed to less scattering of lights at the canopy level. In addition to that, snow-covered surfaces produce higher surface albedo than bare soil surfaces and therefore the chances of background effects increases during winter when trees are less variable in heights. In deciduous forests, the figure shows two clusters of trees, one with low and the other with high rugosity (Figs. 8a,c,e). These clusters individually show declining trends in surface reflectance with increasing rugosity, especially in May and August.

3.3 Surface reflectance as a function of slope, elevation and aspect

Surface reflectance in all wavelengths decreases with increase in slopes and are less variable at higher slopes, especially in evergreen forests (Fig. 9). In evergreen forests, the mean surface reflectance in all wavelengths was much higher at slopes $<10^\circ$. This is consistent with the observation of shorter tree heights with less height variability in lower slopes. Thus producing slightly higher surface reflectance in the presence of homogeneous canopy surfaces in comparison with shadowing and absorption of solar radiation due to taller trees with greater height variability. The condition is similar for trees in deciduous forest. The variability of surface reflectance was much greater in both land cover classes during March. In May and August, the change in surface reflectance was small for both LC classes. Such a large change in surface reflectance during March could be attributed to the differences in the level of snow accumulation and melting rates at different slopes (Sommer et al., 2015). In addition to that, masking effects by trees in evergreen forests and leaf-off conditions in deciduous forests increases variability.

There is a decreasing trend of surface reflectance with increase in elevation in evergreen forests (Figs. 10b,d,f). Likewise, two clusters of trees in deciduous forests individually show declining surface reflectance with increase in elevation (Figs. 10a,c,e). This is consistent with the findings that tree heights, rugosity and canopy cover increases with increase in elevation (Fig. 4). However, such relationships are much more distinct in trees located in the southern aspects. The close relationship between elevation and surface reflectance is related to what was observed before, i.e., taller and denser trees are distributed in higher elevation. The less noisy relationship between surface reflectance and elevation compared to Figs. 6-8 indicates that this is an integrated effect of height, rugosity and canopy cover on surface reflectance.

As expected, the relationship between surface reflectance and aspect shows an interesting pattern (Fig. 11). For deciduous forest, higher surface reflectance in the southern aspect indicates less shadow effect due to topography, even the trees are shorter, less covered in the northern slope. For evergreen forest, surface reflectance is not primarily dependent on aspects but rather a combination of other factors such as elevation (Figs. 10b,d,f). This suggests that the shadow effects from topography and tree crowns on surface reflectance are both significant.

3.4 Modelling the relationships of topography and canopy structure with surface reflectance

Topography impacts vegetation growth and its structure. Surface reflectance is highly sensitive to change in slope, elevation, canopy cover, tree height, and rugosity. In deciduous forest, the variability is much greater when trees are in low slopes and elevation as well as shorter, less height differences and less canopy cover. On the other hand, evergreen forests are not highly sensitive to change in topography and canopy structures. In March, the higher sensitivity at shorter heights and rugosity could be attributed to surface reflectance from the snow-covered ground surfaces. In May and August, surface reflectance from ground surface (including understory vegetation) can contribute to the overall sensitivity. As the height, rugosity, slope and elevation increases the decrease in sensitivity could be attributed to greater solar radiation absorption at the canopy level (Gough et al., 2019).

The multivariate OLS regression model revealed that slope and canopy cover alone could explain 50% and 56%, respectively, the variance in visible and near infrared reflectance in March for evergreen forests. The OLS model derived adjusted R-squared values were 0.50 and 0.56, respectively. However, we observed a strong improvement in the model prediction when a non-linear function was considered through the GAM approach. The GAM model explained between

74% and 76% of the variance in the visible and near infrared reflectance, respectively by canopy cover, rugosity, slope, elevation and aspects. It is important to note that both elevation and canopy cover individually explained nearly 40% of the variance (Table 1). For deciduous forests, topographic variables (slope, elevation and aspect) alone explained between 42% and 52% of the variance in visible and near infrared reflectance, respectively in March based on multivariate OLS regression model derived adjusted R-squared values of 0.42 and 0.52, respectively. On the other hand, the GAM based on non-linear relationships explained between 60% and 68% of the variance in surface reflectance of visible and near infrared bands, respectively for the same scenes. Such a relationship confirms that the topography plays a dominant role in the variation in surface reflectance from visible and near infrared bands in deciduous forests while a combination of topography and tree structure change controls surface reflectance in evergreen forests. Predicted surface reflectance in visible and near infrared bands for March scene based on GAM approach suggests a good fit to the model with most of the data points clustered around 1-to-1 line of observed versus predicted values (Fig. 12).

