Université du Québec à Chicoutimi

Measurements of albedo changes resulting from the afforestation of boreal open woodlands with an unmanned aerial vehicle (drone)

par Suyash Khare

Mémoire présenté à l'Université du Québec à Chicoutimi en vue de l'obtention du grade de Maîtrise ès sciences (M. Sc.) en ressources renouvelables

Québec, Canada

RÉSUMÉ

La fraction du rayonnement solaire entrant qui est réfléchie par la surface de la Terre, appelée albédo, joue un rôle essentiel dans la régulation du climat terrestre. L'impact des changements d'utilisation des terres sur l'albédo de surface est donc un facteur à considérer pour déterminer leurs effets sur le climat. La forêt boréale canadienne comprend de vastes surfaces ouvertes, comme les landes à lichens, caractérisées par un albédo élevé en raison de la présence d'une couverture neigeuse pendant près de cinq mois de l'année. Celles-ci font l'objet d'efforts de boisement visant à augmenter la séquestration du carbone dans la forêt boréale. Toutefois, le boisement dans ces zones peut entraîner une diminution considérable de l'albédo de surface, en particulier pendant les mois d'hiver enneigés, ce qui peut annuler les avantages climatiques liés au piégeage du carbone.

Cette recherche vise à mesurer le changement de l'albédo de surface résultant du boisement des landes boréales à lichens, en utilisant un véhicule aérien sans pilote (UAV) équipé de pyranomètres et d'un appareil photo numérique à haute résolution. Des mesures de l'albédo ont été effectuées sur deux sites expérimentaux situés dans la forêt boréale du Québec, Canada, près des villes de La Doré et de Chibougamau. À chaque site, l'albédo de surface a été mesuré sur quatre types de couverture terrestre : des landes à lichens non reboisées, des forêts matures (> 80 ans) d'épinette noire (*Picea mariana* [Mill]), ainsi que des plantations monospécifiques d'épinette noire et de pins gris (*Pinus banksiana* [Lamb]) âgées de 12 à 23 ans. L'étude a examiné les variations saisonnières de l'albédo sur chacune des parcelles, ainsi que les effets de la couverture neigeuse, de la densité des arbres et de la couverture de lichens.

Les résultats montrent que les forêts matures ont un albédo inférieur, en particulier en hiver lorsque la couverture neigeuse est présente. À Chibougamau, les landes à lichens avaient un albédo hivernal moyen d'environ 0.35, tandis que les forêts matures enregistraient l'albédo le plus faible, soit 0.24. Les plantations d'épinette noire (0.32) et de pin gris (0.34) affichaient des valeurs légèrement inférieures à celles des landes à lichens. À La Doré, l'albédo hivernal variait de manière similaire entre les types de couverts, mais il était systématiquement inférieur de 0.05 à 0.09 par rapport à celui de Chibougamau, variant de 0.15 dans les forêts matures à 0.27 dans les landes à lichens. La relation albédo-couvert arboré n'était pas significative dans les plantations en hiver, suggérant que les différences d'albédo entre les deux sites provenaient des caractéristiques du couvert neigeux (par ex., épaisseur, âge). En été, les variations de l'albédo étaient moins prononcées mais les tendances restaient les mêmes. Les plantations de pin gris et d'épinette noire présentaient des valeurs moyennes d'albédo estival similaires (0.12-0.13), supérieures à celles des forêts matures (~0.09), mais légèrement inférieures à celles des landes à lichen (0.15 à La Doré et 0.12 à Chibougamau). Les landes à lichen présentaient systématiquement un albédo estival supérieur de 0.03 à 0.06 à celui des forêts matures sur les différents sites, ce qui pourrait s'expliquer par une différence de couleur et de structure de la canopée. La couverture de lichens n'a pas eu d'impact significatif sur l'albédo d'été.

Ces résultats montrent que le boisement des landes boréales à lichens a un effet négligeable sur l’albédo de surface à court terme, mais que cet effet pourrait être de 0.11-0.12 en avril et de 0.03 à 0.06 en été sur le long terme. Ce travail souligne l'importance de prendre en compte l'albédo lors de l'évaluation de l'impact sur le climat du boisement des zones ouvertes de la forêt boréale. Les mesures par drone sont une technique précieuse pour la surveillance à haute résolution de l'albédo, qui fournit des données sur l'interaction terre-atmosphère importantes pour la modélisation du climat et l'élaboration de politiques liées au boisement.

Mots-clés : Albédo; véhicules aériens sans pilote (UAV); boisement; épinette noire; pin gris; forêt boréale.

ABSTRACT

The fraction of incoming solar radiation reflected by the Earth's surface, referred to as albedo, plays a vital role in climate regulation. The impact of land-use changes on surface albedo is thus an essential factor in determining their climate impacts. The Canadian boreal forest includes vast areas of open woodlands (OWs), observed for their high albedo due to the presence of snow cover for almost five months of the year. These OWs are increasingly the focus of afforestation efforts intended to improve carbon sequestration. However, afforestation in these areas can result in considerable decreases in surface albedo, especially during the snow-covered winter months, which may offset the climatic advantages of carbon sequestration.

This research aims to measure albedo variation resulting from the afforestation of boreal OWs, utilizing an unmanned aerial vehicle (UAVs) mounted with pyranometers and a high-resolution digital camera. Albedo measurements were performed at experimental sites in La Doré and Chibougamau, located in the boreal forest of Quebec, Canada, across a range of land cover types, including OWs, mature forest, and 12- to 23-year-old black spruce (*Picea mariana* [Mill.]) and jack pine (*Pinus banksiana* [Lamb]) plantations. The study examined seasonal variations to assess the effects of snow cover, tree density, and lichen cover on albedo.

Results show that afforestation leads to a significant decrease in surface albedo, particularly during winter when snow cover was present. In Chibougamau, OWs had the highest winter albedo around 0.35, while mature forests recorded the lowest at 0.24, whereas black spruce (0.32) and jack pine (0.34) plantations (0.32 and 0.34, respectively) displayed slightly lower values than OWs. At La Doré, winter albedo followed a similar pattern but remained consistently lower by 0.05–0.09, ranging from 0.15 in mature forests to 0.27 in OWs. In plantations, the albedo-tree cover relationship in winter was not significant at both sites. During the summer, the variations in albedo were less pronounced. Jack pine and black spruce plantations showed similar average summer albedo values (0.12–0.13), which were higher than those of mature forests (~0.09) but lower than those in OWs (0.15 at La Doré and 0.12 at Chibougamau). Open woodlands consistently exhibited a summer albedo that was 0.03–0.06 higher than that of mature forests across both sites, likely due to differences in canopy colour and structure. Lichen cover was not found to significantly impact summer albedo.

These results show that afforestation of OWs has a negligible short-term effect on surface albedo, but that this effect could reach 0.11–0.12 in April and 0.03–0.06 in summer over the long term. These findings highlight the importance of considering albedo effect when making climate impact assessments of boreal afforestation. UAV-based measurements are a valuable technique for high-resolution monitoring of albedo, which provides land-atmosphere interaction data important for climate modeling and policy-making related to afforestation.

Keywords: Albedo; unmanned aerial vehicles (UAVs); afforestation; black spruce; jack pine; boreal forest.

Table of Contents

RÉSUMÉ ii
ABSTRACT iv
Table of Contents v
LIST OF TABLES vii
LIST OF FIGURES viii
ACKNOWLEDGMENTS x
CHAPTER I 1
GENERAL INTRODUCTION 1
CHAPTER II 5
Measurements of albedo change resulting from the afforestation of boreal open woodlands with an unmanned aerial vehicle (drone) 5
2.1 Abstract 6
2.2 Introduction 7
2.3 Material and methods 12
2.3.1 Study Area 12
2.3.2 Experimental Design and Site Description 12
2.3.3 UAV Platform and Instruments 14
2.3.4 Zenmuse P1 Digital Camera 15
2.3.5 Irradiance measurements with pyranometers and the METEON 2.0 Datalogger 15
2.3.6 Albedo calculation method 16
2.3.7 Delta albedo (Δ albedo) 16
2.3.8 Data Acquisition 17
2.3.9 Data Extraction and Data Processing 18
2.3.10 Determination of Tree Cover and Lichen Cover Using the Excess Green Index (ExG) 22
2.3.11 Statistical analyses 24
2.4 Results 25
2.4.1. Influence of Land Cover Type on albedo 25
2.4.2 Seasonal Variations in irradiance and albedo 29
2.4.3 Effect of land cover type on albedo seasonal changes 32
2.4.4 Spatial variations in albedo 33
2.4.5 Impact of tree cover on plantations winter albedo 36

