Quantifying the Impacts of Nova Scotia Forest Management Practices on Forest Stand Albedo and Surface Temperatures

by

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Abstract

In an effort to mitigate climate change, the Canadian government has increased focus on natural carbon sequestration through afforestation (i.e., the planting of forests where there were previously no forests) and reforestation (i.e., the planting of forests to replace a forest than was removed or disturbed). Traditionally, these forest management practices have preferred coniferous (softwood) tree species, which has led to wide scale species conversion across Europe and North America, increasing coniferous forest cover. Recent studies have linked these forestation practices to increased surface temperatures in managed forests. Coniferous forests have lower albedo than deciduous forests, absorbing a greater ratio of solar energy, which is re-emitted as heat and raises surrounding temperatures. This thesis tested the hypothesis that forest management practices in Nova Scotia increase coniferous tree cover, which in turn reduces canopy albedo and raises surface temperatures.

Remote sensing methods were used to test the relationship between forest treatments and stand biophysical characteristics. Albedo, surface temperature, and Normalized Difference Water Index outputs for Nova Scotia were derived from multispectral and thermal satellite imagery collected by Landsat 8 over July and August 2022. Forest stand data shared by the Nova Scotia department of Natural Resources and Renewables identify 216,235 forest stands, classified into two groups: 89,171 treated forest stands, and 127,064 natural forest stands. Analysis successfully demonstrated relationships between forest management practices and forest stand biophysical characteristics using remote sensing derived measurements. Contradicting the original hypothesis, treated stands exhibited higher mean albedo than natural stands, a process partially explained by the scarce canopy cover of young replanted forests. Further, mean surface temperatures in treated stands were 0.4-1.2 °C warmer than comparable natural stands. This relationship indicates current forestry policies may, in fact, be increased surface temperatures in managed forests. While further discriminant analyses failed to meet confidence thresholds, classification accuracies of ~70% suggest some discriminant ability within the predictor variables (albedo, surface temperature, and NDWI). The overall results of this thesis indicated that forest management is creating higher forest surface temperatures, but this phenomena is not related to decreased albedo in treated stands, and is likely caused by underlying processes not addressed in this study.

The outcomes of this work call into question the efficacy and validity of using forests as climate change mitigators. Specifically, whether Canada should continue to implement climate change policies that promote reforestation and afforestation if these methods may warm surface temperatures. In-depth analysis assessing the value forestation as a climate mitigation strategy should be conducting; contrasting the cost of increased surface temperatures caused by forest management against the considerable carbon sequestration ability of forests.

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Chapter 1: Introduction

1.1 Motivation

Climate change caused by the increasing accumulation of greenhouse gases in the atmosphere is creating substantial and increasing risks to natural and human systems (NOAA, 2022). The Intergovernmental Panel on Climate Change (IPCC) advises that global mean temperatures have already reached 1°C above pre-industrial levels and that an additional increase to 1.5°C will cause catastrophic and irreversible damage to earth's biosphere (IPCC, 2022). In the face of these potentially devastating outcomes, Canada has increased focus on nature based carbon sequestration (ECCE, 2020), specifically through afforestation (i.e., the planting of forests where there were previously no forests) and reforestation (i.e., the planting of forests to replace a forest than was removed or disturbed). A concern has been raised, however, that the choice of tree species being cultivated may actually be contributing to warming surface temperatures--potentially undermining the effectiveness of forests as climate mitigators (Naudts et al., 2016).

Traditionally, conifer (i.e., cone and needle-bearing) trees have frequently been selected for forestation due to their rapid growth rate and high commercial harvest value . Beginning in the sixteenth century, these stand management practices have led to wide-scale species conversions across Europe and North America (M. J. McGrath et al., 2015), shifting deciduous and mixed-woods to more commercially productive soft-wood forests with an unexpected consequence. Recent studies have linked these forest changes to lowered albedo (i.e., the ratio of solar radiation reflected by a surface)and subsequently increased local surface temperatures (Schwaab et al., 2020)

As afforestation and reforestation strategies are being increasingly implemented (Government of Canada, 2020), it is necessary to fully understand how forest management practices alter biophysical interactions between forests and the atmosphere to develop strategies that can effectively leverage forests as carbon sinks (Otto et al., 2014). In response, this thesis studied the relationship between forest treatments (managed or unmanaged forest stands) and biophysical factors (albedo, Normalized Difference Water Index [NDWI], and surface temperature) at a stand level. The results reflect on the impacts of historic and current forestry policy on local climates, and this work discusses the effectiveness of forestation as a climate mitigation strategy.

1.2 Background

Globally, the area of forests under management strategies (by both public and private sectors) has increased by 233 million hectares since 2000 (FAO, 2020). Managed forests tend towards low diversity, specifically conifer-dominant stands that produce higher densities of commercially profitable trees (Betts et al., 2022). These forestry practices have resulted in a large species conversion towards conifer dominant forests.

Surface temperature increases resulting from shifts in forest species composition have been established in recent literature. A study by Naudts et al (2016) quantified the impacts of forest management practices across Europe and determined that increases in conifer forest cover caused a 0.12°C rise in summertime temperatures. A similar study by Schwaab et al., (2020) established that, when compared to conifers, deciduous stands are more effective at regulating heat fluxes and can reduce the local impacts of short-term heat spikes. These results highlight the concern that continuing afforestation and reforestation methods preferencing conifers could add to warming global mean temperatures.

Increased surface temperatures associated with softwood forests are believed to be linked to the lower canopy albedo of conifer species. Albedo is the fraction of energy reflected from a surface back to the atmosphere (Halim et al, 2019). Coniferous stands have a lower albedo than deciduous stands (Otto et al., 2014), thus absorbing a higher ratio of solar energy and reradiating heat, resulting in an increase in surrounding air temperatures (Halim et al., 2019). Though hypothesized in much of the current literature, there is a lack of studies available quantifying the impact of species change on the forests' biophysical interactions with the atmosphere. Specifically, there is a gap of knowledge on how Canadian forest management practices have affected species composition, and how this may alter surface temperatures through canopy albedo levels.

1.3 Introduction to the Study

To address the gap in scientific knowledge discussed above, this thesis examined Nova Scotian forests as a case study to quantify the impacts of forest management practices on stand albedo and surface temperatures. The research question and associated hypotheses are:

To what extent have forest management practices in Nova Scotia impacted forest albedo and surface temperatures?

H*o*: Forest management practices have no significant impact on forest stand albedo and surface temperature.

H*a*: Forest management significantly decreases forest stand mean albedo and increases mean surface temperature.

Remote sensing methods were used to generate albedo, surface temperature, and Normalized Difference Water Index (NDWI) maps of Nova Scotia from optical satellite imagery collected during summer 2022. Treated and natural stands, identified by forest treatment data provided by the Nova Scotia Department of Natural Resources and Renewables, were then assigned mean albedo, surface temperature, and NDWI values using spatial analytics. Differences in the derived biophysical characteristics of silvaculturally treated and natural stands were then tested using ANOVA statistics, and further examined by running discriminant analysis.

Chapter 2: Literature Review

As the threat of climate change magnifies, understanding how forests can both offset or contribute to global warming is critical. This literature review will begin by outlining how historic forestry practices have shaped the current state of forests, then discuss the biophysical relationship between forest canopy, albedo, and surface temperatures. Attention will be drawn to Canadian forests, and their potential to mitigate climate change locally and globally, though large knowledge gaps on how forestry practices have altered Canadian forest are identified.. This chapter will also review recent studies quantifying the impacts of increased softwood forest cover on forest-atmosphere interactions and conclude by addressing the need for further stand-level studies focusing on Canadian forests.

2.1 The Evolution of Modern Forestry

Forestry, in its most basic understanding, is the use and care of forests (Kirby, 2015). Forest management has been practiced since the Neolithic period (Kirby, 2015), and to this day, forests remain a key source of food, fuel, and medicines for billions of people (FAO, 2020). Practices have grown and evolved with the increased anthropogenic reliance on forest products (Glatzel, 1991), but as we begin to depend on forests for their climate change mitigation potential as well, responsible management of these ecosystems must balance demand for timber and other forest products with conservation efforts (Günter et al., 2011). The beginning of this literature review will discuss the evolution of western forestry practices, and their influence on Canadian forests.

2.2.1 Europe

The foundation of western forestry practices was developed in Europe, and defined by the establishment of maximum sustainable yield harvesting. This method entails harvesting forests during their intermediate life stage to maximize continual and rapid timber production (Numbere, 2022). The results of this management strategy tends to be dense, even-aged, and low diversity woodlands. This principle has continued to guide forestry across Europe and many of its colonized countries (Lieffers et al., 2020).

2.2.2 Canada

The colonization of North America by European empires brought with it colonial forestry practices; specifically, forestry policies in Canada remain inextricably linked to traditional British timber practices (Oosthoek & Hölzl, 2018). Historically, the Indigenous peoples have stewarded Canada's forests, manipulating the landscape through selective harvesting and clearing of woodlands. In the Wabanaki-Acadian forests covering Nova Scotia and New-Brunswick, the Mi'kmaw First Nations maintained the deciduous dominant characteristics of the land with annual light burns of encroaching undergrowth and coniferous species (Drushka, 2003); but the Canadian landscape was radically altered with European settlement. Forested lands were cleared for agriculture, and timber was heavily relied on for homes, barns, and other infrastructure (Lieffers et al., 2020). The practice of maximum sustainable yield was applied as the primary forest management strategy. Consequences of this practice are becoming apparent in today's forestry industry, where the continuous management for dense and monocultured stands has lowered the production and quality timber (Vos et al., 2023). Recently, forestry practices have begun to shift towards other ecological management options to counter-act this effect (Lieffers et al., 2020).

2.2.3 Nova Scotia

Colonization and settlement in Canada began in the Maritime Provinces (Nova Scotia, New Brunswick, and Prince Edward Island) as early as 1603 (Biggar, 1926). The province of Nova Scotia was principle in some of the first forestry policies in North America (Drushka, 2003). In 1801, the British Crown ordered a forest inventory of Nova Scotia to assess the timber wealth held on the land. This assessment resulted in new legislation regulating the use and harvest of woodlands, and represents the first natural resource legislation in Canada (Leeming, 2012). Some of Canada's oldest forestry practices began in Nova Scotia, and as such, the province is an ideal area to study the long-term impacts of these policies.

2.2 Forest Species Conversion

Globally, forest management strategies have altered forest species compositions (M. J. McGrath et al., 2015; Saito, 2009). The applications of selective logging, replantation, and undergrowth management have continuously changed tree species composition to increase conifer tree yields (Bürgi & Schuler, 2003). This is because conifer stock has been historically considered as highly productive and valuable stock (Saito, 2009). The following section will outline the current literature on forest species conversions, and enduring knowledge gaps.

2.3.1 Europe

Significant tree species conversion has been documented across Europe, resulting in a considerable increase of conifer forest land cover (Naudts et al., 2016). This conversion occurred in two stages. Between the 1600s and 1800s, extensive amounts of native forests were converted to agricultural land (M. J. McGrath et al., 2015). Since the modernization of the agri-food industry in the mid 1800s, there has been a steady trend of afforestation, converting vacated farm-land to managed softwood-forests. This initial loss of native mixed-wood forests followed by the establishment of cultivated coniferous stands, has increased European softwood landcover by 29% since 1750 (Naudts et al., 2016).

2.3.2 Canada

While there lacks similar studies on forest species conversion in Canada, from historic forestry practices and comparable trends in Europe, a similar trend toward conifer dominant forests can be assumed. For instance, in the 1960s, the Ontario provincial government mandated regeneration plans for forest harvest blocks in an effort to restock the province's timber supply (Lieffers et al., 2020). Similar policies exist in many other timber reliant provinces, all requiring (until recently) that harvested areas be replanted or managed to produce 'optimal stocks', traditionally coniferous species (Lavender et al., 1990). Herbicides and other chemical weeding substances are also commonly applied to prevent the regeneration of first successional species (i.e., deciduous trees) and optimize conifer regrowth (Halim et al., 2019; Lieffers et al., 2020). Thus, through policies created to protect timber stocks and optimize harvest yields, there has likely been a wide-spread conversion towards softwood dominant forests, though more in-depth research is needed to quantify this theory.

2.3.3 Nova Scotia

As discussed earlier in this review, Nova Scotia has an long standing forestry sector, yet there are still considerable knowledge gaps in how the forests have been altered by continuous management. A large component of forestry in Nova Scotia includes reforestation methods (i.e., tree planting), planting both new forests and densifying established stands (Department of Natural Resources and Renewables, 2017). Reforestation is done to ensure the regrowth of preferred species in managed stands, and currently consists entirely of softwood species (Betts et al., 2022; Department of Natural Resources and Renewables, 2017). Thus, like the rest of Canada, it is probable that long-term management of Nova Scotian forests for 'optimal yield' as the primary objective has resulted in a continuous conversion towards conifer dominant stands, yet there is considerable research gaps addressing this theory

2.3.4 The Current State of Forest Management

As our understanding of forest ecosystems deepens, forest management practices are shifting away from prioritizing high-production, and are instead incorporating ecological management strategies to promote biodiversity and increase resiliency (Canadell & Raupach, 2008). These practices aim to both restore timber product quality and to utilize forests as effective climate change mitigators (ECCE, 2020). To promote these goals, further research on how management strategies impact forests and their interactions with the earth and atmosphere are crucial to inform new, adaptive policies.

2.3 Forests and Climate Change

The following section will highlight the current state of our climate and will discuss the use of forests as climate change mitigators in Canada.

2.4.1 Climate Change

Climate change has been defined as the long-term change in average meteorological variables such as precipitation and temperature, and is caused primarily by the accumulation of greenhouse gases in the atmosphere (Vos et al., 2023). One of the symptoms of climate change is global warming. The current global mean temperature have risen 1°C above pre-industrial levels; a further increase to 1.5°C will have catastrophic effects on natural and human systems (IPCC, 2022), including mass species extinctions, reduced global crop yields, and unprecedented frequencies and intensities of extreme weather events. Predicting global warming behaviour remains complicated due to the simultaneous and cumulative effects of different drivers (Varamesh et al., 2022). To respond to this threat, climate mitigation strategies are being implemented to reduce the concentration of carbon dioxide in the atmosphere, and limit net greenhouse gas emissions.

2.4.2 Climate Change in Canada

Canada experiences heightened effects of climate change because of the country's high latitude. Rising ambient temperatures, increasing extreme weather events, melting glaciers and sea ice, as well as shifting and expanding species distributions are occurring at higher rates than the global average (Kaplan & New, 2006). To address these impacts, the Canadian government has implemented climate change adaptation policies (ECCE, 2020), many of which revolve around the regions extensive natural resources. Canada's climate plan emphasizes the use of nature based solutions to mitigate climate change; a primary goal of these interventions is to protect and enhance the extensive amounts of carbon stored in the forests, soils, wetlands, grasslands, and oceans (Environment Canada, 2021). So, while Canada remains at an elevated risk from climate change, the country's abundance of natural resources has potential for effective and sustainable mitigation solutions.

2.4.3 Forests as a Climate Change Solution

Conserving and increasing forest land cover in Canada is a key climate mitigation strategy. Forests are highly effective at capturing and storing carbon from the atmosphere (Cunha-e-Sá et al., 2013), and sequester about 2.4 -billion tons of CO_2 each year (Wang et al., 2015). While a single nation, Canada possesses 20% of the world's forests and has considerable carbon sequestration potential (FAO, 2020), that it plans to expand by halting deforestation and applying afforestation and reforestation methods to further expand forest landcover (ECCE, 2020). One of these initiative is the "2-Billion Tree" program, where the federal government plans to invest up to 3.2 billion dollars to plant two-billion trees across the country (Environment Canada, 2021). As current reforestation trends and infrastructure support predominantly coniferous species (Department of Natural Resources and Renewables, 2017; Lavender et al., 1990; Lieffers et al., 2020), these efforts are likely to boost softwood forest cover in Canada.

2.4 Forests and the Atmosphere

As forests cover a substantial portion of the Earth's terrestrial surface, they have the potential to significantly influence both local and global climates (FAO, 2020). For instance, in the mid-Holocene, the northward movement of the boreal treeline caused a 4 °C local warming, and a 1°C global warming (Foley et al., 1994). This surface warming stemmed from a shift in landcover, where forests replaced tundra snow cover and drastically decreasing the surface albedo, raising surrounding air temperatures. There is increasing reliance on afforestation as a means of sequestering carbon from the atmosphere, and it is crucial to understand how forests impact their surrounding environment if they are to be effective and sustainable climate change mitigators. The following section will discuss the biophysical interactions between forests and the atmosphere, focusing on albedo and surface temperature.

2.5.1 Albedo and Surface Temperature

Albedo is the proportion of light reflected by a surface or object and has a direct relationship with surface temperatures. Objects or surfaces with higher albedo reflect more light, while less reflective surfaces absorb the energy (Varamesh et al., 2022). Only about 30% of the solar radiation (or "insolation") that hits the earth is reflected back into space--the rest is absorbed and re-emitted as longer infrared wavelengths, also known as heat. The Earth's average albedo remains relatively stable, but can be impacted by large events. After the 1991 Mount Pinatubo volcanic eruption, large amounts of aerosols entered the stratosphere, scattering sunlight and increasing the earth's albedo. This event reduced the global temperature by 0.7°C for over a year (Perkins, 2019). Changes in land cover and land use also have measurable heavily impacts Earth's albedo. Urbanization greatly alters surface albedo, and is known to create 'urban heat islands', where metropolitan centres are up to 5°C warmer than surrounding rural areas (Jacobson & Hoeve, 2012; Jiang & Tian, 2010). Altering surface albedo, both through natural or anthropogenic causes, can affect both regional and global temperatures, and large shifts in landcover, such as afforestation, may impact global warming behaviour.

2.5.2 Tree Species and Albedo

Forests cover one third of Earth's terrestrial surface and their albedo influences both local and global climate (FAO, 2020; Naudts et al., 2016). The albedo of forest canopy is influenced by several factors including stand age, canopy height, and seasonality (Halim et al., 2019; Otto et al., 2014). However, the largest determinant of albedo is species composition of the forest. Coniferous stands possess significantly lower albedo levels than deciduous, and absorb a higher ratio of solar energy (Schwaab et al., 2020), caused by a combination of stomatal conductance, canopy density and colour, and evapotranspiration. For example, Chapin III et al., (2000) concluded deciduous trees have twice the albedo of coniferous stands, and transfer 50-70% less heat into the surrounding atmosphere. Extrapolating, it is reasonable to hypothesize that modifying the species composition of a forest will likely change the surface albedo and could modify local temperatures.