In summer, the OLS regression model showed the role of canopy cover and slope in explaining the variance of near infrared reflectance but with a lesser degree, adjusted R-squared values of 0.35 for evergreen forests. While, the effect of topography (i.e., slope, aspect and elevation) remained dominant for deciduous forests with the OLS regression model explaining 43% of the variance. When, non-linearity term through the GAM approach was introduced in the model, the adjusted R-squared values have improved over the OLS regression model (Table 1). When model results were compared, it showed that both the models were effective in explaining the data in winter scenes that in summer scenes. Such a difference could be attributed to the differences in surface conditions and change in solar zenith angle.

4. Discussion

The mean surface reflectance and coefficient of variation is slightly higher in deciduous forest than in evergreen forest. During the snow season, deciduous forests lose foliage in response to seasonal changes. Such conditions allow satellites to see more background and thus produce higher surface reflectance than the evergreen forests which maintain foliage all year. The greater variation in surface reflectance in the visible and near infrared region of the electromagnetic (EM) spectrum is an indicator of the differences in surface heterogeneity in March than in May and August for both forest types. Such heterogeneity is typically associated with differences in snow accumulation and melting rates in boreal regions due to spatial variability in tree structures (Schneider et al., 2019). Heinilä et al. (2019) observed higher variability in surface reflectance in presence of snow layers during winter. In addition to that, evergreen forests (conifers) have much more absorptive capacity than deciduous forests (Williams, 1991). The role of background reflectance from snow-covered surfaces is confirmed by the observation of the highest mean and wider range of surface reflectance in March for both visible and near infrared bands than in May and August for both LC classes. While, the reflectance from shortwave infrared bands in March was lower than in May and August due to higher moisture contents due the presence of snow and snowmelt in the ground. Such a variation in surface reflectance during different months and throughout the ranges of the EM spectrum is consistent with the creation of a highly heterogeneous surface due to differential accumulation and melting rates of highly reflective snow in the study area. This, together with canopy cover that are highly absorptive in nature for incoming solar radiation, is likely producing a wider range of surface reflectance in March (Webster and Jonas, 2018). The results further indicate that the variation in surface reflectance in our study during different seasons is controlled

in part by the land cover classes (Pan et al., 2015) together with snow-vegetation interactions and creation of heterogeneous surfaces.

The non-linear relationships between canopy cover with tree height and rugosity have a great implication when assessing the impact of vegetation structure on surface reflectance and albedo. Because, canopy cover alone is not sufficient to explain the variability in surface reflectance due to saturation issue. Thus tree height and rugosity (height variability) are important vegetation structure parameters to look at. Atkins et al. (2018) observed that under high light conditions canopy rugosity is positively correlated to fraction of photosynthetically active radiation. In addition to that rugosity was linked to primary production (Atkins et al., 2018). These relationships indicate that beside local climate conditions, surface topographic characteristics control vegetation structure characteristics at landscape scale. In addition to that, elevation and slope orientation are two important factors determining vegetation types, height and rugosity, which in return affect surface reflectance at stand scale. Our non-linear modelling effort confirms the finding that in addition to canopy cover, tree height and rugosity also affects surface reflectance and albedo (Dore et al., 2012; Lukeš et al., 2013). Generally, higher canopy structural complexity is associated with greater light absorption, and thus greater photosynthesis and vegetation growth (Gough et al., 2019, 2020). The close association between canopy cover, tree height and rugosity and their correlation with surface reflectance imply an inherent relationship between structure and surface reflectance which is being modeled using the geometric optical and radiative transfer (GORT) theory (Ni, et al., 1999; Ni-Meister et al., 2010), also confirmed by our non-linear GAM model.