2.4.6 Impact of lichen cover on plantations' summer albedo 37
2.5 Discussion **40**
2.5.1 Impact of different land cover types on albedo 42
2.5.2 Seasonal effect on surface albedo 47
2.5.3 Impact of vegetation on surface albedo 47
2.5.4 Conclusion 49
2.6 Supplementary materials **51**
CHAPTER III **55**
GENERAL CONCLUSION **55**
REFERENCES **58**

LIST OF TABLES

Table 1. Geographic coordinates of experimental plots by site and land cover type. 13
Table 2. UAV data collection schedule by location, season, and land cover type. 18
Table 3.Results of the ANOVA assessing the effects of season and land cover type on albedo at the Chibougamau and La Doré sites. 27
Table 4. Seasonal average albedo, number (No.) of albedo points /flight, incident radiation and reflected radiation measurements for all land cover types at Chibougamau and La Doré. 31
Table 5.Results of ANCOVA assessing the effects of tree cover, site, and species on albedo. 37
Table 6. Results of ANCOVA assessing the effects of lichen cover, site, and species on albedo. 39

LIST OF FIGURES

Figure 1. Map of the study area showing both experimental sites located in Chibougamau and La Doré in Quebec, Canada. The insets show the four experimental plots (land cover types) at each site. 14
Figure 2. Picture of the DJI M300 RTK quadcopter mounted with Zenmuse P1 digital camera, two pyranometers (PR1; Kipp & Zonen; Delft, The Netherlands) and a data logger METEON 2.0 (Kipp & Zonen; Delft, The Netherlands). 15
Figure 3. Flow chart showing the procedure to derive average albedo from digital camera images and pyranometer data. 22
Figure 4. Steps performed to achieve grid-based analysis. 24
Figure 5. Albedo values for all land cover types at Chibougamau and La Doré in summer. Each box contains the interquartile range (IQR), which shows the middle 50% of the data, and the horizontal line inside each box is the median value. Red diamond points represent the mean albedo values for each group. Whiskers stretch to 1.5 times the IQR, and dots represent outliers. This figure displays both a central tendency and variability in albedo values among sites and land cover types, allowing a comparison of how albedo differs during the summer season. 28
Figure 6. Albedo values for all land cover types at Chibougamau and La Doré in winter. Red dots indicate average albedo values. Each box contains the interquartile range (IQR), which shows the middle 50% of the data, and the horizontal line inside each box is the median value. Red diamond points represent the mean albedo values for each group. Whiskers stretch to 1.5 times the IQR, and dots represent outliers. This figure displays both a central tendency and variability in albedo values among sites and land cover types, allowing a comparison of how albedo differs during the winter season. 29
Figure 7. Difference of surface albedo between winter and summer (Δ albedo $_{[season]}$) for all land cover types at the Chibougamau (top panel) and La Doré (bottom panel) experimental sites. 32
Figure 8. Spatial variation of albedo within four land cover types (open woodland, mature forest, and 23-year-old black spruce and jack pine plantations) in winter and summer at Chibougamau. Albedo values measured during the flights are shown on the orthomosaics. 34
Figure 9. Spatial variation of albedo within four land cover types (open woodland, mature forest, and 12-year-old black spruce and jack pine plantations) in winter and summer at La Doré sites. Albedo values measured during the flights are shown on the orthomosaics... 35
Figure 10. Relationship between albedo and tree cover (%) in black spruce and jack pine plantations at the Chibougamau and La Doré experimental sites in winter. 36
Figure 11. Relationship between albedo and lichen cover (%) in black spruce plantations, jack pine plantations and open woodlands at the Chibougamau and La Doré experimental sites in summer. 38
Figure 12. Incident radiation, reflected radiation and albedo values measured during the flights in black spruce plantations in both the winter and summer seasons at Chibougamau (a and b) and at La Doré (c and d). 51
Figure 13. Incident radiation, reflected radiation and albedo values measured during the flights in jack pine plantations in both the winter and summer seasons at Chibougamau (a and b) and at La Doré (c and d). 52

Figure 14. Incident radiation, reflected radiation and albedo values measured during the flights in open woodlands in both the winter and summer seasons at Chibougamau (a and b) and at La Doré (c and d). 53
Figure 15. Incident radiation, reflected radiation and albedo values measured during the flights in mature forest in both the winter and summer seasons at Chibougamau (a and b) and at La Doré (c and d). 54

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my supervisor, Dr. Patrick Faubert, and cosupervisors, Dr. Charles Marty and Dr. Maxime Boivin, for their invaluable guidance, support, and encouragement throughout the course of my master's research. Their insights and mentorship have been instrumental in shaping the direction and quality of this work. I am also thankful for their constructive feedback, thoughtful discussions, and continuous support, which have greatly enriched this project.

I would also like to extend my appreciation to the entire Carbone boréal, whose support and collaboration made this research possible. I am especially grateful to Carbone boréal and Fondation de l'Université du Québec à Chicoutimi for providing financial support during my master's studies, enabling me to carry out fieldwork and data analysis with the necessary resources and independence.

The study was also funded by the Ministère des Ressources naturelles et des Forêts (MRNF) of Québec. Carbone boréal is also grateful for the in-kind contributions from the MRNF and the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation of Québec.

To my colleagues and friends in the lab, thank you for creating a supportive and intellectually stimulating environment that made each step of this journey both meaningful and enjoyable. Finally, I am deeply thankful to my family and friends for their unwavering support and encouragement, near or far they have been a constant source of strength and motivation.

CHAPTER I

GENERAL INTRODUCTION

This study includes surface albedo in the assessment of the climate impacts of forestry operations in Quebec, focusing on comparing biophysical effects, specifically albedo modification, versus biochemical effects such as carbon sequestration. While the role of albedo in maintaining the climate had already been known (Betts & Ball, 1997), its application in land management planning was still limited until advances in remote sensing technology allowed greater specificity. In Quebec, a study by Bernier et al. (2021) and collaborators brought to the forefront the climatic effects of afforestation in low-vegetation boreal sites, posing significant questions regarding the net climatic advantage of such efforts. Based on this, our research considers the change of albedo through various land covers and over the course of forest stand development in an attempt to further understand whether afforestation efforts yield a net cooling or warming impact.

This research is driven by several environmental, political, economic, and social factors. Environmentally, it seeks to contribute to a better understanding of the influence of Quebec's boreal forest landscapes on surface albedo. This understanding is important to support the improvement of climate change mitigation through science-based land management. Politically, the study is highly timely given Canada's nationwide afforestation initiatives, including the federal commitment to plant two billion trees (https://www.canada.ca/en/campaign/2-billion-trees.html). As surface albedo is generally overlooked in climate impact research on afforestation and reforestation projects, including it into climate effect analyses may challenge prevailing assumptions about the net climate benefit of afforestation in certain non-forest regions. There are also economic implications, where albedo effect will have an impact on investment choices and carbon offsetting markets for which afforestation is a significant mechanism. Furthermore, any alteration of afforestation policy or practice can influence social priorities, especially in Quebec, where forest management coincides with biodiversity conservation goals—e.g., caribou habitat protection in the context of lichen-dominated open woodlands. By contrasting a suite of land cover scenarios, this study aims to inform these multifaceted discussions and provide more conclusive guidance on the climate effectiveness of afforestation programs when albedo is considered.

The primary source of energy on Earth is solar radiation, and has a significant impact on the occurrence, formation, and evolution of the Earth's weather and climate system. This radiation is classified as shortwave (280 to 2,800 nm) and longwave (2,800 to 100,000 nm) (Tsangrassoulis 2013). Shortwave radiation from the sun accounts for approximately 85% of the radiant flux density. The remaining 15% consists of long-wave radiation, emitted by gases, particularly water vapor and CO_2, found in the atmosphere (Klassen & Bugbee 2015). The solar constant, which represents the average amount of solar radiation received per unit area at the top of Earth's atmosphere on a plane (i.e., flat surface) perpendicular to the Sun's rays, is equal to 1370 W m^{-2} of shortwave radiation at the top of the atmosphere at the Earth's mean distance from the sun. Because of scattering and absorption by moisture, gases, and particulate matter in the air, radiation delivered through the atmosphere to the Earth's surface is heavily filtered in both quantity and spectral quality. In the absence of clouds, on average, 65 to 75% of extra-terrestrial radiation (900-1000 W m^{-2}) reaches the Earth's surface (terrestrial), with the remainder dispersed or absorbed by water vapor, carbon dioxide, ozone, and particulates (Tsangrassoulis 2013). A fraction of the incoming shortwave solar radiation is absorbed by the Earth's surface, and another is reflected back to space. The absorbed energy increases the surface temperature, evaporates water, melts and sublimates snow and ice, and energises the turbulent heat exchange between the surface and the atmosphere's lowest layer. The proportion of incoming incident solar radiation that is reflected back to space is called surface "albedo", derived from the Latin word "alba" which means "whiteness." Thus, surface albedo is an important component of the Earth's energy balance and plays a crucial role in land-climate interactions.