2.5 The Climactic Impacts of Forest Management

Forest management strategies have caused a significant increase in softwood forests which—as discussed in previous sections— have a drastically lower albedo than deciduous forests. From this theoretical understanding, recent studies have further hypothesized that forestry practices have, and continue to, significantly alter surface albedo and warm surface temperatures. Research by Naudts et al., (2016) quantified this phenomenon in a meta-analysis of the climactic impacts of European forest management. The study linked the replacement of broadleaf forests with coniferous species to a 0.08°C increase in peak summertime temperatures: driven by changes in forest cover, impacting the sensible and latent heat flux of the forest stands and decreased evapotranspiration, meaning the atmospheres ability to release thermal heat was reduced (Naudts et al., 2016). The study also identified afforestation, and wood extraction as two other main but lesser drivers of warming summertime temperatures, each responsible of 0.02°C increase. A similar study by Schwaab et al., (2020) observed a cooling effect of 0.3-0.75 °C is associated with increased broadleaf presence in European forests. This effect is amplified during extreme heat events, where the cooling potential reached up to 1.8 °C during the hottest periods. While this study identified a possible solution to mitigate local impacts of hot temperature extremes, an 80% increase in the deciduous tree fraction is required to see significant cooling effects (Schwaab et al., 2020). The full impacts of forest species conversion is only beginning to be understood, and so far research has been limited to European forests.

There has been more extensive research on the climactic impacts of afforestation, though current literature on the topic is somewhat confounding. As an example, Juang et al., (2007) found that the conversion of old pastures to planted coniferous forests caused a 0.9°C increase in average surface temperatures. And further research by Canadell & Raupach (2008) suggests that reforestation efforts in the northern hemisphere are counterproductive as they replace high albedo areas (i.e., snow cover) with softwood stands, thus lowering surface albedo, which heightens the local impacts of global warming during winter months. In contrast, though, this relationship established in the previous examples is contested by Jackson et al., (2005), who found that tree plantations decreased summertime temperatures by 0.3°C in the southern United States. As well, in an extensive study of the land conversion across Brazil, Bright et al., (2017) found that replacing forests with croplands was directly associated with a 0.5°C increase in local surface temperatures. The analysis also found that forest cover gain (from reforestation and afforestation) led to notable annual cooling (Bright et al., 2017). The current knowledge on the climactic effects of afforestation is disputed and inconsistent. The research is also limited by the complexity of differentiating the impacts of local afforestation effects from rising global mean temperatures (Canadell & Raupach, 2008). Further studies are integral to clarify if forestation efforts are possibly exacerbating global warming.

2.6 Knowledge Gaps and Limitations

There are several knowledge gaps and limitations identified in the current body of literature surrounding the impacts of forest species conversion. The first relates to the spatial scale at which many of the studies are conducted. Remote sensing based methodologies were applied in all of the studies discussed above, many of which used Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data (Bright et al., 2017; Schwaab et al., 2020).

For broad regional-scale analysis, this platform is ideal because it collects at a 1-kilometer spatial resolution, reducing the computational load associated with finer resolution imagery. Albedo and surface temperature data from MODIS were used in both Naudts et al., (2016) and Schwaab et al., (2020) studies quantifying the effects of forest species conversion. While MODIS data was likely chosen because it provides both broad-band albedo and surface temperature products, it's application introduced sources of error into the studies. Forest cover can vary drastically within a 1km^2 area, and using a coarse spatial resolution averages the signal from several landcover types and may introduce confounding variables, thus limiting the validity and strength of the results. To counteract this, furthering studies should be conducted on a more local spatial scale with finer spatial resolution data (if available), allowing for stand-level analysis.

There also remains a gap in literature assessing both the species conversion trends within Canada, and how this may impact albedo and local surface temperatures. Research on this phenomenon tends to be limited to Europe and has only been conducted using coarse spatial resolution data at broad scales. Studies on the impacts of afforestation are also lacking within Canada, with a majority of this research conducted in the southern United States (Jackson et al., 2005; Juang et al., 2007) or South America (Bright et al., 2017). As Canada is home to 20% of the world's forests (FAO, 2020) and is experiencing heightened impacts of global warming due to its northern latitude (NRTEE, 2009), studies on how forest management may alter local climates is pressing and necessary.

2.7 Conclusion

This literature review covered both how forest management practices have caused an increase in coniferous forest landcover, and how this in turn is raising local surface temperatures by lowering canopy albedo. This trend has been quantified in two European meta-analyses, though this chapter also outlined the considerable knowledge gaps surrounding how Canadian forests have been impacted by forestry, and whether this is causing similar warming to European trends. Whether afforestation practices can help or hinder global warming is still debating within the literature, though there is notable gap in Canadian studies here as well. Overall, as Canada has experienced similar forestry practices which lowered surface albedo in Europe, theoretically this should result in comparable warming surface temperatures. This is the knowledge gap which this thesis attempted to solve.

Chapter 3: Methods

3.1 Overview

This study aims to determine the extent to which forest management practices have impacted forest albedos and subsequently impacts stand level surface temperatures by contrasting forests stands in Nova Scotia known to have undergone silviculture treatments. Three biophysical variables were derived (albedo, surface temperature, Normalized Difference Water Index [NDWI]) from optical, multispectral satellite imagery collected by the Landsat series of satellites. Mean values were then assigned to identified forest stands across the province. Spatial data processing tasks and data management was conducted using the ESRI ArcGIS Pro™ platform; data was then exported to SPSS for further statistical analysis. This analysis included one-way ANOVA and Discriminant Analysis to test for relationships between stand treatment types (natural, treated) and the three continuous variables.

3.2 Study Area

3.2.1 Nova Scotia Ecoregions

The provincial boundaries of Nova Scotia were used as the study area in this thesis, because forest data was provided by the Nova Scotia Provincial government, and covering Nova Scotia exclusively. Nine Ecoregions have been identified in Nova Scotia's recent Ecological Classification assessment (Figure 1). Ecoregions partition the province by factors such as climate, physiography, vegetation, and soil type (Neily et al., 2017). In Nova Scotia, the determining criteria when delineating ecoregion boundaries is often elevation and proximity to the Atlantic Ocean coast. Each ecoregion displays distinctive terrestrial ecosystems and range in size from 416 km^2 to 16,870km^2 (Neily et al., 2017). The ecoregion that each forest stand falls was identified, and stands were compared within ecoregion to assure similar climactic and ecological influences.

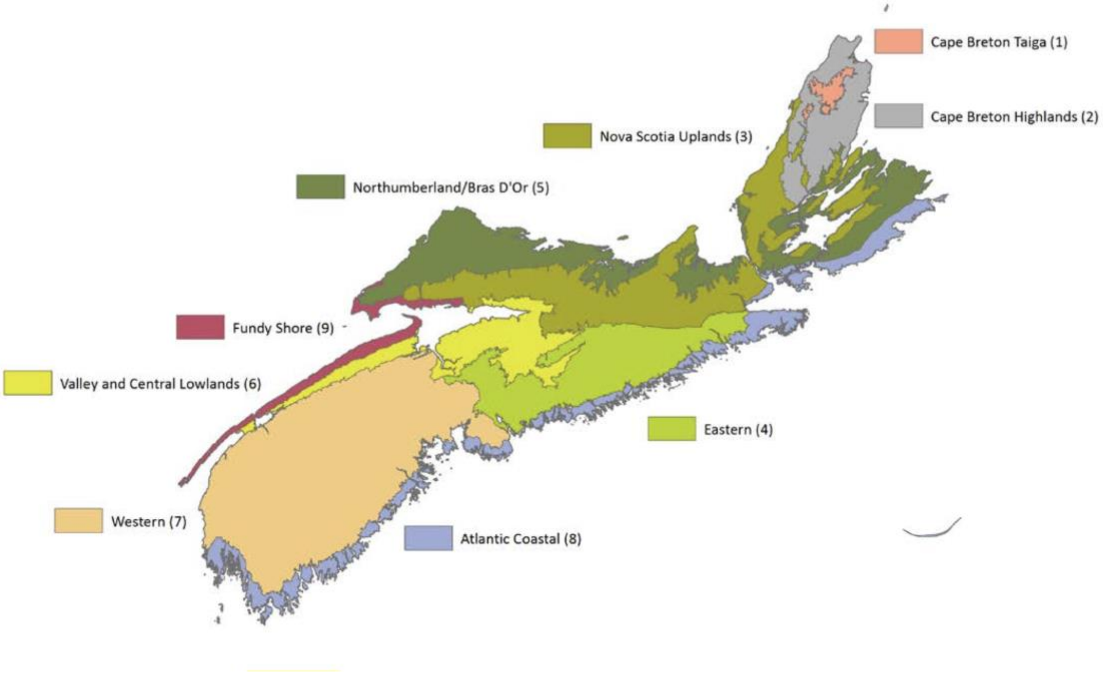

Figure 1: Map of Nova Scotia displaying the province's nine ecoregions (image Source: Department of Natural Resources, 2017)

3.3 Forest Stand Identification

3.3.1 Forest Stand Datasets

This study was conducted at a stand level, meaning one mean value for each biophysical variable was assigned to each stand. Forest stand data was received from two sources. Natural stands were identified using the Nova Scotia Forest Inventory (2021), an open-source geographic database of forest data provided by the province. The inventory was first created in 1985 and has undergone several revisions over time. As of 2021, the database is continuously updated by the Nova Scotia Department of Natural Resources and Renewables using a combination of satellite imagery, aerial imagery, and field data (Department of Natural Resources and Renewables, 2017).

Treated stands were identified from a geodatabase of silviculture treatments provided in a data sharing agreement with the forestry division of the Nova Scotia department of Natural Resources and Renewables. The geodatabase contains records of location (as a polygon) and type of silviculture treatments of forest stands. Additional characteristics such as treatment category (pre-commercial thinning, plantation, etc..), year of treatment, and species composition are included in the attribute table for most stands (NS Department of Natural Resources and Renewables, Forestry Division, 2024).

3.3.2 Natural Forest Stands

To determine if forest management practices have impacted forests biophysical interactions with the atmosphere, natural (i.e., unmanaged) stands were selected to act as a control group. Natural stands were defined in this study as any forested area that has not undergone silviculture treatment and has either not undergone any harvesting or has regrown with no management to state where the impact of the harvest is no longer apparent. These sites are termed ‘natural stands’ in the forest inventory and should reflect the natural tree composition of that ecoregion in a later successional phase. As an example, an unmanaged stand in the Cape Breton Highlands (Ecoregion 2, Figure 1) is likely composed of balsam fir (*Abies balsamea*), white spruce (*Picea glauca*), heart-leaf birch (*Betula cordifolia*), and white birch (*Betula papyrifera*) (Neily et al., 2017).

Untreated stands were identified from the provincial forest inventory. Untreated or ‘Natural’ stands were isolated through a select by attribute search and then exported to a new ‘Natural Stands’ feature class. Urban trees groupings and highway buffer stands were originally included as ‘natural’ in the forest inventory; however these stands were removed from the dataset to reduce any impacts related to the proximity of these stands to areas of urban expansion on stand surface temperature and albedo that could bias the analysis. Urban forest stands were identified by creating a 1km buffer around all paved road [data from the Nova Scotia Road Network (Service Nova Scotia, 2024)] and all stands intersecting the road buffer were removed. The final dataset contained 130,588 stands.

3.3.3 Treated Forest Stands

All 114,334 forest stands provided in the forest treatment geodatabase were included in the ‘Treated Stands’ dataset. Stand characteristics such as treatment year, species composition, age, and density were considered for use in the analysis. While these attributes were provided for some stands within the dataset, they were not provided for a considerable number of stands and were ultimately omitted from the analysis.

3.3.4 Complete Stand Dataset

The natural and treated stand datasets were merged (Merge Tool ArcGIS Pro™) into one polygon feature class containing a total of 244,922 stands. Treated stands retained their treatment category class; natural stands were assigned a new treatment category of ‘natural’ for this attribute. A new float attribute named ‘Treatment’ was created, where treated stands = 1 and natural stands = 2, to maintain to two original groups.

3.4 Scene Selection

3.4.1 USGS Earth Explorer and Landsat Imagery

The optical, multispectral satellite imagery necessary to derive Albedo and Surface Temperature were obtained through the United States Geological Survey (USGS) Earth Explorer platform (https://earthexplorer.usgs.gov). This portal allows users to search and download publicly available satellite and aerial imagery based on user defined parameters (U.S. Geological Survey, 2022).

Albedo and surface temperature values at the pixel level were derived from optical remote sensor data (multispectral imagery), collected by the Landsat satellite series and available through USGS Earth Explorer. Landsat satellites 4 through 9 provide the spectral resolution necessary to estimate broadband albedo from narrow bands, and the platform also collects thermal infrared wavelengths used to estimate surface temperature. The temporal limits on this approach is that imagery availability is limited post-1982 (U.S. Geological Survey, 2023). However, to synchronize imagery with current forest stand data, scenes searches were limited to between 2020 and 2023. Imagery collected over this temporal range comes from the Landsat-8 satellite using the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) sensors. The resolutions of imagery collected are listed in Table 1.

Table 1: Landsat 8 OLI and TIRS sensor resolutions

Sensor	Resolution Type	Resolution
OLI	Temporal	16 days
	Spectral	9 bands (coastal aerosol, blue, green, red, near-infrared, SWIR 1, SWIR 2, Panchromatic, Cirrus)
	Radiometric	12-bit
	Spatial	30 meters 15 meters for panchromatic
TIRS	Temporal	16 days
	Spectral	2 bands (TIRS 1 and TIRS 2)
	Radiometric	12-bit
	Spatial	100 meters (resampled down to 30 meters)

A search criterion was applied on Earth Explorer to limit dataset searches to Landsat-8. Both Level 1 (Top of Atmosphere) and Level 2 (Bottom of Atmosphere) products are necessary for each scene. Top Of Atmosphere (TOA) products are radiometrically corrected for band specific sensitivities and solar illumination

Bottom of Atmosphere (BOA) products were used to estimate surface temperatures and NDWI values because the bands has been radiometrically corrected for solar illumination and atmospheric effects to accurately depict surface reflectance. Radiometric corrections were manually applied to Level 1 products to generate TOA scenes necessary for albedo calculations. Top of Atmosphere corrections account for solar illumination and sensor sensitivities, but do not correct for atmospheric conditions.

Imagery was selected from summertime months (July and August) for two reasons. One, rising peak temperatures are one of the greatest concerns associated with global warming (Dongjin Cho et al., 2020; IPCC, 2022), and two, to capture peak canopy coverage before deciduous canopy is lost during autumn. Furthermore, to obtain imagery for the entire province, several collection dates were necessary as the Landsat series does not capture the entire province on a single orbital pass. Lastly, a search filter was applied as a parameter when selecting scenes on Earth Explorer to display images with less than 15% cloud cover to maximize the probability of identifying cloud free scenes. This step is particularly important as clouds are high albedo features — not present at ground level— that create spurious results in albedo calculations when present. Finally, to limit the search range to our study area, in Earth Explorer a polygon was manually drawn covering Nova Scotia. A summary of the search criteria applied is shown in Table 2, and the output was collection of 10 scenes covering Nova Scotia, captured by Landsat-8 in July and August 2022.

Table 2: Search terms and ranges adopted to select appropriate imagery of Nova Scotia

Search Criteria	**Input**
Date Range	Search (mm/dd/yyyy) from 07/01/2020 to 08/31/2023 Search months July and August
Cloud Cover	Range of 0-10%
Datasets	Landsat-8 Collection 2: level-1 & level-2 products
Search Area	Select 'Use map' and manually draw polygon covering the whole of Nova Scotia

3.5 Image Processing

The selected scenes were processed individually to produce albedo, surface temperature, and Normalized Difference Water Index (NDWI) raster layers (a grid of regularly sized pixels making up the image). Scenes collected on the same date (i..e, same path, but different row) were mosaiced to create four rows (vertical strips of images) covering the province. Finally, using the Zonal Statistics tool in ArcGIS Pro, mean values of the biophysical variables were calculated for each forest polygon.

3.5.1 Rescaling of Landsat Products

While the original data was collected in 12-bit radiometric resolution, the Level 1 and Level 2 products provided by USGS Earth Explorer are rescaled to unsigned 16-bit integers, eliminating decimal points in a less complex pixel depth and thus reducing the computational load associated with large scale remote sensing data. To back calculate the digital numbers (DNs) to meaningful measurements (e.g., reflectance or surface temperature), a scale factor and offset are applied, provided in the image metadata for each spectral band. Each band can be multiplied by the scale factor and adding the offset, returns the DNs or Brightness Values (BVs) to measures of interest. As this study uses both Level 1 and Level 2 products, two separate conversion methods were applied. The output of the rescaled surface reflectance should range from 0 to 1 (representing the fraction or proportion of incident EMR is reflected from the surface of the object or feature). Similarly, surface temperature is rescaled to degree Celsius.

3.5.2 Level 1 Top of Atmosphere Reflectance

To derive estimated albedo, spectral bands measurements corrected to Top of Atmosphere (TOA) reflectance were needed. Following the Landsat-8 Data User Handbook, Equation 1 was used to calibrate for TOA conditions for all Level 1 spectral bands in each scene:

Equation 1: Landsat 8 conversion from Level 1 Digital Numbers to TOA reflectance

$$\rho_{\lambda}' = M_{\rho} * Q_{cal} + A_{\rho}$$

(US Geologic Survey, 2019)

Where:

ρ_{λ}' = TOA Planetary Spectral Reflectance, without correction for solar angle.

M_{ρ} = Reflectance multiplicative scaling factor for the band (from metadata)

A_{ρ} = Reflectance additive scaling factor for the band (from metadata).

Q_{cal} = Level 1 pixel value

Then to achieve true TOA reflectance, the spectral imagery was corrected again for the solar elevation angle using Equation 2:

Equation 2: correct planetary reflectance for solar elevation angle

$$\rho_\lambda = \frac{\rho_\lambda'}{\sin(\theta_{SE})}$$ (US Geologic Survey, 2019)

Where:

ρ_λ = TOA planetary reflectance

θ_{SE} = Local sun elevation angle; the scene center sun elevation angle in degrees is provided in the metadata

To reduce the number of manual calculations required, and the potential for individual errors, an iterative cartographic model was created in ArcGIS Pro™ in the Model Builder extension. In this model, Level 1 data was rescaled to TOA values using the with manual inputs of scaling factors and sun elevation angles unique to each scene.

3.5.3 Albedo

Once calibrated, the TOA surface reflectance bands were used to calculate surface albedo. Albedo was derived from a narrow to broad band conversion using the weighted sum by Liang (2001) for Landsat multispectral bands.

$Equation\ 3: conversion\ for\ narrow\ to\ broad\ band\ albedo$

$$\alpha = \frac{0.356\rho_1 + 0.130\rho_3 + 0.373\rho_4 + 0.085\rho_5 + 0.072\rho_7 - 0.0018}{0.356 + 0.130 + 0.373 + 0.085 + 0.072}$$

Where

$\alpha = albedo$

$\rho_n = pixel\ value\ of\ band\ n$

Broadband albedo is the total reflectance of all electromagnetic wavelengths by a surface. Satellite multispectral data can be used to approximate broad band albedo using a weighted sum of the narrow spectral bands. This methodology allows albedo approximations to be made at a much finer spatial resolution than the available broadband-albedo-specific sensor data such as MODIS (spatial resolution = 1km) (Liang, 2001)

Liang's equation was further adopted for the Landsat-8 OLI bands by Naegeli et al. (2017). Outputs of this equation have been tested against in-situ albedo observations and deemed reliable (±0.07 accuracy) (Naegeli et al., 2017).