Nevo (2001) has indicated that variable topography could have resulted in uneven tree growth due to lack of soil moisture and nutrient availability. This has likely contributed to the observed canopy structural complexity (i.e., the variations in tree heights and rugosity) in relation to slopes

and elevation in both forest types. In deciduous forests, the observed higher surface reflectance with greater variability in the southern aspects than in the northern aspects could be due to the shadowing effect by topography. On the other hand shorter and less variable trees in evergreen forests suggest aspect control vegetation growth and vegetation types. [Kumar et al. \(1997\)](#) have indicated the effects of slope and aspects on the variability of daily solar radiation. Slope could result in spatial heterogeneity in vegetation structure and composition ([Chen et al., 2013](#)). This has been confirmed in our final GAM model which showed the overall contribution of canopy structures (such as tree height, rugosity and canopy cover) together with added complexity due to topography (slope, elevation and aspect) in controlling surface reflectance in our study area.

This research has some limitations considering all issues. The study area is small and thereby lacking representativeness and applicability of the results to a larger area of different land cover classes, the range of canopy metrics and topography. The reflectance data was not corrected for bidirectional reflectance effect due to topography, this may add additional variation in reflectance data. In addition to that, the non-linearity term between surface reflectance and independent variables used in the GAM non-linear regression needed a detailed assessment which could be effectively be addressed using machine learning techniques for interpreting such complex relationships. Therefore a full assessment of the applicability of this study to a larger area is required prior to implementation of these findings for parameterization in climate change models. Given all these caveats, our quantitative analysis confirmed a large-scale spatial heterogeneity in canopy structures and topography effects on surface reflectance. We will be implementing the knowledge gained from this study to a much larger area to enable fusion of high resolution LiDAR measurements with Landsat surface reflectance and surface albedo estimates. In addition to that,

time-series analysis of surface reflectance and surface albedo by increasing the number of scenes will enable us to gain a better knowledge of vegetation conditions.

5. Conclusions

Our study suggests that canopy structure and topography interplay and influence surface reflectance in a complex way particularly during the snow season. First we found topographic aspects and elevation influences vegetation type and structure distribution. The southern slope of our study region is dominated by deciduous forests with taller trees and denser canopy cover than evergreen forests. While evergreen forests are evenly distributed in both southern and northern slopes with taller trees and larger height variability in the southern slope than in the northern slope. Taller and denser trees are located at higher elevation in the southern slope. In the northern slope, vegetation structures do not show any relationship with elevation.

In general, surface reflectance shows similar relationships with canopy cover, height and rugosity, mainly due to close relationships between these parameters. Surface reflectance decreases with increasing canopy cover, tree height, and rugosity especially for evergreen forest which is consistent with the canopy radiative transfer modeling results. Deciduous forest shows larger variability of surface reflectance, particularly in March, mainly due to the mixing effect from snow and vegetation. For similar canopy cover, evergreen forest has lower surface reflectance than deciduous forest for all seasons.

The relationship between vegetation structure and surface reflectance is greatly impacted by topography. Vegetation in the southern aspects tends to have higher reflectance than in the northern aspects. Aspect controls vegetation growth, and vegetation types. In the southern aspect, more deciduous trees, trees taller than the northern aspect. Vegetation metric is also related to elevation.

Higher elevation and taller trees from both vegetation types, particularly for trees in the southern aspect. Vegetation structure and surface topography form a complex relationship and affect surface reflectance in a hierarchy scale. Surface topography (elevation, slope and aspect) form certain vegetation structure characteristics at a larger scale. At a finer scale vegetation heterogeneity (canopy cover, height and rugosity) combined with large-scale shadowing effect due to slope, its aspect and elevation affect surface reflectance in a complex way. The generalized additive models (GAM) based on non-linear relationships between response (surface reflectance) and predictor (canopy metrics and topography) variables suggests the shadow effect from topography and tree crowns on surface reflectance play a different role for deciduous and evergreen forests. For deciduous forest, topographic shadow effect on surface reflectance is stronger than from tree shadowing for all seasons. For evergreen forest, shadow effects from topography and tree crowns on surface reflectance are both equally dominant, however tree shadow effect is more significant in March than in May and August.

This study not only confirms the relationship between surface reflectance and canopy structure described by the Geometric Optical-Radiative Transfer (GORT) models, but also provides valuable information for parameterizing the vegetation structure inputs for the GORT models and integrate the global vegetation structure measurements from the Global Ecosystem Dynamics Investigation (GEDI) mission with the canopy radiative transfer model in the Dynamic Vegetation-Ent to model land surface reflectance and albedo patterns at continental and global scales.