Surface albedo varies across space and time due to factors such as land cover, vegetation, the presence of snow, and human-induced changes. This variation is especially important in high-latitude regions. It is particularly important for Carbone boréal, a scientific initiative led by the Université du Québec à Chicoutimi (UQAC) and focused on afforestation and carbon offsetting in the boreal forest region of Quebec, Canada. It aims to carry out afforestation projects in open areas of Quebec's boreal forest to help mitigate climate change and support research on this ecosystem, making it one of the few programs of its kind globally (Faubert et al. 2023). Carbone boréal intends to afforest uncovered and unused boreal lands, which are typically lichen-dominated open woodlands, by planting native species such as black spruce (*Picea mariana* [Mill]) and jack pine (*Pinus banksiana* [Lamb]). These plantations are designed to absorb and sequester atmospheric carbon dioxide and serve as experimental sites for studying deeper ecological impacts of afforestation in the boreal biome (Faubert et al. 2023). The program has, over time, provided valuable information regarding rates of carbon sequestration, measurement of soil carbon, forest growth, and, more recently, surface albedo, an important yet commonly overlooked climate variable.

Albedo reflects the ability of the Earth to reflect incoming solar radiation; lighter surfaces, such as snow, show higher reflectivity, whereas darker surfaces, such as coniferous canopies, show greater absorption. This relationship becomes especially important in boreal regions, where snow cover persists for several months each year. Therefore, measurements of albedo changes resulting from the afforestation of boreal open woodlands using an unmanned aerial vehicle (UAV; unmanned aircraft [drone]) contributes directly to this research focus. We used UAV-mounted pyranometers and high-resolution camera to quantify albedo changes across various land cover types and seasons at Carbone boréal's experimental sites located in Chibougamau and La Doré. The aim of this research was to develop a UAV-based method for measuring albedo and to evaluate the influence of land cover types and seasonal variation on the average albedo of open woodlands, 12- to 23-year-old plantations (black spruce and jack pine) and mature black spruce forests. This research seeks to determine whether afforestation has a positive or negative impact in terms of the warming effect caused by albedo in the boreal forest.

CHAPTER II

Measurements of albedo change resulting from the afforestation of boreal open woodlands with an unmanned aerial vehicle (drone)

Authors:

Suyash Khare[1,2,*], Charles Marty[1,2], Maxime Boivin[2,3,4], Patrick Faubert[1,2,5]

Affiliations:

[1]Carbone boréal, Département des sciences fondamentales, Université du Québec à Chicoutimi, 555, boulevard de l'Université, Chicoutimi, QC, G7H 2B1, Canada

[2]Centre de recherche sur la boréalie, Université du Québec à Chicoutimi, 555, boulevard de l'Université, Chicoutimi, QC, G7H 2B1, Canada

[3]Laboratoire d'expertise et de recherche en géographie appliquée, Département des sciences humaines et sociale, Université du Québec à Chicoutimi, 555, boulevard de l'Université, Chicoutimi, QC, G7H 2B1, Canada

[4]Chaire de recherche sur les espèces aquatiques exploitées, Département des sciences fondamentales, Université du Québec à Chicoutimi, 555, boulevard de l'Université, Chicoutimi, QC, G7H 2B1, Canada

[5]Laboratoire sur les écosystèmes terrestres boréaux, Département des sciences fondamentales, Université du Québec à Chicoutimi, 555, boulevard de l'Université, Chicoutimi, QC, G7H 2B1, Canada

*Corresponding author: skhare1@etu.uqac.ca

Note:

This chapter is presented as a scientific article. The article is planned to be submitted to Canadian Journal of Forest Research.

2.1 Abstract

The impact of afforestation on surface albedo introduces uncertainty in assessing the climate effects of land-use changes in boreal forests. This research project used an unmanned aerial vehicle (UAV) fitted with pyranometers and a high-resolution digital camera to measure surface albedo variation resulting from the afforestation of boreal open woodlands (OWs). Albedo measurements were performed at experimental sites in La Doré and Chibougamau, Quebec (Canada), across a range of land cover types, including OWs, mature black spruce forests (> 80 years), and 12- to 23-year-old black spruce and jack pine plantations. The study analyzed seasonal changes to evaluate how snow cover, tree density, and lichen cover influence surface albedo. The results indicate that afforestation results in a decrease in winter albedo, with the extent of the effect differing according to the age of the forest. Open woodlands recorded the highest albedo values in late winter, reaching approximately 0.35 at Chibougamau and 0.27 at La Doré. In comparison, jack pine and black spruce plantations showed only slightly lower albedo values around 0.32–0.34 at Chibougamau and 0.25–0.26 at La Doré, leading to a minimal 0.01 to 0.03 short-term reduction. However, winter albedo values of mature forests dropped to 0.24 in Chibougamau and 0.15 in La Doré, which represents a permanent decrease of 0.11 to 0.12 compared to OWs; this might be caused by differences in canopy colour, structure, and snow interception. Lichen cover was not found to impact significantly summer albedo. These findings highlight the importance of considering albedo effect when making climate impact assessments of boreal

afforestation. UAV-based measurements are a valuable technique for monitoring albedo at high resolution, providing data on land-atmosphere interactions that are important for climate modelling and afforestation-related policy-making.

Keywords: Albedo; unmanned aerial vehicles (UAVs); afforestation; black spruce; jack pine; boreal forest.

2.2 Introduction

Albedo is an important component of the Earth's energy balance and plays a crucial role in land-climate interactions. Surface albedo is defined as a ratio of solar radiation reflected at the Earth's surface to solar radiation received at the Earth's surface and is a significant controlling factor for the land surface's solar energy absorption (Trenberth et al. 2009). Its value is commonly represented as a dimensionless number ranging from (0 to 1), were 0 representing total absorption without reflection, and 1, representing total reflection without absorption. Albedo varies greatly among various surface types, including snow, vegetation, soil, and urban surfaces, because of colour, texture, moisture, and structure variations (Zhang et al. 2022). Therefore, surface albedo plays an important role in climate regulation and energy exchange processes, making its accurate measurement across various spatial and temporal scales essential to determine land–atmosphere interactions and climate feedbacks.

The two most commonly used methods of data collection for albedo measurements are satellite systems and permanent monitoring stations. Satellite systems, such as Sentinel-2, provide valuable data at relatively high temporal frequencies (2-3 days under optimal conditions) and spatial resolutions ranging from 10 to 60 meters per pixel, which make them ideal for landscape-scale studies spanning tens of kilometres (Roujean et al. 2019). However, these records do not have the requisite resolutions for smaller-scale studies and are most often noisy owing to cloud cover and aerosol contamination. On the other hand, permanent monitoring stations are indispensable in maintaining continuous environmental records. Nevertheless, long-term environmental records from the same locations and narrow spatial coverages can easily bring biases in understanding the spatial heterogeneity which could be critical in some complex ecosystems (Levy et al. 2018). These monitoring stations cannot represent wider landscape variability nor capture changes in the dynamic forest ecosystems, for instance, fine-scale surface albedo changes.

Recently, to make up for the shortcomings of both methods, unmanned aerial vehicles (UAVs), or drones, have emerged as a better option. This is very important because UAVs offer unparalleled flexibility, providing high-resolution measurements at sub-decimeter scales and acquiring data in almost all weather conditions, including under cloud cover. Their mobility enables comprehensive data acquisition across complex landscapes, making them a powerful tool for the study of environmental dynamics with great precision and adaptability. Depending on the battery life and kind of equipment, UAVs may cover areas ranging from 0.01 km^2 to 100 km^2. For these reasons, surface albedo has increasingly been measured using UAVs in the past decade in a variety of ecosystems (Cao et al. 2018; Levy et al. 2018; Roberts et al. 2008; Sproles et al. 2020). In addition, UAV-based albedo measurements may provide a good source of calibration and validation data for satellite observations and albedo models.