Equation 4: narrow to broad band albedo conversion adopted for Landsat 8 multispectral imagery

$$\alpha = 0.356\rho_2 + 0.130\rho_4 + 0.373\rho_5 + 0.085\rho_6 + 0.072\rho_7 - 0.0018$$

Though this adaptation of Liangs (2001) work (Equation 4) was originally created for glacier albedo measurements, several studies have translated this methodology to estimate vegetation albedo (Fernández-Guisuraga et al., 2021; Li et al., 2022; Santos Orozco et al., 2023). This weighted sum uses a combination the visible, near-infrared, and shortwave-infrared (SWIR) bands (Table 3). Notably, the visible-green band is excluded from the equation, Liang (2001) determined that the standard deviation of band 2 was too large; removing the band and refitting the equation did not significantly alter the results.

Table 3: Landsat-8 spectral bands used in albedo calculations

Band	**Qualitative Band Name**	**Wavelength Range (µm)**
b_2	Blue	0.45-0.51
b_4	Red	0.64-0.67
b_5	Near-Infrared	0.85-0.88
b_6	SWIR 1	1.57-1.65
b_7	SWIR 2	2.11-2.29

The raster calculator tool (ArcGIS Pro™) was used to calculate albedos for each scene, creating an albedo raster output with pixel values between 0 –to 1 (i.e., proportion).

3.5.4 Level 2 Bottom of Atmosphere Reflectance and Surface Temperature

Bottom of Atmosphere products were used to derive both surface temperature and NDWI values. Contrary to Level 1 conversions, the same scale factor and offsets can be applied to all scenes when rescaling to BOA products, and iterative models were created to rescale both multispectral reflectance and temperature bands. Multispectral bands were rescaled using the scale factor and offsets from Table 4 to produce surface reflectance values. Surface

Temperature values were achieved using the conversion factors in Table 4 and subtracting an additional 273.15 to convert from Kelvin to degrees Celsius.

Table 4: Rescaling factors applied to Landsat products

Product	**Scale Factor**	**Offset**
Level 2 BOA Surface Reflectance	0.0000275	-0.2
Level 2 BOA Surface Temperature	0.00341802	149 (- 273.15)

3.5.5 Normalized Difference Water Index

Normalized Difference Water Index (NDWI) was incorporated into this study to account for possible underlying water pixels in forest stands. Water has a very low albedo (i.e., it absorbs a high ratio of solar energy) and can distort mean stand albedo values. The Normalized Difference Water Index acts as an estimate for water presence in stands and ranges from -1 to +1, where higher values indicate aqueous surfaces. The index was calculated using the method outlined by Phankamolsil and Kosirsakulai (2020) as follows:

Equation 5: NDWI calculation from satellite multispectral imagery

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

Visible green wavelengths are used to maximize the reflectance of water, and the near infrared (NIR) band to differentiate between water and other ground cover. While water has a high absorption of NIR, vegetation and soil reflect a substantial proportion of NIR, meaning NDWI applications can differentiate bodies of water from natural land cover (Phankamolsil & Kositsakulchai, 2020). NDWI may introduce uncertainty is when attempting to differentiate between water and built areas, as they can both return high (>0) values (Szabo et al., 2016). Level 2 BOA reflectance bands were used to derive NDWI for each scene, where: Green = band 3, NIR = band 5.

3.5.6 Single Band Mosaics of Biophysical Variables

The ten scenes covering Nova Scotia were collected over 5 dates (July 9th,18th, 19th, and August 21st, 2022) in 4 rows (vertical columns of overlapping images). To minimize edge effects and encourage continuity across the study area, single band mosaics were created for each target variable, merging bands with the same collection date together using a mean operator (the mean value was taken of all overlapping pixels). The boundaries of the mosaic layers were then calculated (Raster to Polygon tool, ArcGIS Pro™), and combined into one shapefile, and labelled by raster row (006-009). Finally, using the spatial join tool (ArcGIS Pro™), a new float field was created in the forest stand dataset listing which raster row (i.e., mosaiced band) each stand fell within. This row ID field identifies which mosaic variable scene was used to calculate stand values (e.g., mean albedo).

3.5.7 Masking Cloud in Variable Mosaics

While satellite imagery with <15% cloud cover were selected, it was necessary to remove some clouds from each scene. A cloud and cloud shadow mask was created using the Level 1 quality assessment pixel band (QA_pixel) provided by USGS that identifies pixels containing cloud, cloud shadow, snow, or ice. The cloud mask consisted of a binary raster layer where cloud/cloud shadow = 0, and any other pixel = 1. Using the raster calculator tool, each variable layer was multiplied by the cloud mask, the output was cloud (and cloud shadow) pixels = 0 and all other pixel values unchanged. Lastly, the Set Null tool was applied to set all cloud pixels(value = 0) as No Data.

3.5.8 Assigning Mean Variable Values to Forest Stands

A mean albedo, surface temperature, and NDWI value was calculated for each stand in the dataset using zonal statistics (ArcGIS Pro™ Tool zonal statistics as table). A tabular join (Join Field Tool) was then executed, (joining tables by object ID) to assign the derived mean values to the corresponding forest stand. Mean values were stored in a new field (e.g., 'mean albedo') as a 32-bit float to allow negative values and decimal places. Stands which contained No Data pixels were assigned a mean of 0 and removed from the dataset. Additionally, stands smaller or thinner than one pixel (30 meters) could not be rasterized, and were also removed. The final dataset table contained 216,235 forest stands.

3.5.9 Ecoregions

Lastly, forest stands were classed by ecoregion using an open source shapefile of Nova Scotia's ecological land classifications (Department of Natural Resources and Renewables, 2015). A spatial join was executed to identify which ecoregion a forest stand was within. Any stands overlapping two ecoregions were assigned to the ecoregion making up the majority of the stand.

3.6 Analysis

The data collected during this thesis is both categorical and continuous (Table 5). As such, one-way ANOVAs and discriminant analyses will be used to assess the relationships.

Table 5: list of all variables assigned to each forest stand

Variable	**Continuous or Categorical**	**Range**
Treatment	Categorical	Natural or Treated
Ecoregion	Categorical	1 to 9
Albedo	Continuous	0 to 1
Surface Temperature	Continuous	3 to 61°C
NDWI	Continuous	-1 to + 1

3.6.1 One-way ANOVA

One-way ANOVA statistics were employed to test for significant differences between variable means in the two treatment groups (Natural and Treated stands). The ANOVA tests were conducted separately in each scene and for each of the three continuous variables (albedo, surface temperature, NDWI). A significance threshold of $p<0.001$ was set, where a p value greater than 0.001 would indicate no significant difference between groups. Data was first tested against assumptions necessary to run an ANOVA. Descriptions of assumptions and the assumption test results in Appendix A.

3.6.2 Discriminant Analysis

Linear discriminant analysis was used to test whether albedo, surface temperature, and NDWI variables could be used to correctly predict a forest stands treatment group (natural or treated). A discriminant analysis uses measured variables to separate observations into (typically dichotomous) categories, (Subramaniam et al., 2023). The analysis identifies the most suitable linear combination of variables to discriminate between groups (Dube et al., 2017). The output is a discriminant function used to categorize the classes, in this case the natural and treated stands, using a measure of generalised squared distances between the observations. If the discriminant analysis is appropriate, there will be a high accuracy of classification, meaning a relationship exists between the predictor variables and the classes. Generally a classification accuracy of >80% considers the model suitable (He et al., 2020) and the metric applied in this study.

Several assumptions must be met within the dataset to apply discriminant analysis. First, the predictor (independent) variables should have a normal distribution (Subramaniam et al., 2023). As well, the within group variance, measured in generalised squared distances, should be approximately equal between groups (He et al., 2020). Lastly, the class membership is assumed to be mutually exclusive, and exhaustive. In other words, one observation cannot belong to multiple groups and the classification system permits all observations to belong to an existing class.

As with the ANOVA tests, discriminant analyses were run within scene rows, and then additional analyses were run within ecoregions within each scene row (if the group membership was approximately equal between treated and natural stands). The output of each analysis provided a classification accuracy (%), an Eigenvalue, and a Wilks lambda statistic. The Eigenvalue defined the amount of variance within the grouping variable (Natural or Treated) explained by the predictor variables (albedo, surface temperature, NDWI); a higher eigenvalue indicated a greater discriminant power. The Wilks lambda output describes the discriminant ability of the independent (predictor) variables and ranges from 0 (discriminant) to 1 (no discriminant power). The suitability of each discriminant function was assessed based on a classification accuracy (where >80% was considered significant), a high eigenvalue, and low Wilks lambda.

Chapter 4: Results

4.1 Imagery

4.1.1 Scene Selection

Data was compiled from a total of 10 scenes spanning 4 rows (006-009) and used to represent the entire province of Nova Scotia (Figure 2). Imagery was collected between July 9th , 2022 and August 21st, 2022, with less than 15% cloud cover per scene. Scene 008.1 was discarded during analysis due to an insufficient (49) count of treated stands fell within the scene.

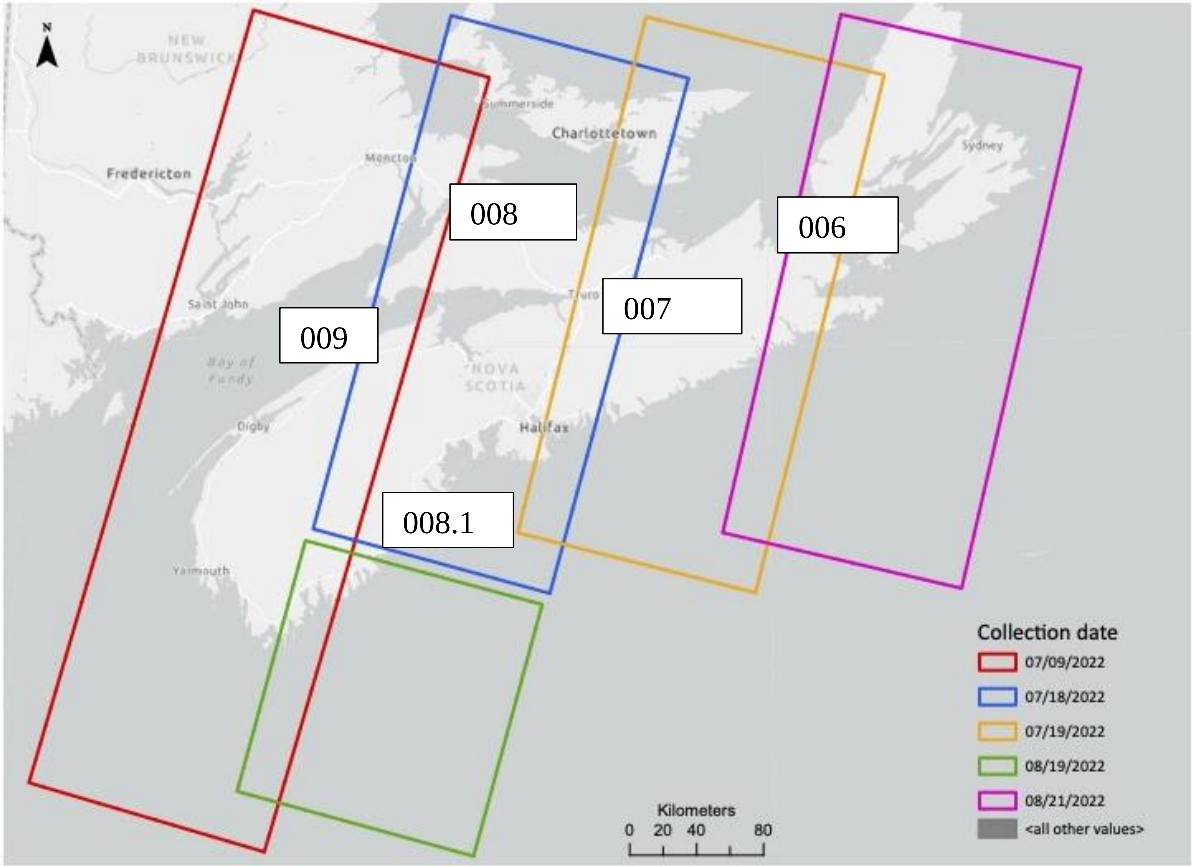

Figure 2: Approximate footprints of compiled scenes and dates of collection (YYYY-MM-DD))

4.1.2 Albedo

The surface albedo of Nova Scotia (*Figure 3*) derived in this study ranges from 0.176 to 0.785, with a mean value of 0.246. A cluster of extreme high values was found around the Halifax Regional Municipality (3-37 st. deviations from mean, high of 0.785). Northern regions of the Province (Antigonish, Inverness, Victoria, Cape Breton counties) displayed higher albedo values when compared to central and southern areas of the province, with particularly high albedo along northern coastal areas. Albedo values were much lower in the south-western regions of the province, ranging 0-3 standard deviations from the mean.

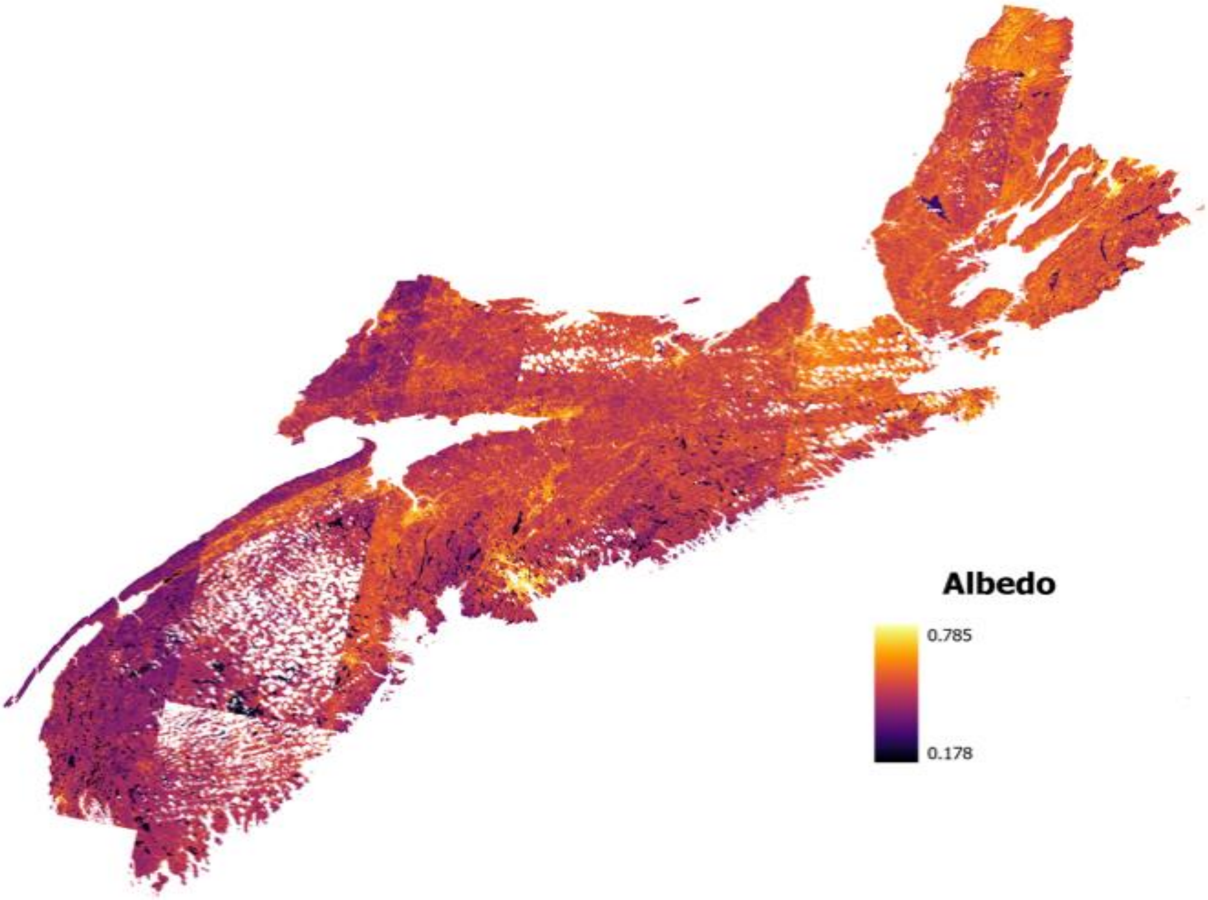

Figure 3: Albedo of Nova Scotia collected July 9 -August 21, 2022 (Landsat 8 OLI)

Cloud cover and cloud shadow were masked out using Landsat quality assessment pixels, and were reclassified to no data. Largest areas of cloud cover were present in row 008, while smaller cloud clusters were also present in rows 007 and 006. Stands that overlapped with cloud or cloud shadow cover were excluded from analysis.

4.1.3 Surface Temperature

Surface reflectance temperatures for Nova Scotia ranged from 3.6°C to 61.0°C, however as multiple collection dates were used to image the entire province, climate varied between scenes (Table 6).

Table 6: Descriptive statistics of surface reflectance temperature per scene row

Scene		**Surface Temperature (°C)**					
Row	Collection Date	Mean	Range	Minimum	Maximum	Median	St. Dev
006	08/21/2022	27.1	42.6	14.9	57.5	26.8	1.9
007	07/19/2022	28.3	52.1	8.9	61.0	28.1	2.1
008	07/18/2022	27.7	45.4	6.3	51.7	27.8	3.1
009	07/09/2022	24.8	44.8	3.6	48.4	24.8	2.5

Highest surface temperatures (Figure 4) were recorded in scene 007, reaching up to 61.0°C. Scene 007 also had the highest mean surface temperature (28.3°C). A cluster of extreme high values was found around Halifax Regional Municipality, with surface temperatures between 35°C and 47°C. The lowest surface temperatures (3.6°C) were found in the south-west corner of the province in row 009, along with the lowest mean row surface temperature of 24.8°C.