Author contributions

Conceptualization and Methodology, B.N. and W.N.-M.; Software, Formal Analysis and Data Curation, B.N.; Writing – Original Draft Preparation, B.N.; Writing – Review & Editing, B.N. and

W.N.-M.; Funding Acquisition, W.N.-M. All authors have approved the content of the submitted and/or published version of the manuscript.

Funding

This study is funded by NASA grant number 80NSSC20K1718.

Data availability statement

Landsat 8 OLI/TIRS surface reflectance data product at 30-m spatial resolution can be ordered freely at <https://earthexplorer.usgs.gov/>. LiDAR data product can be downloaded from <https://glihtdata.gsfc.nasa.gov/>. National Land Cover Database 2011 can be downloaded from <https://www.mrlc.gov/>.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgement

The authors would like to thank anonymous reviewers for their time and effort to review this paper and to improve the quality of this paper.

References

Akaike, H. A New Look at the Statistical Model Identification. *IEEE Trans. Autom. Control*. 1974, *19*, 716–723.

- Alibakhshi, S., Naimi, B., Hovi, A., Crowther, T.W., Rautiainen, M., 2020. Quantitative analysis of the links between forest structure and land surface albedo on a global scale. *Remote Sensing of Environment*. 246, 111854.
- Atkins, J.W., Fahey, R.T., Hardiman, B.S., Gough, C.M., 2018. Forest canopy structural complexity and light absorption relationships at the subcontinental scale. *JGR Biogeosciences*, <https://doi.org/10.1002/2017JG004256>
- Chen, J.M., Chen, X., Ju, W., 2013. Effects of vegetation heterogeneity and surface topography on spatial scaling of net primary productivity. *Biogeosciences*, 10, 4879-4896.
- Chen, J. M., Li, X., Nilson, T., & Strahler, A. (2000). Recent advances in geometrical optical modelling and its applications. *Remote Sensing Reviews*, 18, 227–2262.
- Cherubini, F., Hu, X., Vezhapparambu, S. & Stømman, A. H. High-resolution mapping and modelling of surface albedo in Norwegian boreal forests: from remotely sensed data to predictions. *Geophysical Research Abstracts* 19 (2017).
- Cook, B.D., Corp, L.A., Nelson, R.F., Middleton, E.M., Morton, D.C., McCorkel, J.T., Masek, J.G., Ranson, K.J., Ly, V., Montesano, P.M., 2013. NASA Goddard's Lidar, Hyperspectral and Thermal (G-LiHT) airborne imager. *Remote Sensing* 5, 4045-4066.
- Dore, S., Montes-Helu, M., Hart, S.C., Hungate, B.A., Koch, G.W., Moon, J.B., Finkral, A.J., Kolb, T.E., 2012. Recovery of ponderosa pine ecosystem carbon and water fluxes from thinning and stand-replacing fire. *Glob. Chang. Biol.* 18, 3171–3185.
- Freese, F. *Linear Regression Methods for Forest Research*; US Department of Agriculture, Forest Service, Forest Products Laboratory: Washington, DC, USA, 1964; Volume 17.

- Grabska E, Socha J (2021) Evaluating the effect of stand properties and site conditions on the forest reflectance from Sentinel-2 time series. *PLoS ONE* 16, e0248459. <https://doi.org/10.1371/journal.pone.0248459>
- Gallant, A.L., Binnian, E.F., Omernik, J.M., Shasby, M.B., 1995. Ecoregions of Alaska. U.S. Geological Survey Professional Paper 1567. U.S. Gov. Printing Office, Washington, D.C.
- Goel, N. S. (1988). Models of vegetation canopy reflectance and their use in estimation of biophysical parameters from reflectance data. *Remote Sensing Reviews*, 4, 1–212.
- Gough, C. M., Atkins, J. W., Fahey, R. T., & Hardiman, B. S. (2019). High rates of primary production in structurally complex forests. *Ecology*, 100, 1–6. <https://doi.org/10.1002/ecy.2864>
- Gough, C. M., Atkins, J. W., Fahey, R. T., Hardiman, B. S., & LaRue, E. A. (2020). Community and structural constraints on the complexity of eastern North American forests. *Global Ecol. Biogeogr.* 29: 2107-2118
- Hao, D., Wen, J., Xiao, Q., Wu, S., Lin, X., Dou, B., You, D., Tang, Y., 2019. Simulation and analysis of the topographic effects on snow-free albedo over rugged terrain. *Remote Sensing*, 10, 278; <https://doi.org/10.3390/rs10020278>
- Hardiman, B. S., Bohrer, G., Gough, C. M., Vogel, C. S., & Curtis, P. S. (2011). The role of canopy structural complexity in wood net primary production of a maturing northern deciduous forest. *Ecology*, 92, 1818–1827.
- Hebbali, A.2018. Package olsrr. <https://cran.r-project.org/web/packages/olsrr/index.html>
- Heinilä, K., Salminen, M., Metsämäki, S., Pellikka, P., Koponen, S., Pulliainen, J., 2019. Reflectance variation in boreal landscape during the snow melting period using airborne