Surface albedo fluctuates throughout space due to variations in soil cover, vegetation, topography, and solar angle, and throughout time due to seasonality. For instance, lakes and seas will absorb a large fraction of the incident radiation when unfrozen but will reflect most of it when frozen. Therefore, the spatial and temporal variability of surface albedo is especially important at high latitudes and in mountainous regions because snow build up and melt cycles produce some of the most significant changes on the Earth's surface. In general, densely forested regions have lower surface albedo than bare ground or short vegetation areas because more of the shortwave radiation that falls on them is absorbed and less is reflected into space. This ultimately heats up the Earth’s surface and the lower atmosphere (Anderson et al., 2011). This is particularly true in the boreal zone, where open woodlands and short vegetation areas are covered by a thick snowpack (with a high albedo) for four to six months of the year. Thus, the afforestation of open woodlands may result in a decrease in albedo, potentially diminishing the climate benefit of CO_2 removal from the atmosphere by trees (Bernier et al., 2011; Betts, 2000). As a result, afforestation in the boreal zone can have both cooling and warming effects on the climate, and this area of research is still largely unexplored, especially at a small scale.

As a consequence, there has been ongoing debate about the effectiveness of afforestation in the boreal zone as a climate cooling strategy (Kristensen et al. 2024). For afforestation to result in a net cooling effect, the biochemical benefits such as the removal of CO_2 from the atmosphere must be large enough to surpass the warming effect caused by a reduction in surface albedo (Asselin et al. 2022; Bala et al. 2007; Beaury et al. 2024; Bernier et al. 2011; Betts 2000; Bounoua et al. 2002; Chapin III et al. 2005; Hasler et al. 2024; Kristensen et al. 2024). This is an important question as the boreal forest is the world's largest biome, covering around 14 million km^2 – equivalent to 32% of the world's forest cover (Burton et al. 2003; Pan et al. 2024). It also includes significant areas of open woodlands, which are the results of successive wildfires and other disturbances (Girard et al., 2009; Jasinski & Payette, 2005; Payette & Delwaide, 2018). In Canada, these open woodlands cover about 2 million hectares (Johnson & Miyanishi 1999), including 1.6 million hectares in the province of Québec only, representing approximately 7% of the black spruce feather moss domain of the boreal forest (Girard et al., 2008). Afforestation of these open woodlands may result in a significant net carbon sink at the national scale (Boucher et al. 2012). Using carbon dynamics and budget models and accounting for carbon emissions throughout the value chain, it was estimated that afforested open woodlands may create net carbon sinks of at least 77 t C ha^{-1} over a period of 70 years and could sequester up to 8% of industrial CO_2 emissions in the Province of Québec if implemented on a large scale (Boucher et al. 2012; Gaboury et al. 2009). These open woodlands may therefore be able to host part of the 2 billion trees that the Canadian government has vowed to plant as part of its plan to reduce its emissions to net zero by 2050 (https://www.canada.ca/en/campaign/2-billion-trees.html). However, the balance between the biochemical and biophysical effects resulting from the afforestation of boreal open woodlands must be assessed to make sure this is not counterproductive in terms of climate benefits.

The main objective of this study was to determine the changes in surface albedo following the afforestation of open woodlands in the Quebec boreal zone. Therefore, this study was conceptualised to understand how afforestation in the boreal region affects radiative balance and to get a more precise estimate of its climatic impact, taking into account both biochemical and biophysical effects. The specific objectives were:

1) To develop a method to measure surface albedo using a UAV.
2) To assess the difference in surface albedo among land cover types.
3) To assess the seasonal variation in surface albedo.
4) To assess the impact of tree and lichen covers on surface albedo in young (12 to 23 years old) black spruce and jack pine plantations, and open woodlands.

We hypothesized that afforestation of the open woodlands would directly affect surface albedo, and thus there would be a significant difference between the surface albedo of open woodlands, plantations and mature forest. Surface albedo is expected to vary with season, especially in open woodlands, where snow covers the low vegetation in winter and early spring, leading to high albedo. During the snow-free period, a decrease in surface albedo was predicted in plantations and mature forest compared to open woodlands, as the latter are covered with white terricolous lichens which likely increase albedo compared to the darker canopies of plantations and mature forest. We also hypothesized that an increase in tree cover would lower the albedo in winter, with the lowest values anticipated in mature forest. The surface albedo in jack pine plantations was anticipated to be lower than that in black spruce, especially during winter, due to the generally higher growth rate of jack pine in the initial decade post-afforestation (Fradette et al. 2021; Marty et al. 2023), leading to increased aboveground biomass that obscures the snow and diminishes surface reflectivity. During the summer, the increased aboveground biomass of jack pine would obscure the white terricolous lichens, resulting in a further reduction of albedo in comparison to black spruce.

2.3 Material and methods

2.3.1 Study Area

The study was conducted on Carbone boréal's experimental sites network located north and west of the Lac Saint-Jean (Quebec, Canada) in the black spruce-feather moss boreal forest. These forests are dominated by black spruce (*Picea mariana* [Mill.]) and jack pine (*Pinus banksiana* [Lamb.]). The region's climate is typically boreal, with cool summers and cold winters. The mean annual temperature in the region varies from -1.6°C in the northern area to 4.1°C in the southern area. Winter months (December to February) have mean temperatures ranging from -18°C and -21°C, with recorded extremes as low as -29.8°C to -37.1°C. In contrast, the mean temperature from May to September averages 12.1°C (Antonucci et al. 2017; Historical Climate Data - Climate - Environment and Climate Change Canada).

2.3.2 Experimental Design and Site Description

Albedo measurements were conducted at two Carbone boréal's experimental sites: La Doré (48° 36′ 25″ N, 72° 57′ 47″ W) and Chibougamau (49° 59′ 2″ N, 74° 12′ 14″ W) in Quebec, Canada (Figure 1), during two key periods: summer (August) and late winter (April) of 2023. Measurements were taken at each site across four land cover types: open woodlands, mature forests, and 12- to 23-year-old plantations of black spruce and jack pine. The open woodlands contain sparse lichen ground cover with scattered black spruce trees (<25% cover) and represent the pre-afforestation landscape. The mature forest plots consist of naturally regenerated, closed-canopy forests dominated by black spruce, with an average stand age of over 80 years. The plantation sites were established as part of the afforestation scheme of the Carbone boréal program. At each site, experimental blocks with monospecific plantations established in 2000 at Chibougamau and 2011 at La Doré were selected and were 23 and 12 years old at the time of the study, respectively.

All plantation fields operate under uniform regimes, featuring minimal subgrowth, allowing direct comparisons among land cover classes and sites. Fine-scale site selection enabled us to examine the effect of species type, forest age and seasonal snow cover on surface albedo in a boreal afforestation environment.

Table 1. Geographic coordinates of experimental plots by site and land cover type.

Site	Land Cover Type	Latitude (°N)	Longitude (°W)
La Doré	Open Woodland	48° 36′ 22″	72° 57′ 54″
	Mature Forest	48° 36′ 14″	72° 57′ 40″
	Jack Pine plantation	48° 36′ 25″	72° 58′ 16″
	Black Spruce plantation	48° 36′ 25″	72° 58′ 8″
Chibougamau	Open Woodland	49° 58′ 48″	74° 12′ 14″
	Mature Forest	49° 58′ 48″	74° 12′ 7″
	Jack Pine plantation	49° 59′ 2″	74° 6′ 11″
	Black Spruce plantation	49° 59′ 2″	74° 6′ 18″

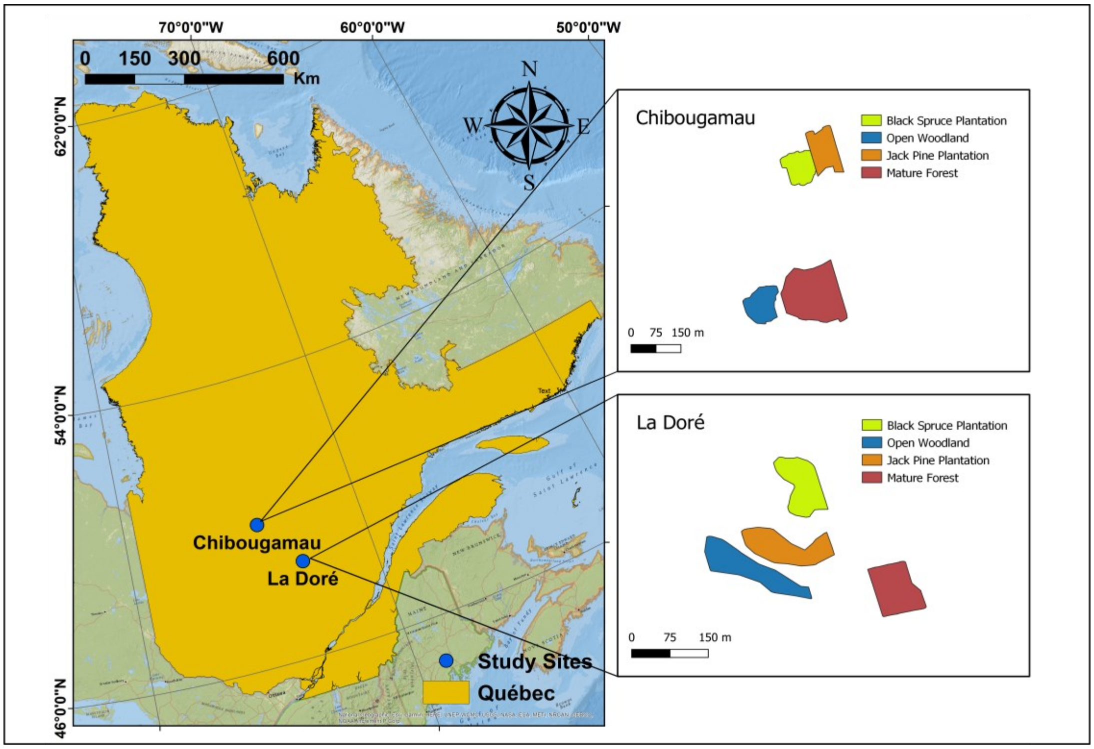

Figure 1. Map of the study area showing both experimental sites located in Chibougamau and La Doré in Quebec, Canada. The insets show the four experimental plots (land cover types) at each site.