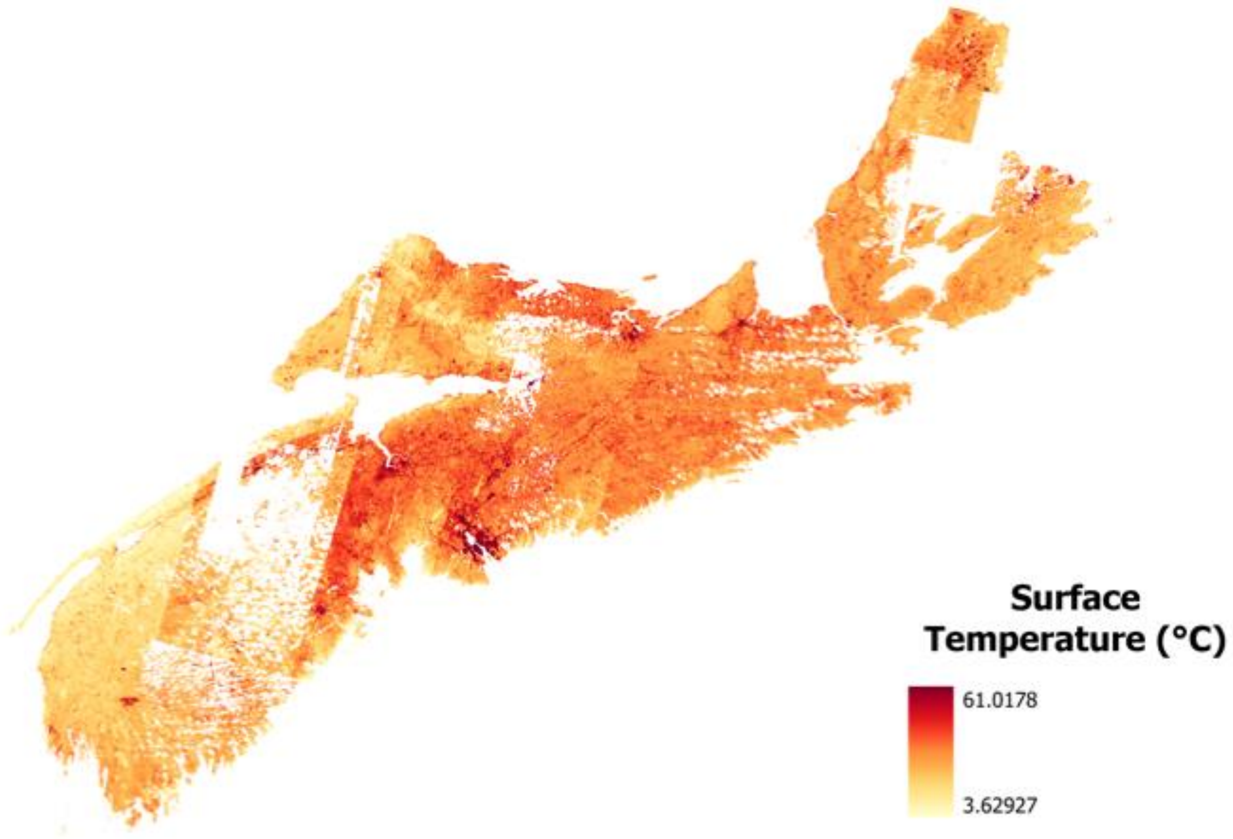

Figure 4: surface temperature of Nova Scotia, collected July 9 - August 21, 2022

4.1.4 Normalized Difference Water Index

The Normalized Difference Water Index (NDWI) derived from the multispectral imagery ranged from a minimum of -0.999 to a maximum of 0.999 (Table 7), almost meeting the full possible range of -1 to 1. This index is sensitive to changes in moisture content or recent rainfall, and as such should be considered separately by collection date.

Table 7: Normalized Difference Water Index (NDWI) descriptive statistics

Scene		**NDWI**					
Row	Collection Date	Mean	Range	Minimum	Maximum	Median	St. Dev
006	08/21/2022	-0.754	1.998	-0.999	0.999	-0.786	0.142
007	07/19/2022	-0.745	1.998	-0.999	0.999	-0.770	0.123
008	07/18/2022	-0.716	1.998	-0.999	0.960	-0.746	0.118
009	07/09/2022	-0.709	1.998	-0.999	0.999	-0.747	0.144

The mean and range of NDWI values were similar across scenes, with 009 having the highest mean NDWI value (-0.709) and 006 the lowest (-0.754). Large water bodies, seen in dark blue in Figure 5: NDWI of Nova Scotia, collected between July 9-August 21 (Landsat 8 OLI), are identified by high positive NDWI values (0.2-0.99), while surrounding land values range mostly from -0.99 to 0, suggesting non-aqueous surfaces. Similar to surface temperature and albedo results, a cluster of high NDWI values is apparent around the Halifax Regional Municipality, likely caused by the sensitivity of the index to built-areas.

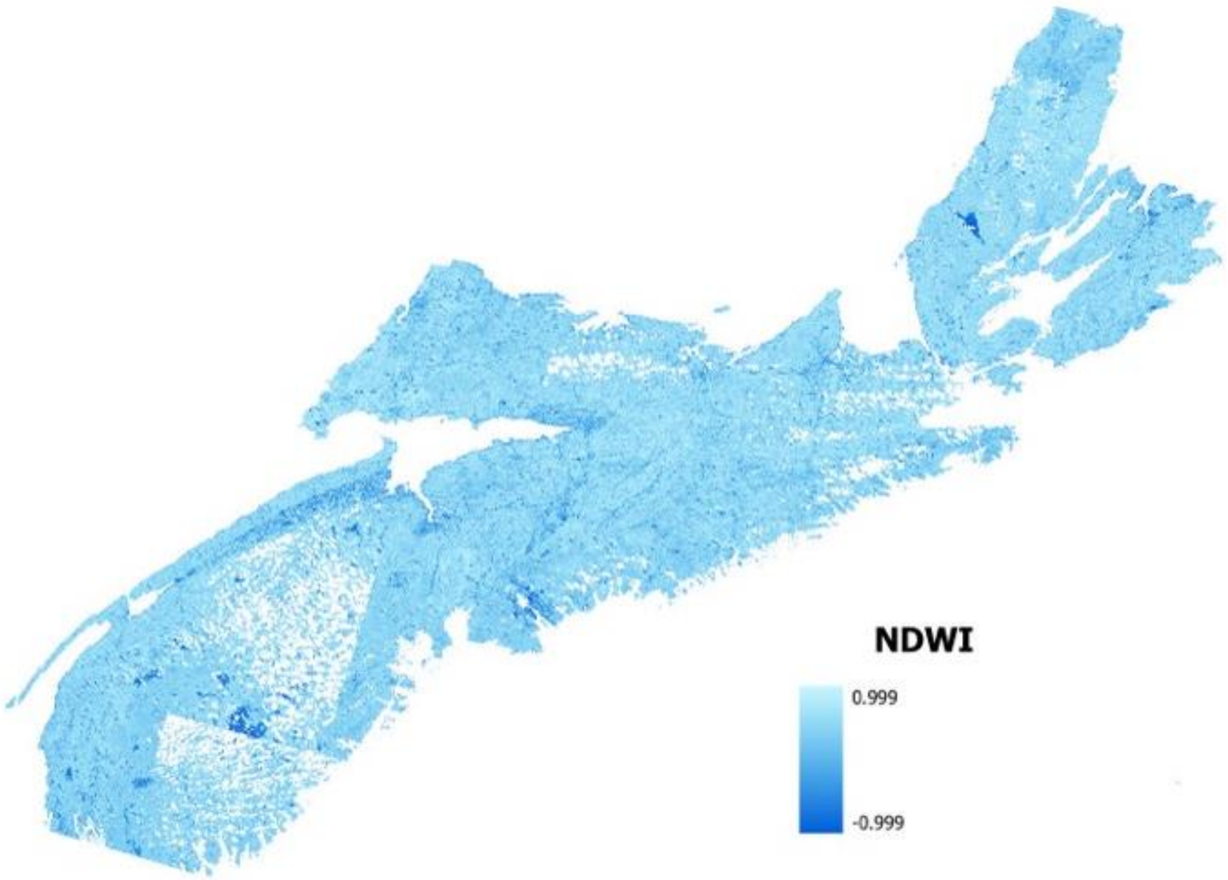

Figure 5: NDWI of Nova Scotia, collected between July 9-August 21 (Landsat 8 OLI)

4.2 Forest Stands

4.2.1 Forest stand dataset

Forest datasets from the department of Natural Resources (114,334 treated stands) and from the Nova Scotia Forest Inventory (130,588 natural stands) were merged to create the complete data of forest stands assessed in this thesis (counts seen in Table 8). Once stands containing cloud or cloud shadow pixels were removed, a total of 216,235 stands remained; 89,171 treated stands (41%) and 127,064 natural stands (59%).

Table 8: Count of Forest stands by Treatment Type and Scene

		Total				
Scene		006	007	008	009	Total
Treatment	Treated	6139	36121	40479	6432	89171
	Natural	13215	32436	39088	42325	127064
Total		19354	68557	79567	48757	216235

To account for climatic variability between satellite imagery scenes the comparison of stands were constrained within individual scenes. The highest count of stands were covered by scene 008, containing 45.4% of all treated stands, and 30.8% of all natural stands (36.8% of total stands). Scene 006 and 009 both contained small quantities of treated stands (6.9% and 7.2%). Scene 006 also contained the lowest amount of natural (10.4%) and total stands (8.9%). The greatest number of natural stands were present in scene 009, (33% of all natural stands), making up 86.8% of all the stands within that scene.

4.2.2 Forest Stands: Albedo

Mean stand-albedo was significantly higher ($p<0.001$) in treated stands across all scenes, when compared against natural stands using one-way ANOVA statistical analysis (Table 4).

The largest mean difference (0.005) was observed between treated and natural stands in scene 007. Stands covered by scene 006 displayed the highest stand albedo values (means: natural 0.254, treated 0.258), while the lowest mean values were found in scene 009 (natural = 0.232; treated = 0.233) (Figure 6). Scene 009 also exhibited the least difference between means by treatment type, with a negligeable 0.001 difference between the mean values.

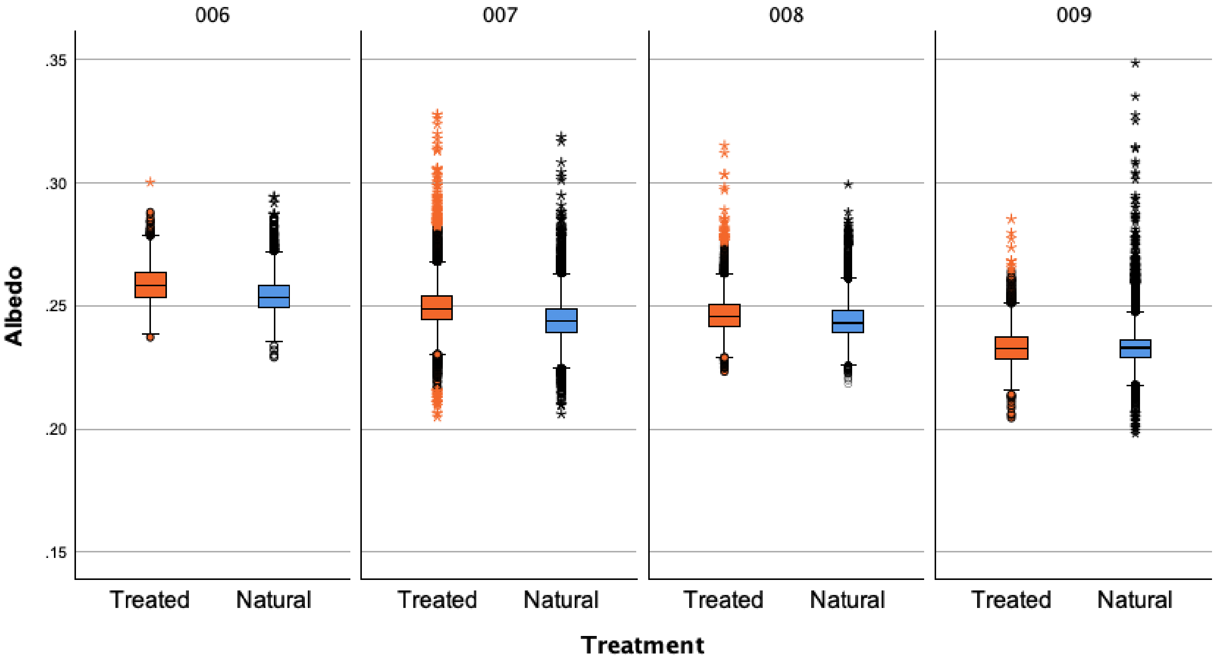

Figure 6: Boxplot of albedo values by stand treatment within scene

Negligeable differences between mean and median statistics (±0.001) suggest these data have no strong outliers skewing results (Table 9). Natural stands in scene 009 displayed the largest range of values (range = 0.15), from a minimum of 0.198 to a maximum of 0.348. Of note, the 009 natural stands also containing both the lowest and highest recorded albedo value within the dataset, yet exhibited the lowest mean albedo (0.2327).

Table 9: Albedo values per scene by stand treatment

		Albedo				
Scene	Treatment	Mean	Range	Minimum	Maximum	Median
006	Treated	.259	.088	.212	.300	.258
	Natural	.254	.065	.229	.294	.253
007	Treated	.249	.123	.205	.328	.249
	Natural	.244	.113	.206	.319	.244
008	Treated	.246	.092	.223	.315	.246
	Natural	.244	.081	.218	.299	.243
009	Treated	.233	.081	.204	.285	.233
	Natural	.232	.150	.198	.348	.233

4.2.3 Forest Stands: Surface Temperature

The differences between mean surface temperatures of natural and treated stands were to be significant with a high level of confidence ($p<0.001$). Treated stand temperatures were significantly higher than natural stands in scenes 006 (mean = 27.0°C), 007 (mean = 28.7°C°) and 008 (mean = 27.7°C) (Figure 7). In contrast, natural stands in scene 009 had higher mean stand temperatures (natural: 23.8°C, treated: 23.0°C), also representing the largest observed difference between means.

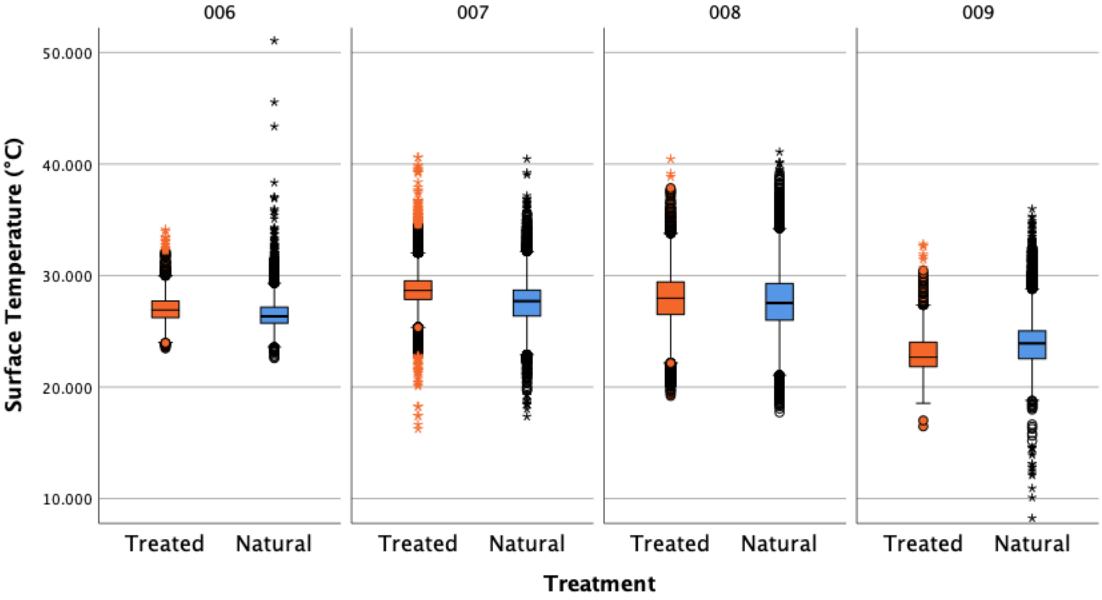

Figure 7: surface temperature of forest stand treatment groups, presented within scene

The highest stand temperatures were found in scene 006, with a maximum temperature of 51.1°C in the natural stands, 006 also showed one of the largest ranges (28.4°C), from 22.6-51.1°C (Table 10). Similarly, natural stands in scene 009 had a large range of 27.7°C, and contains the minimum stand temperature of 8.2°C. The mean and median statistics fell within similar ranges to each other (±0.2) in all groups except in treated 009 stands, where mean temperature was 0.3°C warmer than median (mean: 23.0, median: 22.7).

Table 10: descriptive statistics of stand mean surface temperatures

		Surface Temperature (°C)				
Scene	Treatment	Mean	Range	Minimum	Maximum	Median
006	Treated	27.0	13.0	21.1	34.1	26.9
	Natural	26.5	28.4	22.6	51.0	26.3
007	Treated	28.7	24.4	16.2	40.6	28.7
	Natural	27.5	23.1	17.4	40.5	27.7
008	Treated	27.7	21.2	19.2	40.4	28.0
	Natural	27.5	23.4	17.7	41.1	27.5
009	Treated	23.0	16.3	16.5	32.8	22.7
	Natural	23.8	27.7	8.2	35.9	23.9

4.2.4 Stand data: NDWI

One-way ANOVA analysis showed a significant difference in NDWI between the two groups in each scene. Mean NDWI values ranged from -0.786 (natural 007) to -0.747 (natural 008), displaying minimal variance between all scenes (Table 11). Strong positive skews are seen in each group, up to -0.244 (066 treated). In scenes 006 and 007, treated stands had the largest mean (negative number closer to zero), whereas in the natural stand means were larger in scenes 008 and 009(Figure 8).

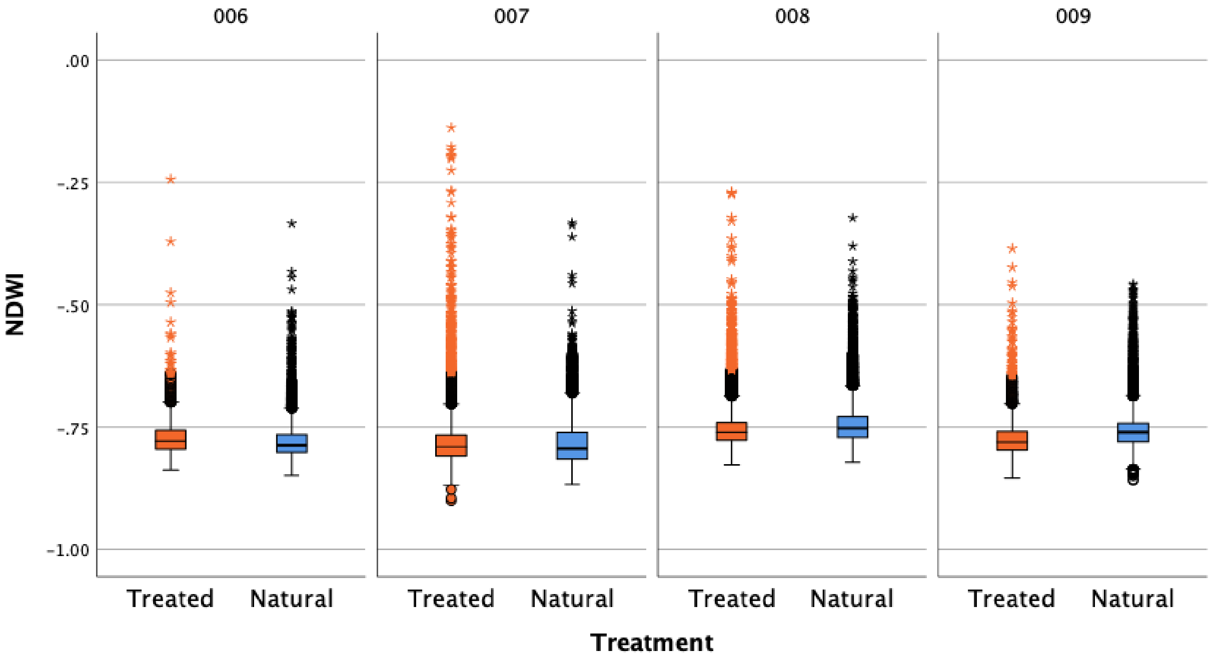

Figure 8: Comparison of stand mean NDWI by treatment group, analysed within scene

NDWI values ranged from -0.867 to -0.244, with two potential invalid observations (1.035, -1.898 natural 007) that fall outside the possible range of the normalized index Table 11. While NDWI may range up to +1, there were no stands within the dataset with positive mean values.