- imaging spectroscopy. *International Journal of Applied Earth Observation and Geoinformation*, 76, 66-76.
- Jost, G., Weiler, M., Gluns, D.R., Alila, Y., 2007. The influence of forest and topography on snow accumulation and melt at the watershed-scale. *J. Hydrol.* 347, 101–115.
- Kötz, B., Schaepman, M., Morsdorf, F., Bowyer, P., Itten, K., Allgöwer, B., 2004. Radiative transfer modelling within a heterogeneous canopy for estimation of forest fire fuel properties. *Remote Sensing of Environment*, 92, 332-344.
- Kumar, L., Skidmore, A.K., Knowles, E., 1997. Modelling topographic variation in solar radiation in a GIS environment. *International Journal of Geographical Information Science*, 11, 475-497.
- Lukeš, P., Stenberg, P., Rautiainen, M., 2013a. Relationship between forest density and albedo in the boreal zone. *Ecol. Model.* 261–262, 74–79.
- Maack, J., Lingenfelder, M., Weinacker, H., Koch, B., 2016. Modelling the standing timber volume of Baden_Wuerttemberg – a large-scale approach using a fusion of Landsat, airborne LiDAR and national forest inventory data. *International Journal of Applied Earth Observation and Geoinformation*, 49, 107-116.
- Markiet, V., Möttus, M., 2020. Estimation of boreal forest floor reflectance from airborne hyperspectral data of coniferous forests. *Remote Sensing of Environment*, 249, <https://doi.org/10.1016/j.rse.2020.112018>
- Myneni, R. B., Ramakrishna, R., Nemani, R., & Running, S. W. (1997). Estimation of global leaf area index and absorbed par using radiative transfer models. *IEEE Transactions on Geoscience and Remote Sensing*, 35, 1380–1393.

- Nevo, E., 2001. Evolution of genome-phenome diversity under environmental stress. *Proceedings of the National Academy of Sciences of the United States of America*, 98, 6233-6240.
- Ni, W., Li, X., Woodcock, C., Roujean, J-L., Davis, R.E., 1997. Transmission of solar radiation in boreal conifer forests: measurements and models. *Journal of Geophysical Research*, 102, 29555-29566.
- Ni, W., X. Li, C.E. Woodcock, M. Caetano, and A.H. Strahler, 1999. An analytical model of bidirectional reflectance over discontinuous plant canopies, *IEEE Transactions on Geoscience and Remote Sensing*, 37, 987-999.
- Ni, W. and C.E. Woodcock, 2000. Effect of canopy structure and the presence of snow on the albedo of boreal conifer forest, *Journal of Geophysical Research*, 105, 11879-11888.
- Ni-Meister, W., W. Yang, and N. Kiang, 2010. A clumped-foliage canopy radiative transfer model for a global dynamic terrestrial ecosystem model I: Theory, *Agriculture and Forest Meteorology*, 150, 881-894, doi:10.1016/j.agrformet.2010.02.009.
- Ni-Meister, W., Gao, H., 2011. Assessing the impacts of vegetation heterogeneity on energy fluxes and snowmelt in boreal forests. *Journal of Plant Ecology*, 4, 37-47.
- Ogunjemiyo, S., Parker, G., Roberts, D., 2005. Reflections in bumpy terrain: implications of canopy surface variations for the radiation balance of vegetation. *IEEE Geoscience and Remote Sensing Letters*, 2, 90-93, doi: 10.1109/LGRS.2004.841418.
- Pan, P., Chen, G., Saruta, K., Terata, Y., 2015. Snow cover detection based on visible red and blue channel from MODIS imagery data. *International Journal of Geosciences*, 6, <http://dx.doi.org/10.4236/ijg.2015.61004>