2.3.3 UAV Platform and Instruments

This study utilised the DJI Matrice 300 RTK UAV, a flying platform designed for commercial and professional aerial photography (Figure 2). It has a hover time of around 55 minutes without a payload and 25 minutes with the maximum payload (2.7 kg). Sensors can be mounted in appropriate spaces. It has retractable landing gear, which prevents the legs from interfering with sensor data. The ground-breaking Smart Controller Enterprise flight controller controls the Matrice 300 RTK's operating system, which optimises flight control performance. It can also receive and display footage from drone cameras on its built-in 5.5" FHD (1920 x 1080) display.

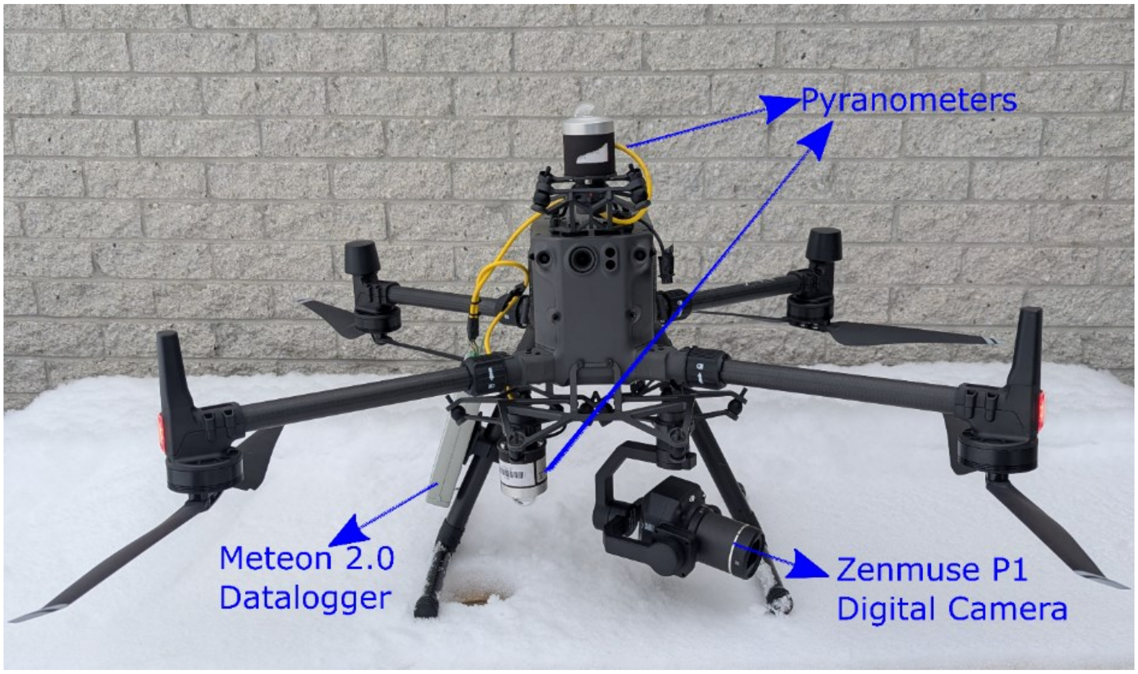

Figure 2. Picture of the DJI M300 RTK quadcopter mounted with Zenmuse P1 digital camera, two pyranometers (PR1; Kipp & Zonen; Delft, The Netherlands) and a data logger METEON 2.0 (Kipp & Zonen; Delft, The Netherlands).

2.3.4 Zenmuse P1 Digital Camera

A digital camera, a pair of broadband pyranometers, and a datalogger were among the instruments mounted on the UAV (Figure 2). The Zenmuse P1 digital camera can shoot 12MP still pictures every 2 or 3 seconds depending on the flight speed. For high along track overlap, 4K video is better since it has the same ground pixel resolution as still pictures but at a considerably higher frequency.

2.3.5 Irradiance measurements with pyranometers and the METEON 2.0 Datalogger

The PR1-V Pyranometer (Kipp & Zonen; Delft, The Netherlands) monitors direct and diffuse sun radiation in the 300 nm to 2800 nm broadband range. It measures sun irradiance (the radiant flux incident on a receiving surface from all directions; W m^{-2}) with a silicon photodiode positioned beneath a cosine-corrected acrylic diffuser on a horizontal surface. The sensor produces a current (A) signal that is proportional to hemispherical sun radiation (W m^{-2}). Because these sensors have a hemispherical field-of-view (FOV), they can easily collect the majority of the incoming and reflected irradiation (Schaepman-Strub et al. 2006).

The METEON 2.0 is a small portable display and data recorder designed for measuring solar radiation in photovoltaic systems. It is capable of measuring, displaying, and logging data from up to eight devices and may hold weeks of data depending on the number of connected sensors and the recording period.

2.3.6 Albedo calculation method

In its most basic form, albedo ($\propto$) is calculated as the ratio of reflected irradiance from the surface (K ↑) to incoming irradiance (K ↓):

$$\propto = \frac{K \uparrow}{K \downarrow}$$

The reflected and the incoming irradiances were respectively measured with one PR1 pyranometers (see section 2.4) mounted at the bottom of the UAV and pointing downwards, and another one mounted at the top of the UAV and pointing upwards (Figure 2).

2.3.7 Delta albedo (Δ albedo)

We calculated the albedo seasonal variation (Δ albedo $_{[season]}$) difference between winter and summer for each land cover type as follows:

$$\Delta \text{ albedo}_{[season]} = \text{albedo}_{[winter]} - \text{albedo}_{[summer]}$$

Where, $albedo_{[winter]}$ corresponds to the mean albedo during snow-covered periods (April), and $albedo_{[summer]}$ corresponds to the mean albedo during snow-free periods (July & August).

2.3.8 Data Acquisition

We conducted albedo measurements during both the summer and late winter seasons. At each location, we conducted measurements on four distinct land cover types (Figure 1).

Before we started collecting data, we used ArcGIS to delimit study area plots for the flights that were about 1 hectare in size. These were then sent to the DJI advanced flight control systems, which used inputs like speed, elevation, front overlap, and side overlap for each type of land cover to make the flight path. Subsequently, we proceeded to mount the camera, METEON 2.0 datalogger, and both pyranometers onto the drone. The pyranometers were positioned so that one was oriented upwards to capture incident solar irradiance and the other was oriented downwards to capture reflected solar irradiance (Figure 2). For the subsequent phase, we aligned the time between the data logger and the drone flight plan in order to guarantee precise timestamps for each recorded flight. In addition, during our first data collection, we configured the speed to 5 km/h, the altitude to 40 m, the front overlap to 90% and the side overlap to 80%. The images captured during these flights had a resolution of 8,192 × 5,460 pixels, with each pixel representing approximately 0.5 cm on the ground.

Data for La Doré were collected in both winter and summer during uninterrupted flight sessions, covering all land cover types (Table 2). In

Chibougamau, the summer data were similarly gathered across all land cover types on August 1st. However, winter data collection in Chibougamau was split across two days due to weather constraints: on April 19, flights were limited to the 23-year-old black spruce and jack pine plantations, while on April 20, data were collected for the open woodland and mature forest sites (Table 2).

Table 2. UAV data collection schedule by location, season, and land cover type.

Location	Season	Date	Time Range (Start - End)
La Doré	Winter	April 10	12:23 - 13:11
La Doré	Summer	July 20	12:47 - 13:12
Chibougamau	Summer	August 1	12:15 - 14:00
Chibougamau	Winter	April 19	10:07 - 10:30
Chibougamau	Winter	April 20	13:27 - 14:11

This structured and mostly same-day approach minimized the effect of changing light and weather conditions, enabling more valid comparisons of albedo across seasons and land covers.