Table 11: descriptive statistics of stand NDWI means

		NDWI				
Scene	Treatment	Mean	Range	Minimum	Maximum	Median
006	Treated	-0.774	0.595	-0.838	-0.244	-0.779
	Natural	-0.780	0.515	-0.849	-0.334	-0.787
007	Treated	-0.785	2.933	-1.898	1.035	-0.791
	Natural	-0.786	0.535	-0.867	-0.332	-0.794
008	Treated	-0.756	0.556	-0.827	-0.271	-0.761
	Natural	-0.747	0.499	-0.822	-0.323	-0.753
009	Treated	-0.775	0.469	-0.854	-0.385	-0.781
	Natural	-0.759	0.401	-0.859	-0.458	-0.761

4.3 Discriminant Analysis

4.3.1 Scene based Classification Accuracies

Discriminant analysis were originally run with surface temperature and albedo values as the only inputs; NDWI was later added to account for potential water pixels in stands and increased classification accuracies in all scenes except 009 (Table 12).

Table 12: results of discriminant analyses by scene, comparing accuracies of each group of inputs

Scene	**Inputs: Surface Temperature & Albedo**			**Inputs: Surface Temperature, Albedo, & NDWI**		
	Eigenvalue	Wilks lambda	Classification Accuracy	Eigenvalue	Wilks Lambda	Classification Accuracy
006	0.089	0.918	69.8%	0.091	0.917	70.0%
007	0.147	0.872	66.4%	0.175	0.851	68.4%
008	0.040	0.962	58.7%	0.064	0.940	60.4%
009	0.039	0.962	86.7%	0.051	0.951	86.4%

Suitable discriminant analysis (classification accuracy >80%) results were only found in scene 009. A classification accuracy of 86.7% was achieved using surface temperature and albedo values as inputs, the addition of NDWI marginally reduced the accuracy to 86.4%. However, low Eigenvalues (0.039 & 0.051) and high Wilks lambda (0.962 & 0.951) indicate the model has poor ability to differentiate between groups, likely caused by the inequality of group sizes (table 3). A total of ten treated stands were correctly classified in scene 009, the remaining 6422 treated stands were incorrectly classed as natural. This misclassification is a result of the discriminant models predicting 99.9% of stands in scene 009 are natural, and may have resulted in the high classification accuracy (86.7%) owing to disproportionate representation (86.8%) of natural stands within the scene.

4.3.2 Discriminant Function Coefficients

The weight of input coefficients varied considerably across discriminant functions (Table 13). Albedo was the strongest discriminant variable in scenes 006, and 008, while surface temperature was weighted more heavily in 007 and 009. NDWI values had smallest coefficients in all functions except scene 008, where surface temperature had a lesser weight of -0.197 (NDWI coefficient = -0.625).

Table 13: standard conical discriminant function coefficients of inputs surface temperature, albedo, NDWI

Scene	**Standardized Discriminant Function Coefficients**		
	Albedo	Surface Temperature	NDWI
006	**1.055**	-0.135	0.121
007	0.473	**0.764**	-0.457
008	**0.963**	-0.197	-0.625
009	-0.804	**0.857**	0.476

4.3.3 Ecoregion based Classification

Further discriminant analyses were run comparing stands within ecoregions (Table 14). Of notice, the eigenvalue and wilk lambda outputs indicate more appropriate models. Additionally, while none of classification accuracies were suitable (>80%), the accuracy results were equal or greater than results when comparing stands solely within scene (Table 6).

Table 14: discriminant analysis of stands compared within ecoregion and scene

Scene	Ecoregion	Inputs: Surface Temperature, Albedo, & NDWI		
		Eigenvalue	Wilks lambda	Classification Accuracy
006	8	0.249	0.801	70.6%
007	3	0.275	0.784	72.3%
	4	0.137	0.880	66.0%
	5	0.112	0.899	67.5%
008	3	0.043	0.959	57.8%
	4	0.276	0.784	69.7%
	6	0.133	0.883	64.9%
	9	0.153	0.867	67.4%

Note: Discriminant analyses were only run in ecoregions with comparable memberships between the two treatment types (40-60% proportions).

Chapter 5: Discussion

Analysis successfully demonstrated relationships between forest management practices and forest stand biophysical characteristics using remote sensing derived measurements. This relationship indicates current forestry policies are warming surface temperatures in managed forests. While discriminant analyses may have failed to meet confidence thresholds, this result may be due to underlying processes not covered in this study. The context and potential causes of these results are discussed below,

5.1 Derived variables maps of Nova Scotia

5.1.1 Albedo

The spatial distribution of surface albedo covering Nova Scotia (Figure 9) displayed a clear north-south pattern, with high albedo values in the northern region of the Province and decreasing in magnitude moving south. This pattern can, in part, be explained by the varied ecological characteristics of the areas. The albedo values observed in the North of the Province are concurrent with expected albedos arising from the known landcover in the region. For example, the Northern Plateau and Cape Breton Highlands (Figure 9, Area A) are defined by large expanses of bedrock, heathlands, and shrubs (Neily et al., 2017), all landcover types associated with high albedo. Similarly, the Nova Scotia uplands and Mulgrave Plateau (Area B) also present with high surface albedo, characteristic of the large expanses of tolerant hardwood forests (Chapin III et al., 2000; Neily et al., 2017).

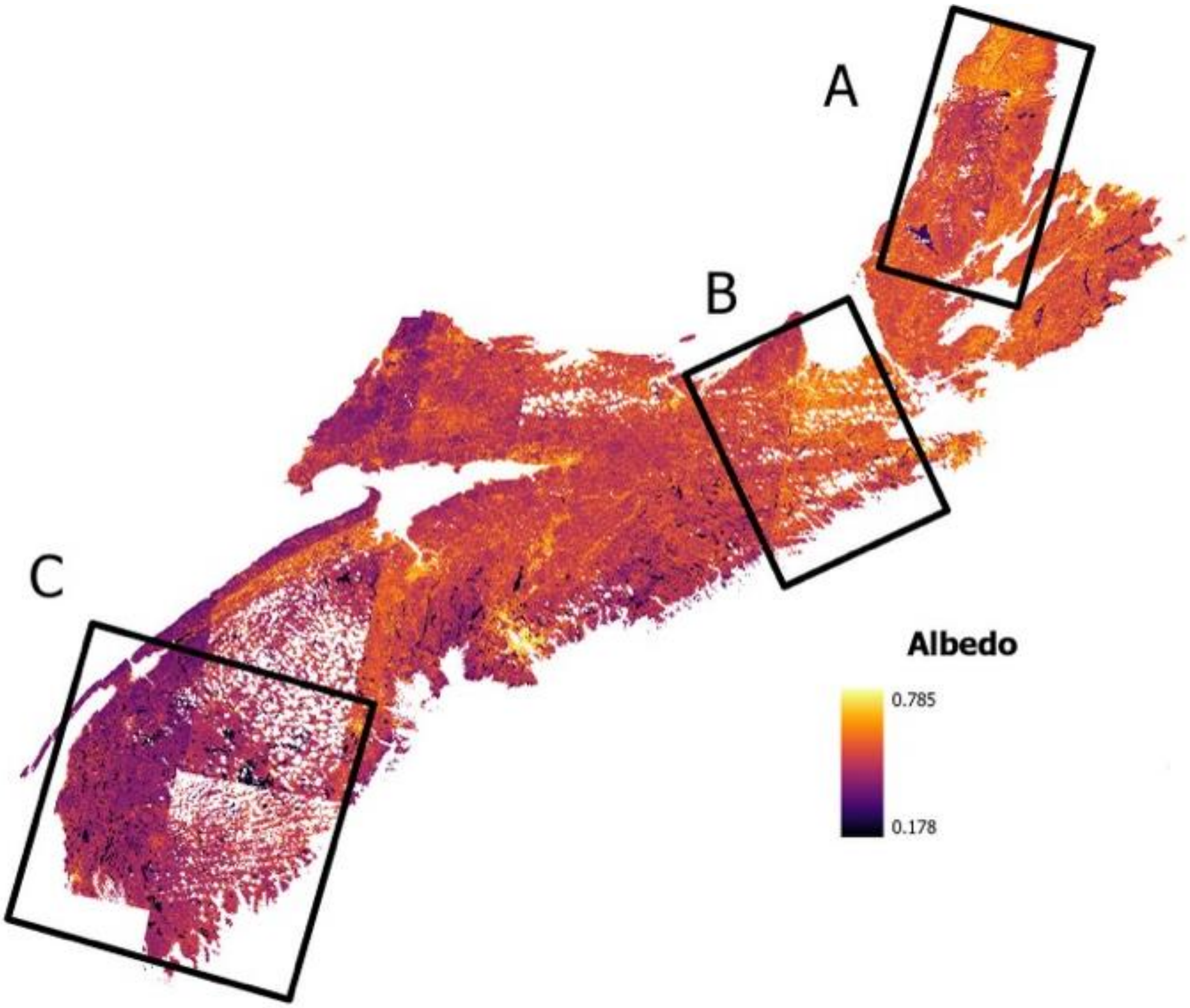

Figure 9: Albedo map of Nova Scotia highlighting areas of interest

Alternatively, low albedo areas (Figure 9, Area C) covering southwest Nova Scotia cannot be explained by ecologic characteristics. The majority of the landcover in the area (74.5%) is composed of mixed wood forests, dominated by deciduous species such as sugar maple, beech, and yellow birch (Neily et al., 2017). These hard- and mixed-wood canopies should (but do not appear to) present with high albedo values comparable to albedo values of similar forest types in the center of the province (Neily et al., 2017; Schwaab et al., 2020). Concentrations of peatlands and bogs in the region may account for some secondary albedo reduction from increased water cover in these habitats (Varamesh et al., 2022). However, examining the spatial distribution of NDWI did not appear to indicate greater water presence in these areas. Consequently, it is likely that albedo in this region is strongly influenced by variables not accounted for in this analysis.

5.1.2 Normalized Difference Water Index

The Normalized Difference Water Index appropriately identified bodies of water as intended (NDWI>0), with a strong distinction from natural land cover (i.e., vegetation and soil NDWI <0). Visual interpretation of the output also illustrated high NDWI values present in built areas, incorrectly symbolizing these surfaces as aqueous. Further classification methods such as a Normalized Difference Built up Index (NDBI) could be applied to differentiate water cover from urban areas; however this step was unnecessary as forest stands were buffered to remove any influence of urban expansion. Thus, it is unlikely this misclassification influenced stand-level NDWI values.

5.1.3 Surface Temperature

The mean surface temperatures derived for each scene were characteristic of mid-summer temperatures (24.8-28.3°C), supporting the validity of surface temperature products used in this thesis. Land surface temperature (LST) estimates were not available over several sections of the study area due to missing auxiliary data in the Landsat Level 2 BOA product. Because all stands containing No Data pixels were removed from the study, the missing-data zones resulted in considerable spatial gaps in the dataset, further introducing uncertainty into the results by potentially obscuring patterns present over these areas.

Possible solutions include extending the temporal scale of data collection to derive mean surface temperature values over an entire growing season.

5.1.4 Halifax Regional Municipality

The Halifax Reginal Municipality (HRM) was prominent ranges of values tending towards the higher observed values in all satellite-imagery-derived variables (albedo, surface temperature, NDWI), and is likely indicative of the urban heat island effect. Urbanized areas are traditionally characterized by high albedo and surface temperatures (Varamesh et al., 2022), and in this study were incidentally also defined by high NDWI. Highly built areas reduce the soils ability to expel heat through evapotranspiration, and the complex geometry of cities traps solar radiation, resulting in warming ambient air temperatures (Greene & Millward, 2017). The effects of urban heat islands were clearly illustrated in the extreme temperatures (35-47°C) around the HRM, with values far above the mean surface temperature (27.7°C) for that aggregate row of images. While the urban heat island effect is not directly linked to the themes of forest management and forest biophysical characteristics addressed in this thesis; this phenomena exemplifies how landcover change can drastically alter surface temperatures, a theory further explored in this discussion.

5.2 Biophysical Characteristics of Forest Stands

5.2.1 Reflecting on Research Objectives

This work questioned how forest management practices in Nova Scotia alter forests' biophysical interactions with the atmosphere, and focused on the effects of post-harvest silviculture treatments on stand surface temperatures. In exploring these relationships, several hypothesis concerning which underlying processes may cause warming surface temperatures in treated stands were created; drawing conclusions from current literature on the subject, and from historic and ongoing forestry policies in Canada and Nova Scotia. These hypotheses, elaborated upon in the Chapter 2, are summarized below:

(1) Historic forest management practices preferred softwood-dominant forests stands and significantly altered Nova Scotia forest compositions to reflect this preference (Betts et al., 2022; T. McGrath, 2018).

(2) As softwood tree canopies have a lower albedo than hardwood canopies (Chapin III et al., 2000), the replacement of natural forests by managed stands lowered canopy albedo due to the increase in softwood cover.

(3) Because lower albedo forests absorb a greater ratio of solar energy, which is re-emitted as heat and raises surrounding temperatures (Perkins, 2019; Schwaab et al., 2020), surface temperatures will be higher in managed forest stands than in comparable natural forests due to the difference in canopy albedo.

These assumptions are over-simplifications of many underlying processes that can impact forest species composition, albedo, and surface temperatures. However, the purpose of this study was to determine if albedo and surface temperature variables differed significantly between forest treatment groups (i.e., natural and treated) and, further, to test if these variables alone could be used to discriminate between treatment groups. Drawing on these results, the possible effects of forest management on stand albedo and surface temperatures are discussed below.

5.2.3 Albedo

This study found that treated forest stands had significantly higher ($p<0.001$) mean stand albedo when compared to natural stands. This outcome contradicts the assumption that albedo is reduced in treated stands due to the increased conifer cover from regrowth management. Rather, these results suggest either (1) forest treatments did not increase coniferous tree cover in stands, or (2) other processes not accounted for in this study have a significant impact on albedo. To account for the latter, one possibility is that underlying water pixels in natural stands could reduce mean albedo values (due to transmission of electromagnetic radiation by water). However, in this analysis mean NDWI values were derived for each stand to account for water content, and natural stands did not appear to display consistently greater NDWI values indicating water pixels present in stands did not have considerable influence on mean albedo values.

Alternatively, the mean albedo findings in this thesis are comparable to results found in a study by Naudts et al. (2016) analyzing the impacts of forestation on surface temperatures across Europe. This European study found areas under forest management did experience a 25% increase in conifers, as similarly hypothesized in this thesis. However despite the lower albedo of coniferous trees, the surface albedo for the managed forests increased. These results were explained by the expansion of surface covered by young forests, who's sparse canopy allows light to reach the forest floor [a high albedo surface]. Arguably, it is likely that a similar phenomenon occurs in Nova Scotia managed forest stands, supporting the higher mean albedo values of treated stands. As outlined in Chapter 2, Nova Scotia has a history of conifer reforestation (Department of Natural Resources and Renewables, 2017), and many of the other silviculture treatments are designed to promote conifer dominant regrowth as well (T. McGrath, 2018). And, though this study was unable to account for stand age, it stands to reason that treated forests would be (on average) younger than natural stands as they undergo regular harvesting, and are hence likely to have sparser canopies. Hence, managed stand characteristics first identified by Naudts et al (2016) offer a probable cause for higher albedo means in treated stands.

5.2.4 Surface Temperature

Treated stand mean temperatures were significantly higher than natural stands across 3 of the four image rows. With the exception of row 009, mean treated stand temperatures were between 0.4 and 1.2 °C higher than natural stands. These results support the original hypothesis that forest management strategies may raise forest stand temperatures. However, due to a lack of stand-species-composition data, this thesis could not associate the warmer temperatures of treated stands with increased softwood cover. Nonetheless, similar studies conducted by Schwaab et al., (2020) and Naudts et al., (2016) also found increased surface temperatures in managed forests (0.3-0.7 °C, and 0.8 °C warmer than natural forests), and *further* linked these raised temperatures to converted coniferous forests. Inferences can therefore be drawn that because [1] this thesis found similar increased temperatures in treated stands to the studies by Schwaab et al., (2020) and Naudts et al., (2016), and [2] because similar forestry practices increasing coniferous forest cover are also occurring in Nova Scotia; it is probable that high temperatures of treated stands found in this study are correlated with increased coniferous tree cover.

5.2.5 Discriminant Analyses

Results of discriminant Analyses approached but did not reach the accepted threshold to suitably differentiation between forest treatment groups (with the exception of row 009 discussed below). While not significant, classification accuracies of approximately 70% indicate some discriminant ability within the predictor variables (Albedo, surface temperature, NDWI). However low eigenvalues and high wilks lambda suggest a low model suitability. The addition of NDWI as a discriminant variable marginally increased classification accuracies, indicating that water presence may vary between stands treatments, and that additional processes outside of stand albedo and surface temperature may act a better predictive variables. As well, the slight increase in both suitability and accuracy of models when comparing stands within ecoregions could also suggest that underlying environmental factors (which are partially accounted for by comparing within ecoregion) are present. The incorporation of additional influencing variables such as canopy cover and stand age would likely boost classification accuracies, and should be derived for future iterations of this study

5.2.6 Row 009

Stands falling in row 009 had noticeably different results from the rest of the dataset: containing the largest range- and lowest mean- albedo values, and the only row with warmer natural stands. Additionally, as discussed above, the albedo values derived from row 009 imagery (southern area of the province) were not reflective of the groundcover in the region, where the presence of deciduous and mixed wood forests would suggest a higher albedo than what was found. Finally, while discriminant models were significant in row 009, the results should not be considered valid owing to the considerable difference in class sizes, with only 13% of total stands belonging to treated group. Combined, these factors suggest stands in row 009 were influenced by processes not considered in this thesis, and further studies are needed to explore this potential.

5.3 Limitations

The potential errors in this research stem from three primary factors: 1) estimations of surface energy interactions from satellite acquired imagery, 2) the zonation of variables in units and applied boundaries, and 3) the temporal limitations of the imagery.

5.3.1 Narrow-to-Broadband Conversion

A narrow-to-broadband conversion of multispectral data was chosen for this study as it offers a much finer spatial resolution that other albedo-specific monitoring satellites (e.g., 1 km vs. 30 metre). Traditionally collected broadband albedos comprise the entire spectrum of solar energy and provide an accurate estimate of a surface's energy balance (Naegeli et al., 2017). The narrow-to-broad conversion weights individual spectral bands and assumes properties of wavelength ranges not measured to best estimate a broadband albedo using multispectral imagery (Liang, 2001).