- Ravindra, K., Rattan, P., Mor, S., Aggarwal, A.N., 2019. Generalized additive models: building evidence of air pollution, climate change and human health. *Environmental International*, 132, <https://doi.org/10.1016/j.envint.2019.104987>
- Schneider, E.E., Affleck, D.L.R., Larson, A.J., 2019. Tree spatial patterns modulate peak snow accumulation and snow disappearance. *Forest Ecology and Management*, 441, 9-19.
- Sommer, C.G., Lehning, M., Mott, R., 2015. Snow in a very steep rock face: accumulation and redistribution during and after a snowfall event. *Front. Earth Sci.* <https://doi.org/10.3389/feart.2015.00073>
- USGS 2020. Landsat surface reflectance. <https://www.usgs.gov/core-science-systems/nli/landsat/landsat-collection-2-surface-reflectance> (accessed on December 1, 2020).
- Varhola, A., Coops, N.C., Weiler, M., Moore, R.D., 2010. Forest canopy effects on snow accumulation and ablation: an integrative review of empirical results. *J. Hydrol.* 392, 219–233.
- Wang, Q., Ni-meister, W., 2019. Forest canopy height and gaps using BRDF index assessed with airborne lidar data. *Remote Sensing*, 11, 2566; doi:10.3390/rs11212566
- Wickham, J., Homer, C., Vogelmann, J., McKerrow, A., Mueller, R., Herold, N., Coulston, J., The multi-resolution land characteristics (MRLC) consortium – 20 years of development and integration of USA land cover data. *Remote Sensing*, 6, 7424-7441; doi:10.3390/rs6087424.
- Webster, C., Jonas, T., 2018. Influence of canopy shading and snow coverage on effective albedo in a snow-dominated evergreen needleleaf forest. *Remote Sensing of Environment*, 214, 48-58.

Williams, D. L. (1991). A comparison of spectral reflectance properties at the needle, branch, and canopy level for selected conifer species. *Remote Sensing of Environment*, 35, 79–93.

S. Wood, *Generalized Additive Models: An Introduction With R*, second edition. London, U.K.: CRC Press, 2017.

Zhu G, Ju W, Chen JM, Liu Y (2014) A Novel Moisture Adjusted Vegetation Index (MAVI) to Reduce Background Reflectance and Topographical Effects on LAI Retrieval. *PLoS ONE* 9(7): e102560. doi:10.1371/journal.pone.0102560

Table 1. Generalized Additive Models (GAM) of the relationships of visible and near infrared band surface reflectance with canopy structure (the variables include canopy cover, tree height and rugosity) and topography (the variables include elevation, slope and aspect) in March and August 2014.

Land cover type	Band	Winter scene (March 2014)		Summer scene (August 2014)	
		Variables	R-sq. (adj)	Variables	R-sq. (adj)
Evergreen forest	Visible	Canopy cover	0.479	nd	nd
		Elevation	0.422	nd	nd
		Canopy cover + Elevation	0.619	nd	nd
		Canopy cover + Rugosity + Slope + Aspect + Elevation	0.738	nd	nd
	Near infrared	Rugosity	0.442	Rugosity	0.43
		Elevation	0.426	Elevation	0.373
		Rugosity + Elevation	0.608	Rugosity + Elevation	0.537
		Canopy cover + Rugosity + Slope + Aspect + Elevation	0.758	Canopy cover + Rugosity + Slope + Aspect + Elevation	0.66
Deciduous forest	Visible	Rugosity	0.129	nd	nd
		Elevation	0.481	nd	nd
		Elevation + Tree height	0.505	nd	nd
		Elevation + Slope + Tree height	0.602	nd	nd
	Near infrared	Rugosity	0.225	Rugosity	0.125
		Elevation	0.586	Elevation	0.469
		Elevation + Tree height	0.598	Elevation + Slope	0.579
		Elevation + Slope + Tree height	0.678	Elevation + Slope + Tree height	0.584

Note: The models were chosen based on the highest adjusted R-squared values, the lowest Akaike information criterion (AIC) (Akaike, 1974), and a variable that produced the highest adjusted R-squared values for canopy structure and topography. Independent variables were chosen when concavity was less than 0.8. Canopy cover was not used for deciduous forest in the March scene because of leaf-off conditions. nd = not done.