2.3.9 Data Extraction and Data Processing

The data extraction and data processing methods are summarized in Figure 3. The raw JPG images were captured using the Zenmuse P1 camera. For irradiance and albedo measurements, data were recorded using the METEON 2.0 logger. The corresponding data table, containing time-stamped incident and reflected irradiance values, were generated using the METEON 2.0 software. We systematically organized all data into folders for further processing and analysis, utilizing the JPG images for two distinct objectives:

1) Orthomosaics were created using Pix4D software through a photogrammetric process, widely applied in creating georeferenced orthophotos from drone aerial Imagery. The process consists of utilizing many overlapping JPG photos taken by a drone and processing Structure from Motion (SfM) techniques for identifying common keypoints, camera location estimation, and sparse point cloud generation (Özyeşil et al. 2017; Westoby et al. 2012). We initially defined the coordinate reference system, scale of the image, and processing settings. Pix4D, during the initial step of processing, georeferences the images and spatially aligns features among them by comparing features between them. Pix4D densifies the point cloud and constructs a 3D textured topography mesh (Barazzetti et al. 2014). Finally, from the dense point cloud and the modelled geometry, Pix4D produces a true-scale, seamless orthomosaic by assembling and orthorectifying the input images in sequence. This procedure compensates for spatial distortions caused by terrain relief and camera tilt, and a true-scale map is rendered (Chen et al. 2014; Wang & Xie 2012).

2) We extracted metadata information from JPG images of each flight using R programming code. The metadata file was formatted as a CSV file and included image number, date, time, latitude, and longitude.

In the next phase, we developed a R programming code that matched the two Excel files according to their respective date and time. A geographical coordinate was allocated for each albedo value using this matching technique. Executing the code resulted in the creation of a distinct Excel file containing the average albedo values for each JPG image obtained during the flight (Figure 3).

Finally, these average albedo values were used to produce two distinct outcomes in the form of 1) graphs showing albedo variation with respect to time; and 2) the orthomosaics displaying the georeferenced albedo values along with the albedo variation as a raster layer generated by kriging interpolation.

To create continuous surface albedo maps, we used kriging interpolation in ArcGIS Pro. Initial albedo measurements were carried out following a pre-programmed zigzag flight mission over each land-cover category. The flight path (shown in the results section in Figure 8), created a series of discrete measurement points where albedo values were recorded every 2 seconds (Table 4). Since these measurements represent point-based observations rather than continuous surfaces, we applied a kriging interpolation to estimate albedo values across the entire plot. We chose this method because of its ability to effectively model spatial relationships and generating reliable predictions along with error estimates, which is especially useful for environmental factors like surface albedo (Li & Heap 2008). Kriging considers not only the distance between points but also how similar or different values are based on their locations. Such an approach makes kriging a more accurate process than simpler methods such as linear interpolation or the nearest neighbour method, especially where there is a strong spatial trend in the data (Li & Heap 2008). Prior to performing the kriging, we determined the spatial pattern of the albedo data through a variogram, which showed us how the values changed with distance. This process is important because kriging relies on this structure to estimate the values (Chen et al. 2014; Li & Heap 2008). Once the variogram model was calibrated, we used it to interpolate albedo values throughout the entire plot for each land cover type and season. The result was a continuous surface map showing albedo spatial variation, even in regions where no direct measurements were taken. These maps enable comparisons of albedo patterns among different land cover types (for example, open woodlands, black spruce and jack pine plantations, and mature forests), as well as between winter and summer seasons. This method allowed visualization of the effect of canopy density, ground cover, and the presence of snow on surface reflectance in a way that was consistent and easy to understand.

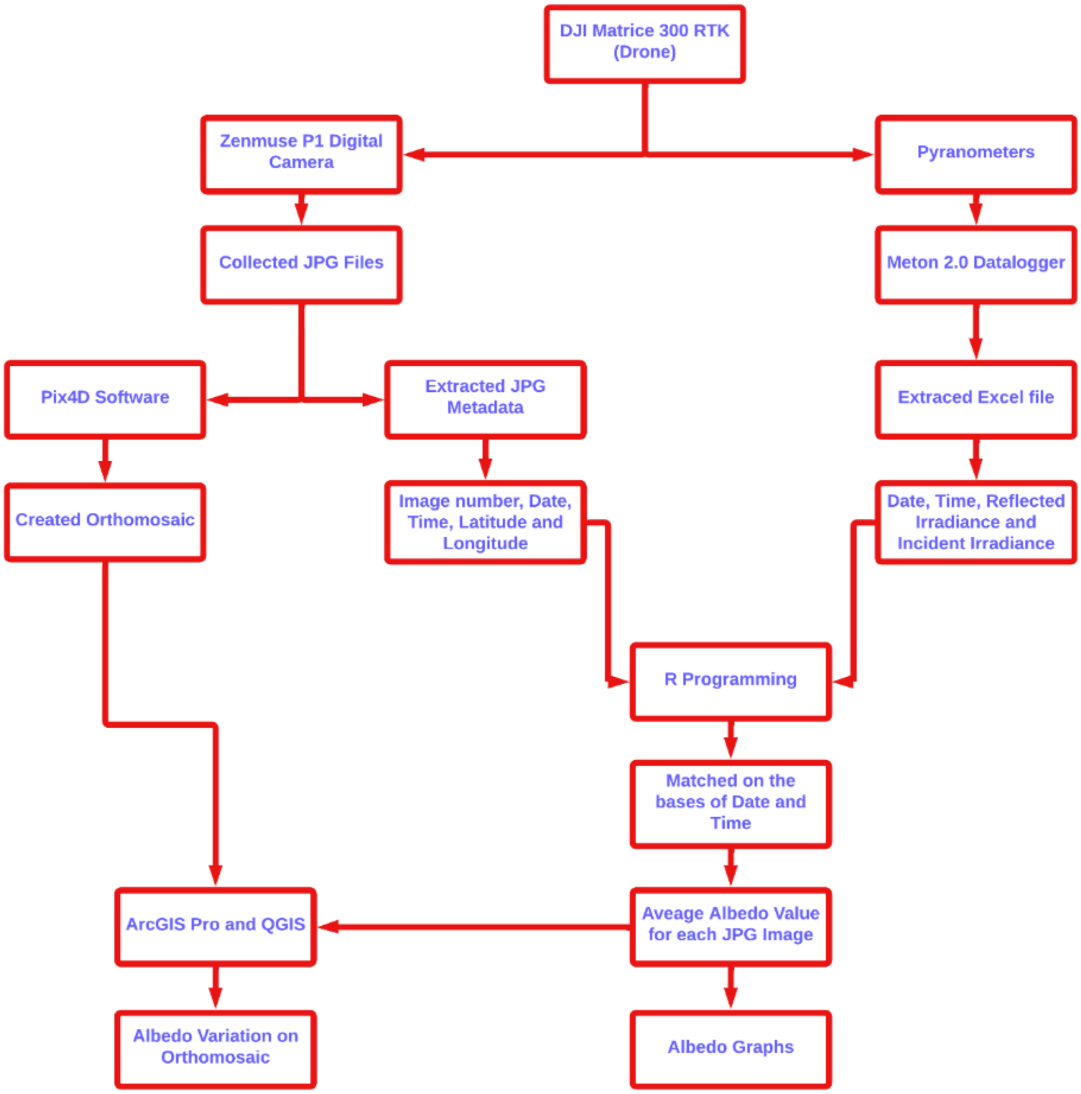

Figure 3. Flow chart showing the procedure to derive average albedo from digital camera images and pyranometer data.

2.3.10 Determination of Tree Cover and Lichen Cover Using the Excess Green Index (ExG)

Later, we used QGIS to calculate the excess green index (ExG) (Eq 1) across all land cover types to assess the percentage of tree and lichen cover. We used the ExG index due to its ability to differentiate vegetation cover from background elements such as soil and snow in a raster image (Antonio et al., 2021). In winter, the ExG index was calculated for black spruce and jack pine at both experimental sites. We verified the pixel values for areas covered by snow and trees. Next, we applied a threshold of 0.1 to the ExG layers, which resulted in the creation of a new binary raster layer. This resulted in the creation of a new binary raster layer, where the pixels representing vegetation were set to 1 and the pixels representing snow were set to 0.

$$\mathrm{ExG} = 2 * g - r - b \qquad \text{Eq. 1}$$

Where, $r = R/(R + G + B)$, $g = G/(R + G + B)$, $b = B/(R + G + B)$, and R, G and B represent the digital number of red, green and blue bands, respectively.