Validation of narrow-to-broad techniques have found minimal difference between the two techniques when an appropriate weighted sum is applied. The most notable source of error is associated with green spectral bands (Liang, 2001; Moustafa et al., 2017), typically removed from conversion formulae. However, uncertainties arise from both the weighting of spectral bands and the assumption of properties of non-measured wavelengths, and this introduced potential errors into this study.

To reduce the potential for inaccurate albedo values, a ground-referenced and validated conversion formula was chosen. The narrow-to-broad band conversion applied in this study was first derived by Liang (2001) (Equation 3), and has since been validated and applied in hundreds of subsequent peer-reviewed articles (Peng et al., 2023; Smith, 2010). The Landsat-8 adaptation of the equation (Equation 4) by Naegeli (2017) for the Operational Land Imager (OLI) was validated against in-situ measurements with a ± 0.07 error value. This adapted formula has been applied and proven adequate in multiple land-cover conversion studies (Fernández-Guisuraga et al., 2021; Li et al., 2022; Santos Orozco et al., 2023). Of note, while this albedo approximation reduces the generalization of landscape by using a finer 30-meter spatial resolution (compared to the traditionally 1km spatial resolution MODIS albedo), uncertainty is still introduced into the study by assuming one albedo value for an entire pixel area.

5.3.2 Surface Temperature

Surface temperature measurements in this study were sourced from USGS Level 2 products, which draws on multiple external sources to produce the estimated measure. Several potential sources of error have been identified related to the data collection and conversion. The accuracy of land surface temperature (LST) measurements is dependent on accurate emissivity data, atmospheric condition corrections, and cloud cover. The two largest contributors of errors being incorrect emissivity data and the presence of clouds (Cook et al., 2014; Duan et al., 2021). Auxiliary emissivity data is used to produce Level-2 LST products, and to limit errors introduced by incorrect emissivity readings, no LST values are derived over areas with high levels of uncertainty in the auxiliary data (usually cloudy areas). However, this introduced an opposing limitation, where surface temperature values were not be available over wide zones within the study area. To best mitigate these limitations, scenes with <15% cloud cover were selected.

Additionally, the resampling of Landsat 8 TIRS thermal bands introduces further uncertainty in surface temperature readings. Thermal infrared bands 10 and 11 are collected at a 100-meter spatial resolution and are then resampled to 30 meters in the Level 2 surface temperature product provided by USGS (US Geologic Survey, 2019). While resampling allows the co-registration of OLI multispectral imagery (collected at 30-meter resolution) with the TIRS thermal bands, an increased chance of erroneous measurements is introduced into the product.

5.3.3 Boundary and the Modifiable Areal Unit Problem

This work was conducted at a stand level, and as such spatially continuous variables were aggregated as mean values by unit (i.e., forest stands). The use of stand level data introduces the modifiable areal unit problem (MAUP): wherein the scale and physical construction of the units has the potential to influence the results of aggregated data (Dark & Bram, 2007). Several partial solutions to MAUP have been proposed, such as grid-based analysis (e.g., tessellation) or moving window statistic (Cunningham et al., 2024); however as the units are predefined stands, most created by past harvesting patterns, these solutions cannot be reasonably employed.

Similarly, ecoregions and scene bounds were employed as artificial boundaries, limiting analyses within these areas and introducing the boundary problem. This problem arises when applied boundaries do not align with true patch boundaries (Cunningham et al., 2024), and can truncate natural patterns or create the appearance of patterns where there are none. Of significance in this study, the mosaiced raster row boundaries limited analysis of stands to within each row. Confining analysis to rows was necessary to ensure comparable climatic influences on all scenes, however these boundaries could divide or cut-off patterns present in the spatial data (Dark & Bram, 2007). Ecoregions were also used as bounding units, yet this boundary problem was moderated because stands were compared within scene first and then further divided into ecoregions.

5.3.4 Assumptions of Normal Distribution and Equal Variance

Both ANOVA and Discriminant Analysis statistics used in this study operate under the same core assumptions: (1) normal distribution of values within groups and (2) equal variance between groups. Many of variable groups presented heterogeneous variance between groups, meaning the assumption of equal variance was not met. However, these assumptions are traditionally not considered fatal, and it is common practice to assume results are trustworthy despite violated assumptions (Subramaniam et al., 2023; Wright, 2006). As such, the statistical results in this thesis were considered reliable, though future research should consider using non-parametric statistics.

5.3.5 Single Temporal Snap-shot

The variables derived for this thesis came from single snap-shot satellite images of Nova Scotia, and may be heavily influenced by climate at time of collection. To reduce this limitation, mean surface values for albedo, surface temperature, and NDWI should be calculated over an entire growing season. In addition to limiting the influence of climate on results, this approach would also address the boundary problem (discussed in Chapter 3) by allowing the comparison of stands across the entire province, rather than only within scene. Lastly, spatial gaps in the dataset from missing surface temperature values would also be reduced as the extended temporal scale of data acquisition would likely account for missing data during some collection dates.

As well, a central theme in addressed in this thesis was the extensive forest species conversions resulting from long-term forest management practices; a process not properly studied by a single temporal snapshot. This thesis instead compared the biophysical features of forest stands across treatment types. To truly characterize the impacts of extended forest management on albedo and surface temperatures, the stands should be studied over an extended temporal frame. However, this method is considerably limited by the availability and quality of historic satellite imagery.

5.3.6 Canopy Cover

The density of canopy cover has a large impact on albedo values (Otto et al., 2014), and could not be controlled for in this study. As illustrating in findings by Naudts et al (2016), though coniferous cover was increased by forest management, the loss of canopy density associated with young forests had a greater impact on the overall surface albedo. The inclusion of canopy cover as a predictive variable in discriminant analysis would likely increase the classification accuracies, and should be included in future iterations of this work.

5.4 Implications beyond this thesis

The findings in this research that treated forest stands have significantly higher surface temperatures than natural stands during summer months both fills a theory gap, and is supported by the current literature. Studies by Naudts et al., (2016) and Schwaab et al.,

(2020) produced similar findings, that managed forests were 0.3°C to 0.8°C warmer than natural forests, and used comparable remote sensing methodologies to this thesis. These studies, however, were limited to Europe, and this research filled a theory gap by demonstrating that similar processes causing increased temperatures in managed European forests are also occurring in Nova Scotia. Further, because Nova Scotia forest management practices are reflective of Canada's forestry policies as a whole, it is probable that managed forests are experiencing higher surface temperatures across the country,

The results of this work question the efficacy and validity of using forests as climate change mitigators. Specifically, should Canada maintain climate change policies that promote reforestation and afforestation if these methods lead to warming surface temperatures? Canada possess 20% of the world's forests (FAO, 2020), and consequently the forest management practices employed across this country have the potential to considerably alter local and regional climates. If current forest management practices are adding to the pressures of global warming, thorough and systemic changes to western forestry is necessary.

Chapter 6: Conclusion

This thesis successfully addressed the original research question:

> *To what extent have forest management practices in Nova Scotia impacted forest albedo and surface temperatures?*

finding significant relationships between treated forest stands and surface temperatures. These results were supported by existing literature that forest management practices increase temperatures in treated forest stands, and filled a knowledge gap by illustrating this phenomena is occurring in Nova Scotia, and likely across Canada. Of note, natural forest stands were found to have significantly lower albedo than treated stands, contradicted the original hypothesis that forest management significantly decreases stand albedo. These results were rationalized by the probable sparse canopies of young treated forests stands.

The outcomes of this work suggest both historic and current forestry practices may be increasing surface temperatures and adding to the threats of global warming. Following the results of this study, it is crucial to identify the drivers of increased surface temperature in managed forests. As no significant relationships were found between treated stands and NDWI or albedo values, other factors not analysed in this thesis are likely causing this warming. Several limitations identified in this study could be addressed by an extended temporal scale, where values for the biophysical factors are derived over an entire growing season. Additionally, future studies should include in-situ sampling of stand canopy cover and species composition: two potential drivers of surface warming. Lastly, to assess the efficacy of forestation as a climate mitigation strategy, in-depth analysis is need to contrast the cost of increased surface temperatures against the considerable carbon sequestration ability of afforestation.

Citations:

Betts, M. G., Yang, Z., Hadley, A. S., Smith, A. C., Rousseau, J. S., Northrup, J. M., Nocera, J. J., Gorelick, N., & Gerber, B. D. (2022). Forest degradation drives widespread avian habitat and population declines. *Nature Ecology & Evolution*, *6*(6), Article 6. https://doi.org/10.1038/s41559-022-01737-8

Biggar, H. P. (1926). The Works of Samuel de Champlain. *The Mississippi Valley Historical Review*, *13*(1), 124–124. https://doi.org/10.2307/1892591

Bright, R. M., Davin, E., O’Halloran, T., Pongratz, J., Zhao, K., & Cescatti, A. (2017). Local temperature response to land cover and management change driven by non-radiative processes. *Nature Climate Change*, *7*(4), 296–302. https://doi.org/10.1038/nclimate3250

Bürgi, M., & Schuler, A. (2003). Driving forces of forest management—An analysis of regeneration practices in the forests of the Swiss Central Plateau during the 19th and 20th century. *Forest Ecology and Management*, *176*(1), 173–183. https://doi.org/10.1016/S0378-1127(02)00270-0

Canadell, J. G., & Raupach, M. R. (2008). Managing Forests for Climate Change Mitigation. *Science (American Association for the Advancement of Science)*, *320*(5882), 1456–1457. https://doi.org/10.1126/science.1155458

Chapin III, F. S., Mcguire, A. D., Randerson, J., Pielke, R., Baldocchi, D., Hobbie, S. E., Roulet, N., Eugster, W., Kasischke, E., Rastetter, E. B., Zimov, S. A., & Running, S. W. (2000). Arctic and boreal ecosystems of western North America as components of the climate system. *Global Change Biology*, *6*(S1), 211–223. https://doi.org/10.1046/j.1365-2486.2000.06022.x

Cook, M., Schott, J. R., Mandel, J., & Raqueno, N. (2014). Development of an Operational Calibration Methodology for the Landsat Thermal Data Archive and Initial Testing of the Atmospheric Compensation Component of a Land Surface Temperature (LST) Product from the Archive. *Remote Sensing*, *6*(11), 11244–11266. https://doi.org/10.3390/rs61111244

Cunha-e-Sá, M. A., Rosa, R., & Costa-Duarte, C. (2013). Natural carbon capture and storage (NCCS): Forests, land use and carbon accounting. *Resource and Energy Economics*, *35*(2), 148–170. https://doi.org/10.1016/j.reseneeco.2012.12.003

Cunningham, C., Beazley, K. F., Bush, P. G., & Brazner, J. C. (2024). Addressing the Boundary and Modifiable Areal Unit Problems Simultaneously when Measuring Landscape Fragmentation Using Patch-Based Metrics: A Case Study of Effective Mesh Size in Nova Scotia, Canada. *Environmental Modeling & Assessment*. https://doi.org/10.1007/s10666-023-09950-w

Dark, S. J., & Bram, D. (2007). The modifiable areal unit problem (MAUP) in physical geography. *Progress in Physical Geography*, *31*(5), 471–479. https://doi.org/10.1177/0309133307083294

Department of Natural Resources and Renewables. (2015). *Nova Scotias Ecological Land Classification* [Shapefile]. Forestry Division.

Department of Natural Resources and Renewables. (2017). *State of the Forest 2016*. Province of Nova Scotia.

Dongjin Cho, Cheolhee Yoo, Jungho Im, Yeonsu Lee, & Jaese Lee. (2020). Improvement of spatial interpolation accuracy of daily maximum air temperature in urban areas using a stacking ensemble technique. *GIScience and Remote Sensing*, *57*(5), 633–649. https://doi.org/10.1080/15481603.2020.1766768

Drushka, K. (2003). *Canada's Forests: A History* (1st ed.). MQUP.

Duan, S.-B., Li, Z.-L., Zhao, W., Wu, P., Huang, C., Han, X.-J., Gao, M., Leng, P., & Shang, G. (2021). Validation of Landsat land surface temperature product in the conterminous United States using in situ measurements from SURFRAD, ARM, and NDBC sites. *International Journal of Digital Earth*, *14*(5), 640–660. https://doi.org/10.1080/17538947.2020.1862319

Dube, T., Mutanga, O., Sibanda, M., Seutloali, K., & Shoko, C. (2017). Use of Landsat series data to analyse the spatial and temporal variations of land degradation in a dispersive soil environment: A case of King Sabata Dalindyebo local municipality in the Eastern Cape Province, South Africa. *Physics and Chemistry of the Earth. Parts A/B/C*, *100*, 112–120. https://doi.org/10.1016/j.pce.2017.01.023

ECCE. (2020, November 27). *Climate change adaptation plans and actions*. https://www.canada.ca/en/environment-climate-change/services/climate-change/adapting/plans.html

Environment Canada. (2021, February 12). *A healthy environment and a healthy economy*. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/climate-plan-overview/healthy-environment-healthy-economy.html

FAO. (2020). *Global Forest Resources Assessment*. FAO. https://doi.org/10.4060/ca9825en

Fernández-Guisuraga, J. M., Suárez-Seoane, S., García-Llamas, P., & Calvo, L. (2021). Vegetation structure parameters determine high burn severity likelihood in different ecosystem types: A case study in a burned Mediterranean landscape. *Journal of*

Environmental Management, *288*, 112462–112462. https://doi.org/10.1016/j.jenvman.2021.112462

Foley, J. A., Kutzbach, J. E., Coe, M. T., & Levis, S. (1994). Feedbacks between climate and boreal forests during the Holocene epoch. *Nature*, *371*(6492), 52–54. https://doi.org/10.1038/371052a0

Glatzel, G. (1991). The impact of historic land use and modern forestry on nutrient relations of Central European forest ecosystems. *Fertilizer Research*, *27*(1), 1–8. https://doi.org/10.1007/BF01048603

Greene, C. S., & Millward, A. A. (2017). Getting closure: The role of urban forest canopy density in moderating summer surface temperatures in a large city. *Urban Ecosystems*, *20*(1), 141–156. https://doi.org/10.1007/s11252-016-0586-5

Groot, A., Lussier, J. M., Mitchell, A. K., & Maclsaac, D. A. (2005). Silvicultural systems perspective on changing Canadian forestry practices. *Forestry Chronicle*, *81*(1), 50–55. https://doi.org/10.5558/tfc81050-1

Günter, S., Weber, M., Stimm, B., & Mosandl, R. (Eds.). (2011). *Silviculture in the Tropics* (Vol. 8). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-19986-8

Halim, M. A., Chen, H. Y. H., & Thomas, S. C. (2019). Stand age and species composition effects on surface albedo in a mixedwood boreal forest. *Biogeosciences*, *16*(22), 4357–4375. https://doi.org/10.5194/bg-16-4357-2019

He, H., Tian, C., Jin, G., & Han, K. (2020). Principal component analysis and Fisher discriminant analysis of environmental and ecological quality, and the impacts of coal mining in an environmentally sensitive area. *Environmental Monitoring and Assessment*, *192*(4), 207–207. https://doi.org/10.1007/s10661-020-8170-0

IPCC. (2022). *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (1st ed.). Cambridge University Press. https://doi.org/10.1017/9781009157940

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., Farley, K. A., Le Maitre, D. C., McCarl, B. A., & Murray, B. C. (2005). Atmospheric science: Trading water for carbon with biological carbon sequestration. *Science (American Association for the Advancement of Science)*, *310*(5756), 1944–1947. https://doi.org/10.1126/science.1119282

Jacobson, M. Z., & Hoeve, J. E. T. (2012). Effects of Urban Surfaces and White Roofs on Global and Regional Climate. *Journal of Climate*, *25*(3), 1028–1044. https://doi.org/10.1175/JCLI-D-11-00032.1

Jiang, J., & Tian, G. (2010). Analysis of the impact of Land use/Land cover change on Land Surface Temperature with Remote Sensing. *Procedia Environmental Sciences, 2,* 571–575. https://doi.org/10.1016/j.proenv.2010.10.062

Juang, J., Katul, G., Siqueira, M., Stoy, P., & Novick, K. (2007). Separating the effects of albedo from eco-physiological changes on surface temperature along a successional chronosequence in the southeastern United States. *Geophysical Research Letters*, *34*(21), 2007GL031296. https://doi.org/10.1029/2007GL031296

Kaplan, J. O., & New, M. (2006). Arctic climate change with a 2 [composite function]C global warming: Timing, climate patterns and vegetation change. *Climatic Change*, *79*(3–4), 213–241. Agricultural & Environmental Science Collection; ProQuest Central. https://doi.org/10.1007/s10584-006-9113-7

Kirby, K. J. (2015). *Europe's changing woods and forests: From wildwood to managed landscapes*. CABI.

Lavender, Parish, Johnson, Montgomery, Vyse, Willis, & Winston. (1990). *Regenerating British Columbia's Forests*. Ministry of Forests, Government of British Columbia.

Leeming, M. (2012). Contested Conservations: Forestry and History in Nova Scotia. *Past Tense: Graduate Review of History*, *1*, 50:66.

Li, Y., Liu, Y., Bohrer, G., Cai, Y., Wilson, A., Hu, T., Wang, Z., & Zhao, K. (2022). Impacts of forest loss on local climate across the conterminous United States: Evidence from satellite time-series observations. *The Science of the Total Environment*, *802*, 149651–149651. https://doi.org/10.1016/j.scitotenv.2021.149651

Liang, S. (2001). Narrowband to broadband conversions of land surface albedo I: Algorithms. *Remote Sensing of Environment*, *76*(2), 213–238. https://doi.org/10.1016/S0034-4257(00)00205-4

Lieffers, V. J., Pinno, B. D., Beverly, J. L., Thomas, B. R., & Nock, C. (2020). Reforestation policy has constrained options for managing risks on public forests. *Canadian Journal of Forest Research*, *50*(9), 855–861. https://doi.org/10.1139/cjfr-2019-0422

McGrath, M. J., Luyssaert, S., Meyfroidt, P., Kaplan, J. O., Bürgi, M., Chen, Y., Erb, K., Gimmi, U., McInerney, D., Naudts, K., Otto, J., Pasztor, F., Ryder, J., Schelhaas, M.-J., & Valade, A. (2015). Reconstructing European forest management from 1600 to 2010. *Biogeosciences*, *12*(14), 4291–4316. https://doi.org/10.5194/bg-12-4291-2015

McGrath, T. (2018). *Nova Scotia's Forest Management Guide* (FRR #100). Forestry Division.