Similarly, we calculated the ExG index in summer for black spruce and jack pine plantations as well as open woodlands, at both experimental sites. To validate the classification thresholds, we used the 'Identify Features' tool in QGIS, which allowed us to interactively inspect individual pixel values directly from the ExG raster layer. By clicking on representative pixels in areas known to be covered by soil, lichen, and vegetation, we were able to observe their corresponding ExG values. This process helped us determine a meaningful threshold that differentiates vegetated surfaces from non-vegetated ones. Based on these observations, we applied and finalized a threshold value of 0.075 to the ExG layers. This resulted in the creation of a new binary raster layer with the lichen pixels represented as 1 and the soil or grass pixels represented as 0.

Finally, we created four grids on each threshold layer, covering only the flight route taken by the drone during data collection. We created a grid of only four cells because the pyranometer has a hemispherical view that covers a large area on the ground. Lastly, we used the zonal statistics plugin in QGIS to compute the mean albedo and the mean vegetation cover in each grid cell (Figure 4). Finally, we extracted these values from the attribute table and stored them in a CSV format.

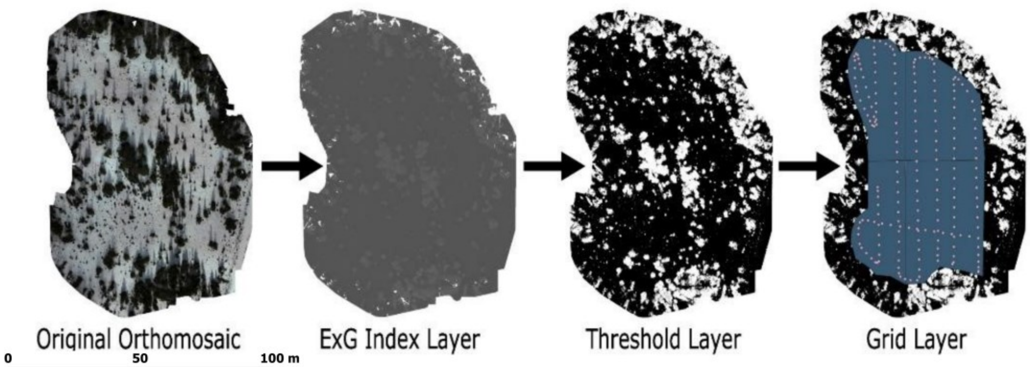

Figure 4. Steps performed to achieve grid-based analysis.

2.3.11 Statistical analyses

An analysis of variance (ANOVA) was performed in R software (R Core Team. (2021) to assess the differences in albedo between seasons (two levels: winter and summer) and land cover types (four levels: open woodland, mature forest, jack pine and black spruce plantations), using a significance threshold of $p < 0.05$. Prior to conducting the ANOVA, we verified that the necessary statistical assumptions had been met. Homogeneity of variances was verified using Levene's test and had established equal variances across groups. Normality of residuals was verified using

Shapiro-Wilk test and by Q-Q plots, both of which validated the assumption of normally distributed residuals. We had also verified that the data were independent. Two types of models were tested. Model 1 incorporates tree or lichen cover and site as covariables, while Model 2 incorporates tree or lichen cover and species as covariables. Subsequently, an analysis of covariance (ANCOVA) was performed to determine how tree cover (%) affected albedo in winter for black spruce and jack pine plantations at both study sites. In the same way, the ANCOVA evaluated the impact of lichen cover (%) on albedo throughout the summer in black spruce and jack pine plantations and open woodland at both sites.

2.4 Results

2.4.1. Influence of Land Cover Type on albedo

The ANOVA indicates that albedo was significantly influenced by land cover type at the Chibougamau and La Doré sites (Table 3). There was also a significant interaction between season and land cover type, meaning that the effect of season on albedo differs according to land cover types. The model has captured a large part of the variance in albedo in the two data sets, as indicated by the relatively low residual sum of squares. These findings emphasise the importance of accounting for seasonal characteristics and land cover types when analysing changes in albedo within boreal ecosystems.

During summer, albedo values varied across land cover types at both La Doré and Chibougamau. Jack pine and black spruce plantations exhibited similar average albedo values, ranging from 0.12 to 0.13, while mature forests showed lower values, averaging around 0.09. Open woodlands displayed albedo values that were 0.03–

0.06 higher than mature forests across sites (Figure 5). The average albedo values were slightly higher at La Doré than at Chibougamau for black spruce (0.13 vs. 0.12) and jack pine (0.13 vs. 0.11) plantations, as well as for open woodlands (0.15 vs. 0.12) (Figure 5).

In winter, albedo values were consistently lower by 0.05–0.09 at La Doré compared to Chibougamau (Figure 6). At Chibougamau, winter albedo values ranged from 0.24 in mature forests to 0.35 in open woodlands. At La Doré site, these values ranged from 0.15 in mature forests to 0.27 in open woodlands. Open woodlands exhibited albedo values that were approximately 0.09 higher than mature forests at both sites. The difference between plantations and open woodlands was small. At Chibougamau, the albedo in 23-year-old black spruce and jack pine plantations was 0.01–0.06 lower than that of open woodlands, whereas in 12-year-old plantations of La Doré the difference ranged from 0.02 to 0.03. Black spruce plantations showed slightly lower albedo than jack pine plantations at both sites, with values of 0.29 at Chibougamau and 0.23 at La Doré for black spruce, and 0.34 at Chibougamau and 0.25 at La Doré for jack pine (Figure 6).

Table 3.Results of the ANOVA assessing the effects of season and land cover type on albedo at the Chibougamau and La Doré sites.

Site	Variable	Df	Sum-Sq	Mean-Sq	F-value	P-value
Chibougamau	Season	1	8.238	8.238	3957.45	< 0.001
	Land Cover Type	3	0.515	0.172	82.48	< 0.001
	Season x Land Cover Type	3	0.101	0.034	16.16	< 0.001
	Residuals	815	1.697	0.002		
La Doré	Season	1	5.998	5.998	1898.16	< 0.001
	Land Cover Type	3	1.656	0.552	174.67	< 0.001
	Season x Land Cover Type	3	0.243	0.081	25.62	< 0.001
	Residuals	1706	5.391	0.003		

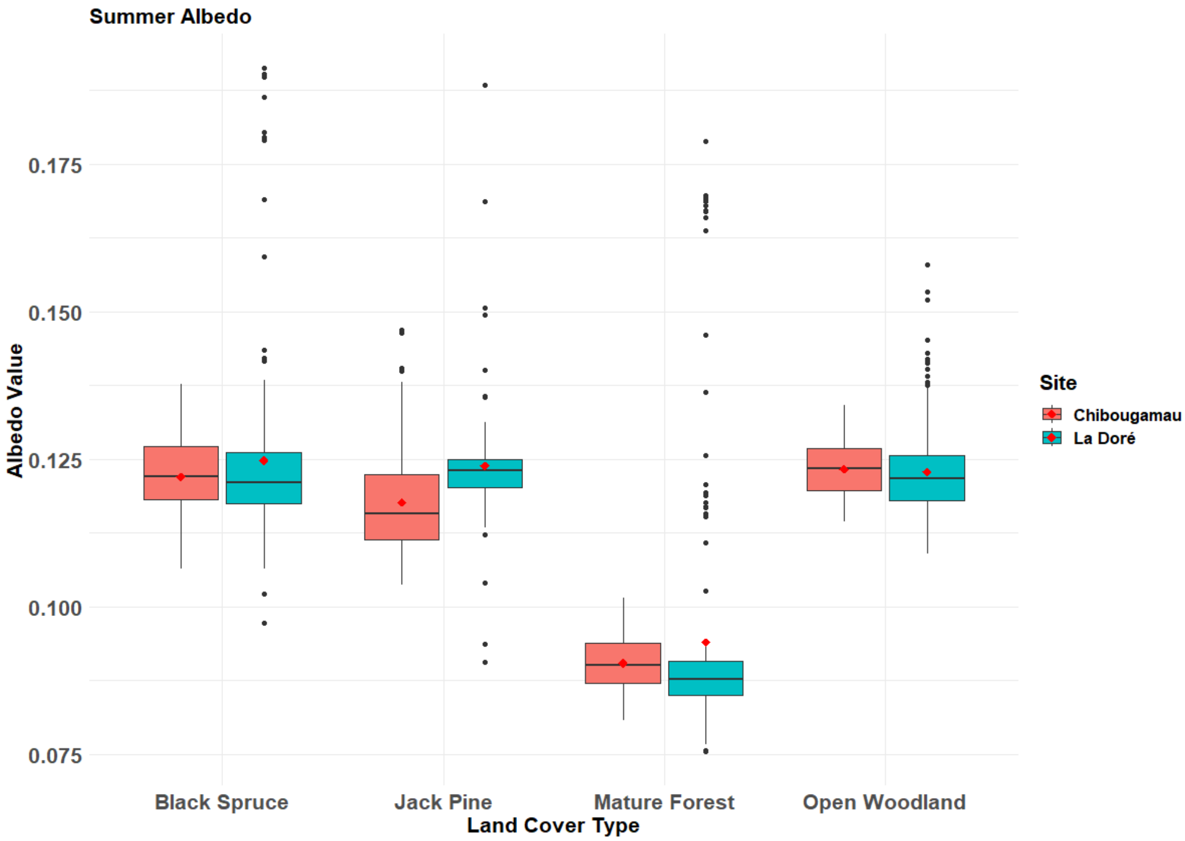

Figure 5. Albedo values for all land cover types at Chibougamau and La Doré in summer. Each box contains the interquartile range (IQR), which shows the middle 50% of the data, and the horizontal line inside each box is the median value. Red diamond points represent the mean albedo values for each group. Whiskers stretch to 1.5 times the IQR, and dots represent outliers. This figure displays both a central tendency and variability in albedo values among sites and land cover types, allowing a comparison of how albedo differs during the summer season.