Moustafa, S. E., Rennermalm, A. K., Román, M. O., Wang, Z., Schaaf, C. B., Smith, L. C., Koenig, L. S., & Erb, A. (2017). Evaluation of satellite remote sensing albedo retrievals over the ablation area of the southwestern Greenland ice sheet. *Remote Sensing of Environment*, *198*, 115–125. https://doi.org/10.1016/j.rse.2017.05.030

Naegeli, K., Damm, A., Huss, M., Wulf, H., Schaepman, M., & Hoelzle, M. (2017). Cross-Comparison of Albedo Products for Glacier Surfaces Derived from Airborne and Satellite (Sentinel-2 and Landsat 8) Optical Data. *Remote Sensing (Basel, Switzerland)*, *9*(2), 110–110. https://doi.org/10.3390/rs9020110

Naudts, K., Chen, Y., McGrath, M. J., Ryder, J., Valade, A., Otto, J., & Luyssaert, S. (2016). Europe’s forest management did not mitigate climate warming. *Science*, *351*(6273), 597–600. https://doi.org/10.1126/science.aad7270

Neily, P., Basquill, S., Quigley, E., & Keys, K. (2017). *Ecological Land Classification for Nova Scotia*. Nova Scotia Department of Resource Management. https://novascotia.ca/natr/forestry/ecological/pdf/Ecological-Land-Classification-guide.pdf

NRTEE. (2009). *True north: Adapting infrastructure to climate change in northern Canada*. National Roundtable on the Environment and the Economy.

NS Department of Natural Resources and Renewables, Forestry Division. (2024). *Forest Treatment Geodatabase* (Geodatabase FOR_TREATMENT_PLU_UT83).

Numbere, A. O. (2022). Chapter 20—Application of GIS and remote sensing towards forest resource management in mangrove forest of Niger Delta. In M. K. Jhariya, R. S. Meena, A. Banerjee, & S. N. Meena (Eds.), *Natural Resources Conservation and Advances for Sustainability* (pp. 433–459). Elsevier. https://doi.org/10.1016/B978-0-12-822976-7.00024-7

Oosthoek, K. J., & Hölzl, R. (2018). *Managing Northern Europe's Forests: Histories from the Age of Improvement to the Age of Ecology*. Berghahn Books, Incorporated. http://ebookcentral.proquest.com/lib/dal/detail.action?docID=5291708

Otto, J., Berveiller, D., Bréon, F.-M., Delpierre, N., Geppert, G., Granier, A., Jans, W., Knohl, A., Kuusk, A., Longdoz, B., Moors, E., Mund, M., Pinty, B., Schelhaas, M.-J., & Luyssaert, S. (2014). Forest summer albedo is sensitive to species and thinning: How should we account for this in Earth system models? *Biogeosciences*, *11*(8), 2411–2427. https://doi.org/10.5194/bg-11-2411-2014

Peng, J., Yu, P., Yu, Y., Jia, A., Wang, D., Wang, H., & Wang, Z. (2023). An evaluation of the NOAA global daily gap-filled VIIRS surface albedo. *Remote Sensing of Environment*, *298*, 113822. https://doi.org/10.1016/j.rse.2023.113822

Perkins, S. (2019). Core Concept: Albedo is a simple concept that plays complicated roles in climate and astronomy. *Proceedings of the National Academy of Sciences - PNAS*, *116*(51), 25369–25371. https://doi.org/10.1073/pnas.1918770116

Phankamolsil, Y., & Kositsakulchai, E. (2020). Revision of Vajiralongkorn Dam's Reservoir Characteristic Curves Using NDWI Derived from Landsat 8 Data. *Warasan Singwaetlom Lae Sappayakon Tammachat*, *18*(2), 134–145. https://doi.org/10.32526/ennrj.18.2.2020.13

Saito, O. (2009). Forest history and the Great Divergence: China, Japan, and the West compared. *Journal of Global History*, *4*(3), 379–404. https://doi.org/10.1017/S1740022809990131

Santos Orozco, D. L., Ruiz Corral, J. A., Villavicencio García, R. F., & Rodríguez Moreno, V. M. (2023). Deforestation and Its Effect on Surface Albedo and Weather Patterns. *Sustainability*, *15*(15), Article 15. https://doi.org/10.3390/su151511531

Schwaab, J., Davin, E. L., Bebi, P., Duguay-Tetzlaff, A., Waser, L. T., Haeni, M., & Meier, R. (2020). Increasing the broad-leaved tree fraction in European forests mitigates hot temperature extremes. *Scientific Reports*, *10*(1), Article 1. https://doi.org/10.1038/s41598-020-71055-1

Service Nova Scotia. (2024). *Nova Scota Road Network* (Shapefile TRNS_NSRN_Roads) [Geodatabase]. Nova Scotia Geographic Data Directory. https://nsgiwa.novascotia.ca/arcgis/rest/services/TRNS/TRNS_NSRN_Roads_UT83/MapServer

Smith, R. (2010). *The heat budget of the earth's surface deduced from space*. Yale University.

Subramaniam, P., Ahmed, A. N., Fai, C. M., Abdul Malek, M., Kumar, P., Huang, Y. F., Sherif, M., & Elshafie, A. (2023). Integrated GIS and multivariate statistical approach for spatial and temporal variability analysis for lake water quality index. *Cogent Engineering*, *10*(1). https://doi.org/10.1080/23311916.2023.2190490

Szabo, S., Gacsi, Z., & Balazs, B. (2016). Specific features of NDVI, NDWI and MNDWI as reflected in land cover categories. *Acta Geographica Debrecina. Landscape and Environment Series*, *10*(3–4), 194–194. https://doi.org/10.21120/LE/10/3-4/13

US Geologic Survey. (2019). *Landsat 8 Data User Handbook* (LSDS-1574 Version 5.0).

U.S. Geological Survey. (2022). *Landsat 8 | U.S. Geological Survey*. https://www.usgs.gov/landsat-missions/landsat-8

U.S. Geological Survey. (2023). *USGS Landsat Data* [Satellite Imagery; Data release]. Earth Explorer.

Varamesh, S., Mohtaram Anbaran, S., Shirmohammadi, B., Al-Ansari, N., Shabani, S., & Jaafari, A. (2022). How Do Different Land Uses/Covers Contribute to Land Surface

Temperature and Albedo? *Sustainability (Basel, Switzerland)*, *14*(24), 16963. https://doi.org/10.3390/su142416963

Vos, M. A. E., den Ouden, J., Hoosbeek, M., Valtera, M., de Vries, W., & Sterck, F. (2023). The sustainability of timber and biomass harvest in perspective of forest nutrient uptake and nutrient stocks. *Forest Ecology and Management*, *530*, 120791. https://doi.org/10.1016/j.foreco.2023.120791

Wang, Y., Yan, X., & Wang, Z. (2015). Global warming caused by afforestation in the Southern Hemisphere. *Ecological Indicators*, *52*, 371–378. https://doi.org/10.1016/j.ecolind.2014.12.004

Wright, D. B. (2006). Comparing groups in a before-after design: When t test and ANCOVA produce different results. *British Journal of Educational Psychology*, *76*(3), 663–675. https://doi.org/10.1348/000709905X52210

Appendix A

A. Testing Assumptions

ANOVA and Discriminant Analyses tests are based on three primary assumptions:

1. Data is normally distributed
2. Homogeneity of variance between groups
3. Observations are independent of each other, and groups are mutually exclusive

Of note, ANOVA is robust in violations of the first two assumptions, meaning that non-normal distributions, or heterogeneous variance in the data can still produce trustworthy ANOVA results (Wright, 2006).

Results of tested assumptions in stand data variables are presented below. Levene's test of covariance was used to test for variance between groups, where p>0.05 indicates homogeneity of variance and the assumption is met. Histograms were created to test for normal distributions and were heuristically assessed.

Row 006

Table 15: Results of Levene test of variance between treatment groups in scene 006

Variable	Levene Statistic (mean)	Significance (p)
Albedo	34.298	<0.001
Surface Temperature	1.298	0.255
NDWI	0.110	0.740

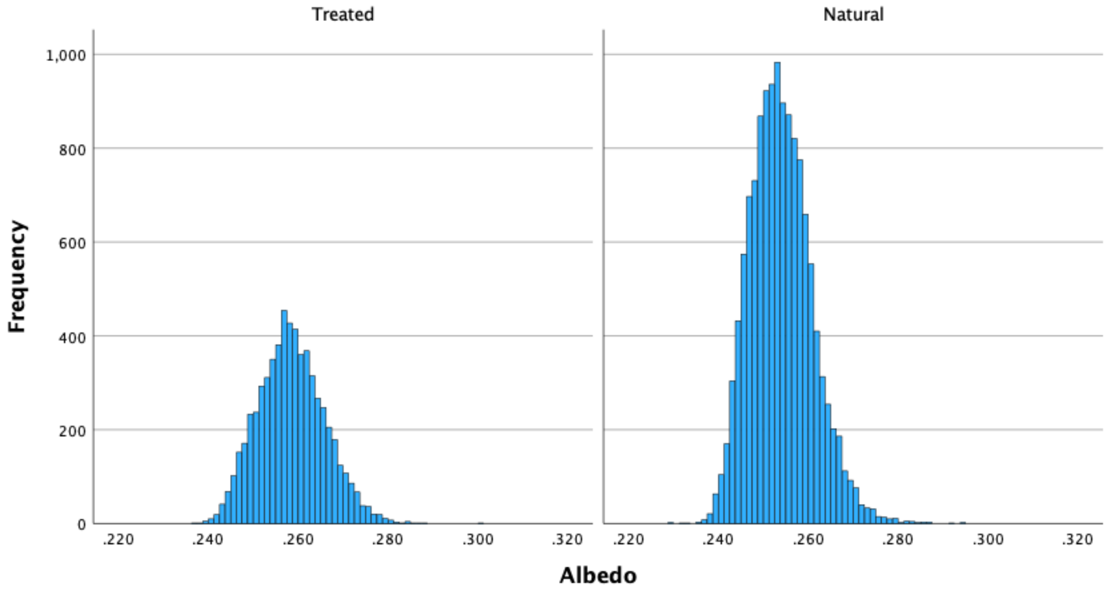

Figure 10: Histogram of mean stand albedo distributions within treatment groups in Row 006

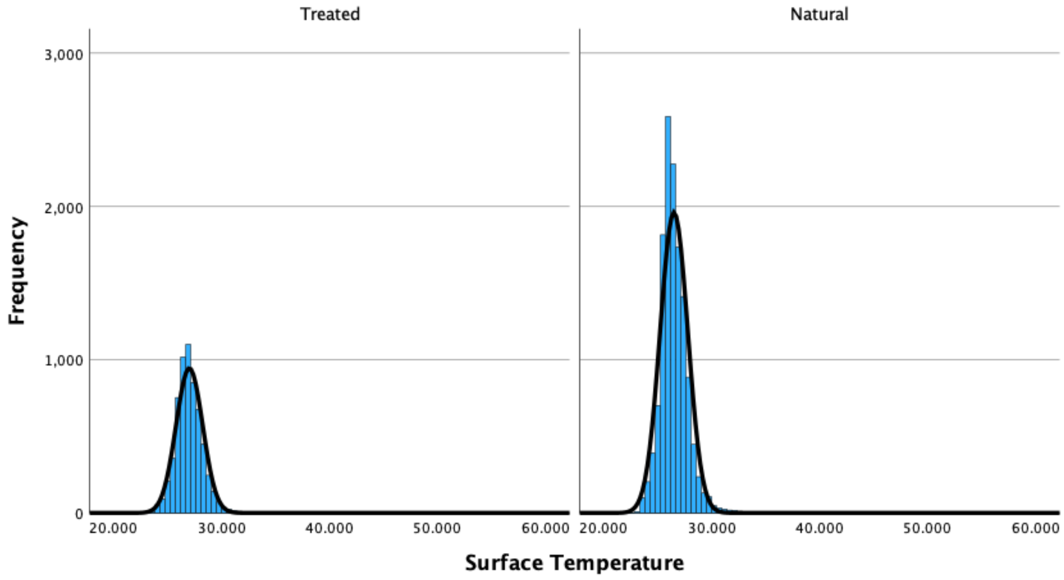

Figure 11: histogram if mean stand surface temperature distributions in row 006

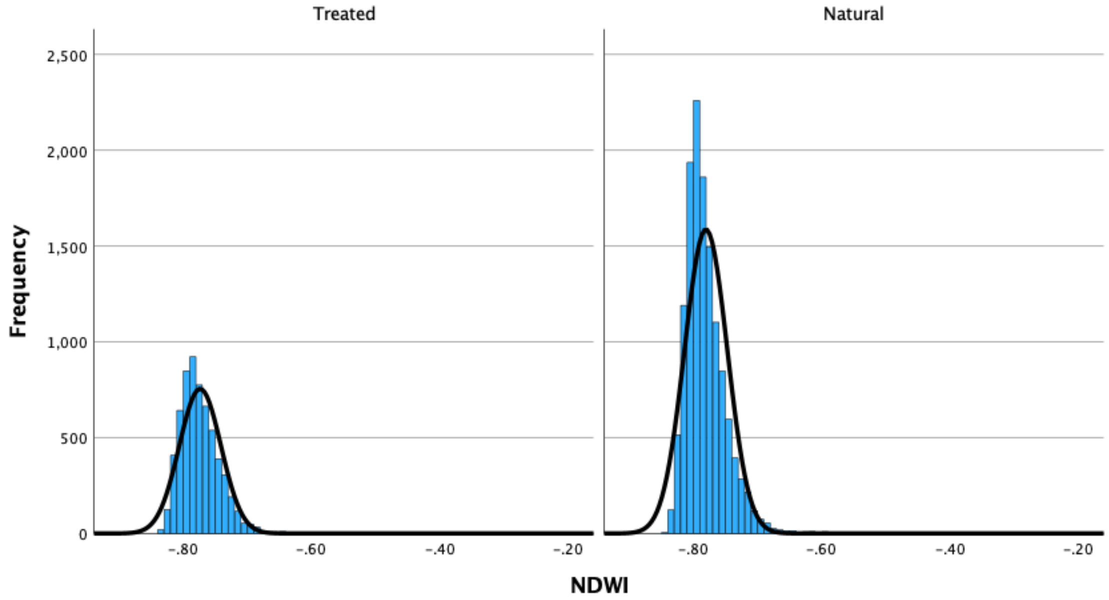

Figure 12: Histogram of mean stand NDWI distribution in row 006

Row 007:

Table 16: Results of Levene tests of variance for variables within scene 007

Variable	Levene Statistic (mean)	Significance (p)

Albedo	25.024	<0.001
Surface Temperature	1243.409	<0.001
NDWI	462.953	<0.001

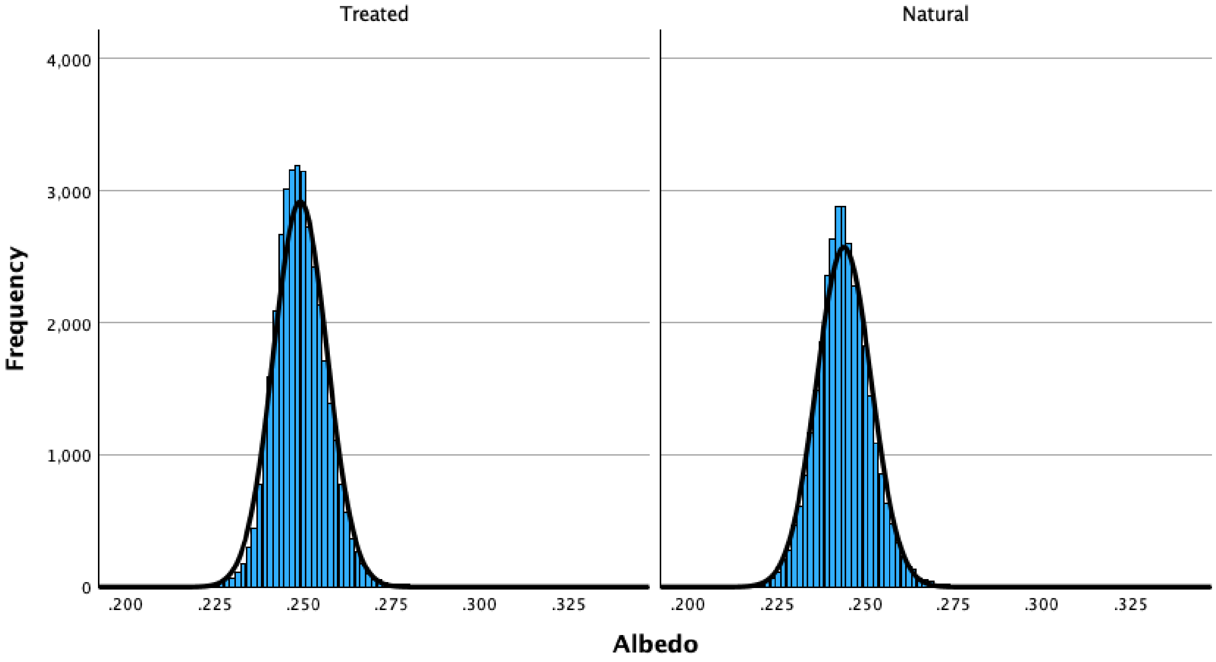

Figure 13: Histogram of mean stand albedo distributions in row 007

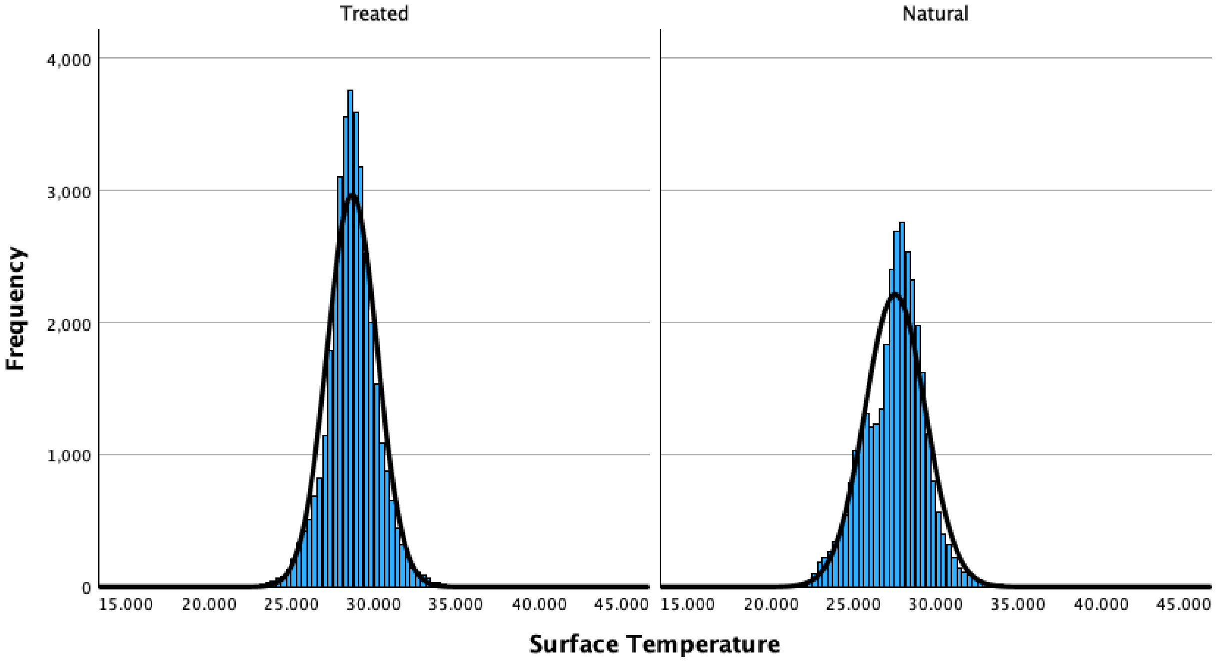

Figure 14: Histogram of mean stand surface temperature distributions in row 007

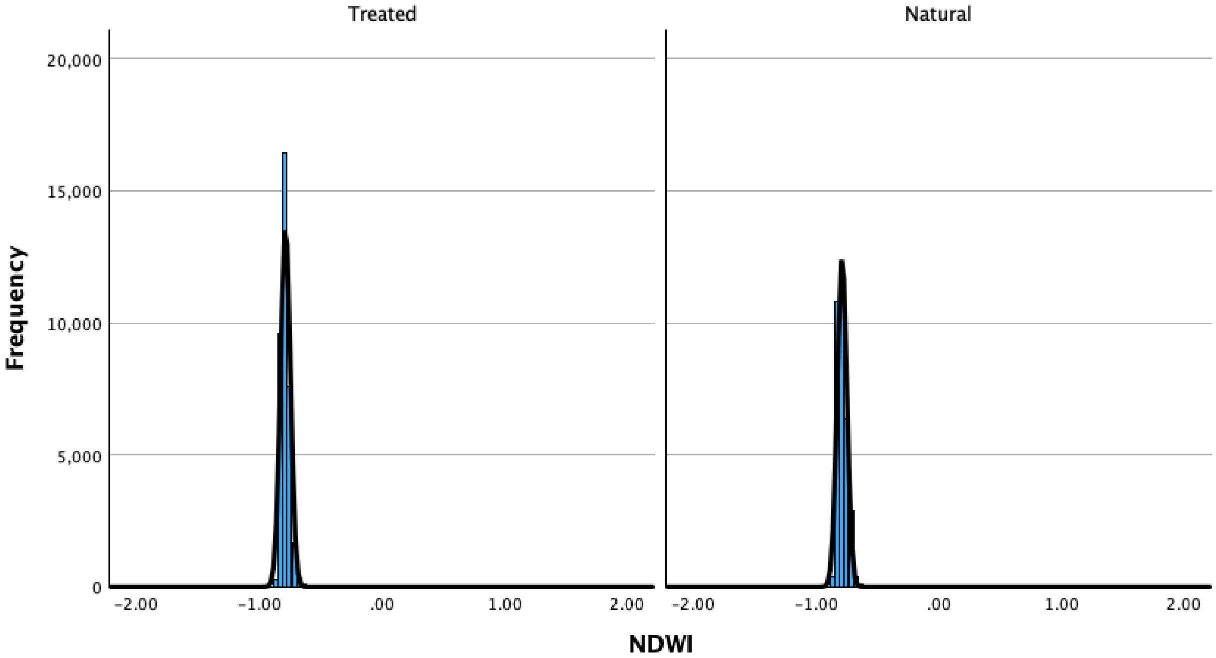

Figure 15: Histogram of mean stand NDWI distributions in scene 007

Row 008:

Table 17: results of Levene tests of variance of variables in scene 008

Variable	Levene Statistic (mean)	Significance (p)
Albedo	381.870	<0.001
Surface Temperature	186.344	<0.001
NDWI	26.143	<0.001

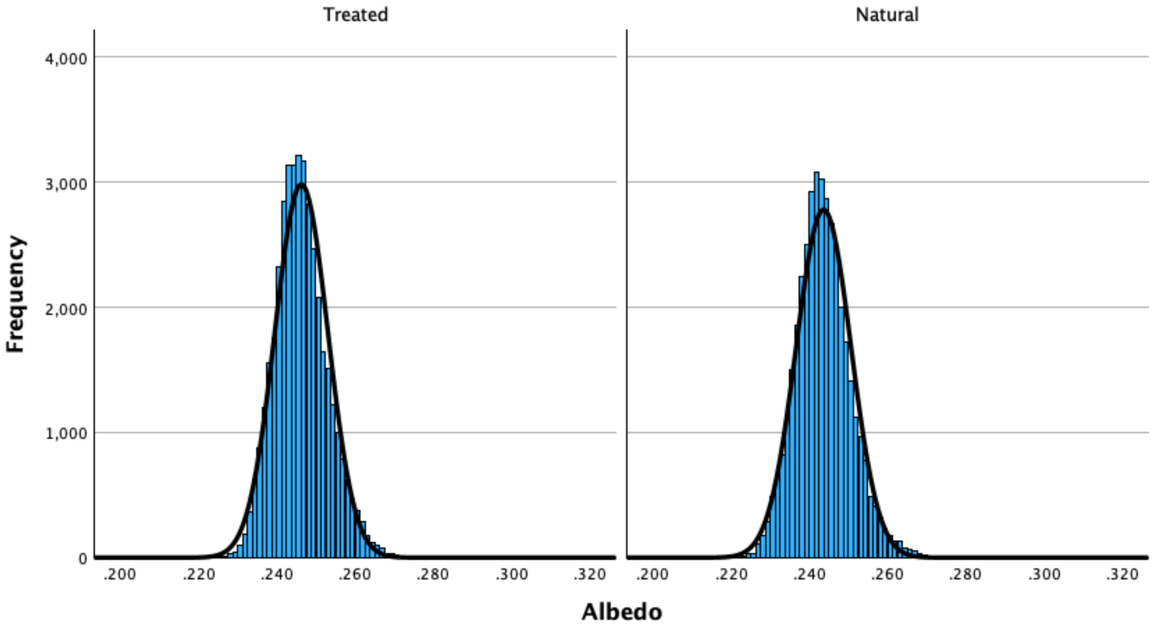

Figure 16: Histogram of mean stand albedo distributions in scene 008

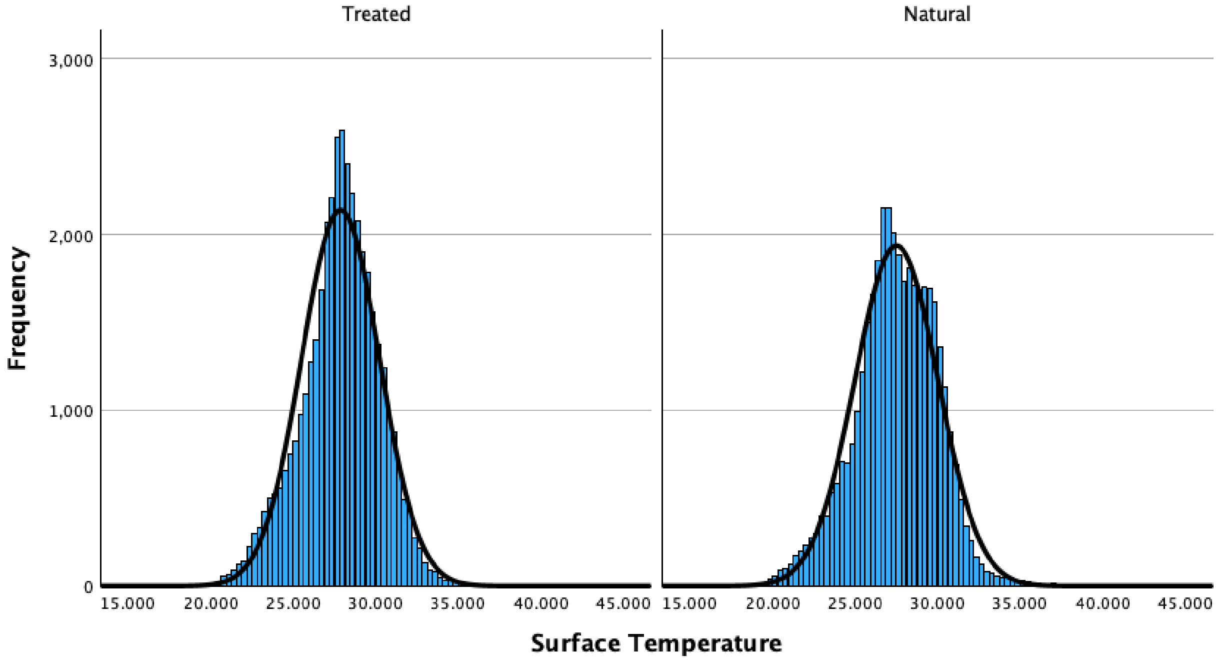

Figure 17: Histogram of mean stand surface temperature distributions in scene 008

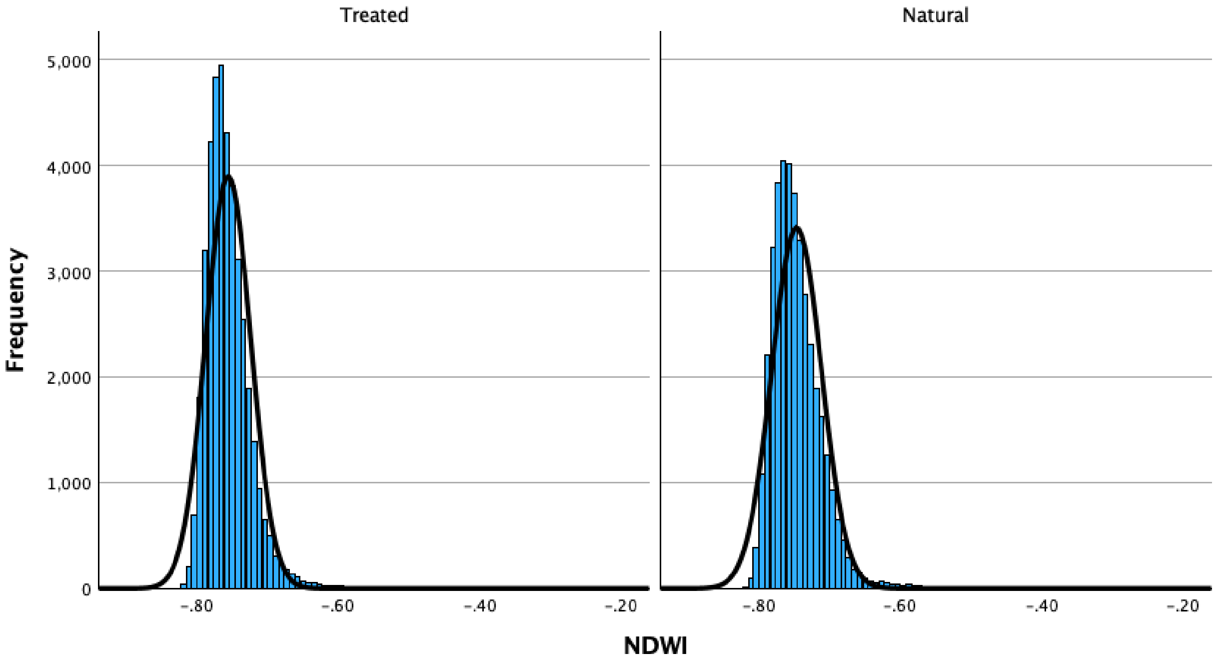

Figure 18: Histogram of mean stand NDWI distribution in row 008

Row 009:

Table 18: results from levenes test of variance for variables within stand 009

Variable	Levene Statistic (mean)	Significance (p)
Albedo	7.950	0.005
Surface Temperature	84.320	<0.001
NDWI	19.976	<0.001

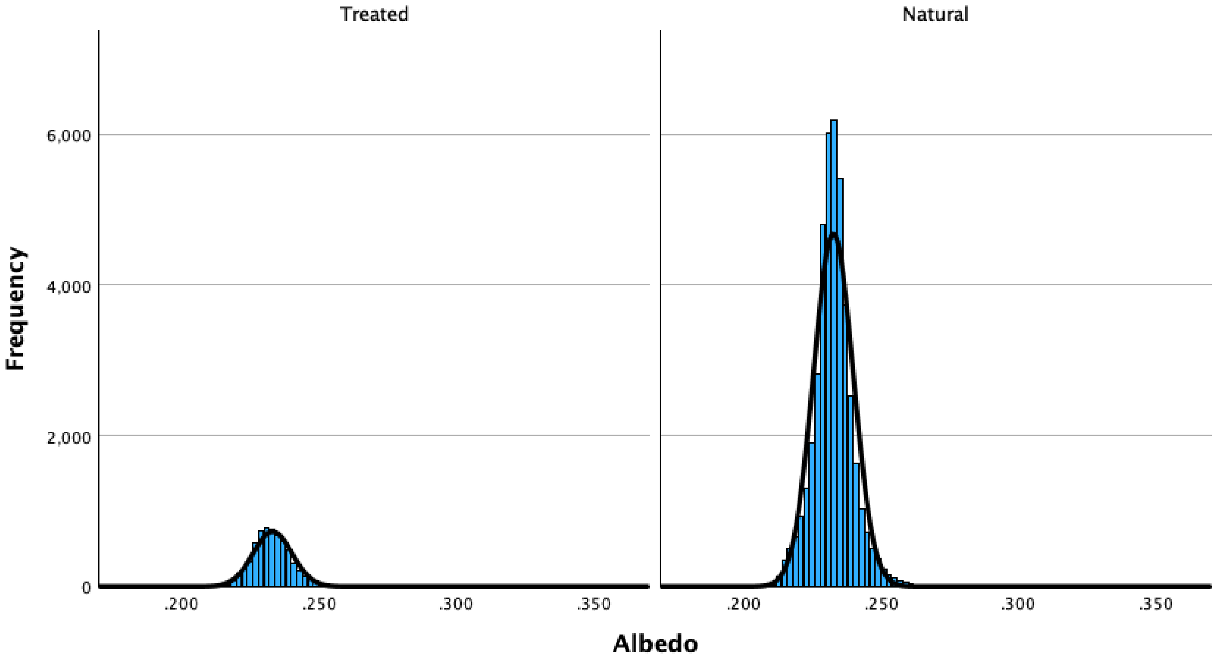

Figure 19: Histogram of mean stand albedo distributions in scene 009

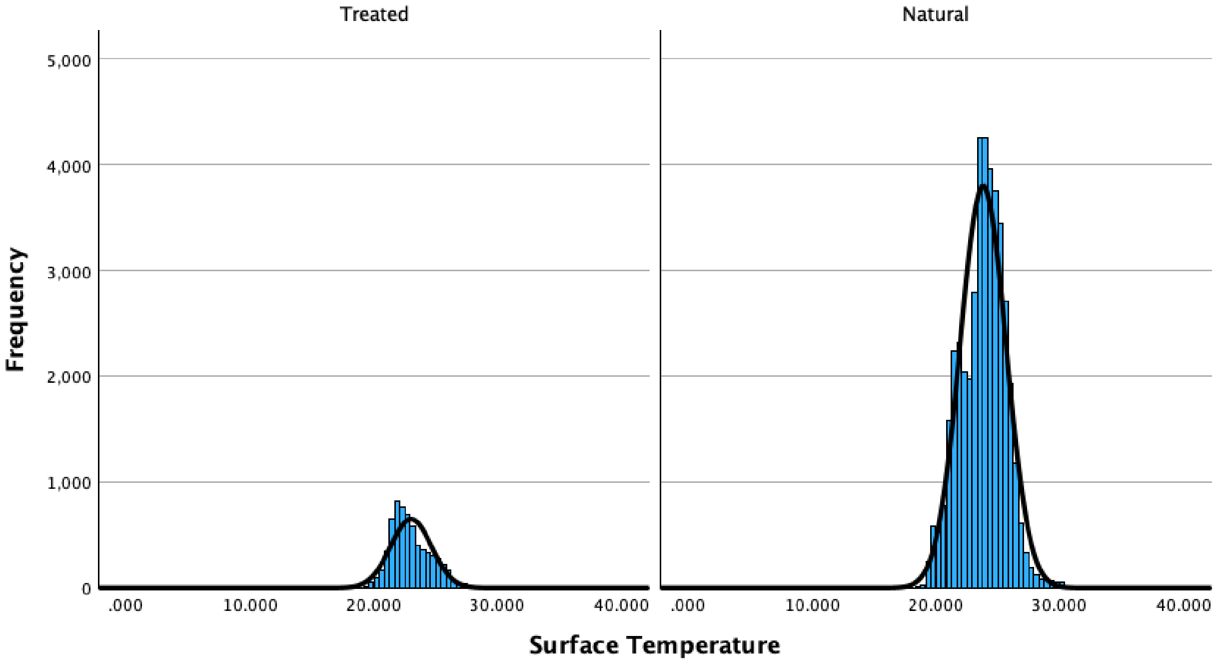

Figure 20: Histogram of mean stand surface temperature distributions in scene 009

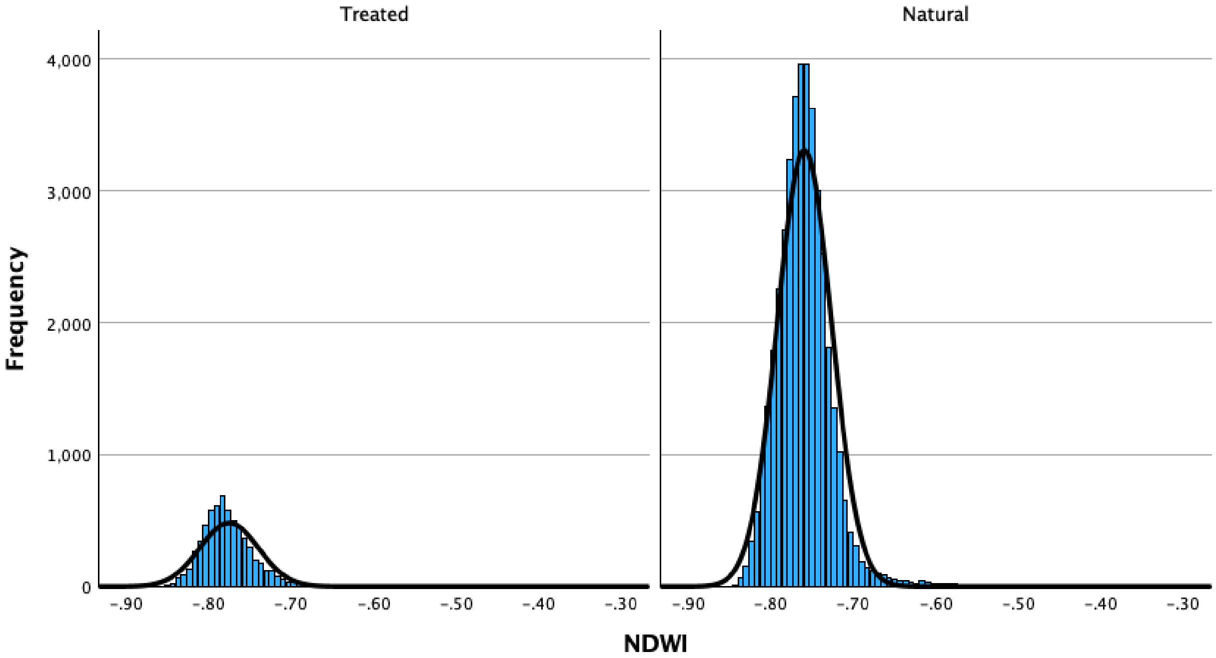

Figure 21: Histogram of mean stand NDWI distribution in scene 009