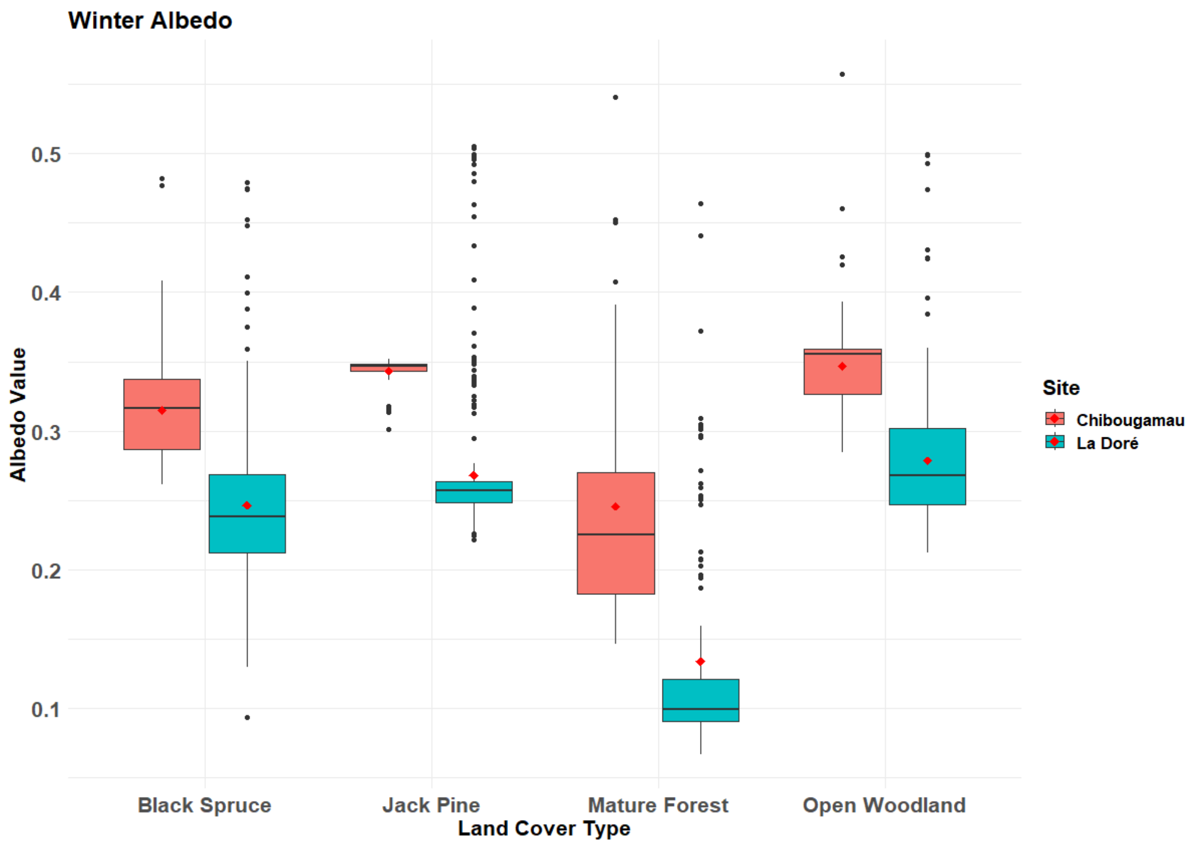

Figure 6. Albedo values for all land cover types at Chibougamau and La Doré in winter. Red dots indicate average albedo values. Each box contains the interquartile range (IQR), which shows the middle 50% of the data, and the horizontal line inside each box is the median value. Red diamond points represent the mean albedo values for each group. Whiskers stretch to 1.5 times the IQR, and dots represent outliers. This figure displays both a central tendency and variability in albedo values among sites and land cover types, allowing a comparison of how albedo differs during the winter season.

2.4.2 Seasonal Variations in irradiance and albedo

In summer, flights were conducted under partly cloudy conditions at both sites, with average incident radiation ranging from 210 to 582 W/m²—except in the mature forest at La Doré, where average radiation reached 1020 W/m², indicating very sunny conditions. Incident radiation was generally lower in winter, especially at Chibougamau, with values typically between 200 and 450 W/m²—except in the black spruce plantation at La Doré, where radiation reached 761 W/m², likely reflecting clearer skies (Table 4).

In open woodlands, albedo was significantly higher in winter, with 0.35 (± 0.04) in Chibougamau and 0.27 (± 0.02) at La Doré, compared to 0.12 (± 0.004) and 0.15 (± 0.05) in summer, respectively (Table 4; Supplementary materials: Figure 14).

Similarly, mature forests showed higher winter albedo values—0.24 (± 0.05) at Chibougamau and 0.15 (± 0.10) at La Doré—than summer values of 0.09 (± 0.005) at both sites (Table 4; Supplementary materials: Figure 15).

Winter albedo in black spruce plantation was 0.29 (± 0.03) at Chibougamau and 0.23 (± 0.04) at La Doré, while summer albedo was consistently lower at 0.12. Jack pine plantation exhibited a similar trend, with winter albedo at 0.34 (± 0.001) in Chibougamau and 0.25 (± 0.01) in La Doré, compared to 0.12 (± 0.009) and 0.13 (± 0.04) for summer, respectively (Table 4; Supplementary materials: Figures 12 and 13).

Table 4. Seasonal average albedo, number (No.) of albedo points /flight, incident radiation and reflected radiation measurements for all land cover types at Chibougamau and La Doré.

		Chibougamau				La Doré			
Land Cover Type	**Season**	**No. of Albedo points /Flight**	**Average Albedo**	**Incident Radiation (W/m²)**	**Reflected Radiation (W/m²)**	**No. of Albedo points /Flight**	**Average Albedo**	**Incident Radiation (W/m²)**	**Reflected Radiation (W/m²)**
Black spruce plantation	Winter	92	0.29±0.03	219.48±1.41	64.18±6.47	122	0.23±0.04	761.20±216.88	170.20±38.8
	Summer	97	0.12±0.007	582.77±26.2	69.39±1.55	118	0.12±0.006	385.64±118.68	46.52±13.64
Jack pine plantation	Winter	95	0.34±0.001	273.80±0.84	92.20±0.45	107	0.25±0.01	315.57±35.08	79.89±8.30
	Summer	105	0.12±0.009	377.98±19.3	43.39±2.92	109	0.13±0.04	377.93±22.95	41.54±18.46
Open woodland	Winter	112	0.35±0.04	229.26±4.30	80.74±11.3	110	0.27±0.02	342.62±19.26	93.62±12.74
	Summer	103	0.12±0.004	456.03±9.46	56.71±2.22	114	0.15±0.05	210.99±46.69	29.92±9.70
Mature black spruce forest	Winter	108	0.24±0.05	247.54±10.7	58.70±15.01	115	0.15±0.10	438.39±103.48	64.35±11.05
	Summer	98	0.09±0.005	468.22±11.2	41.54±2.16	106	0.09±0.005	1020.25±120.2	88.04±11.30

2.4.3 Effect of land cover type on albedo seasonal changes

The seasonal variation in Δ albedo [season] was most pronounced in Chibougamau for open woodland (0.23) and jack pine plantations (0.22) compared to black spruce plantations (0.17) and mature forests (0.15) (Figure 7). At La Doré, the seasonal variation was about twice lower than at Chibougamau across all land types. Open woodland, jack pine plantation, and black spruce plantation showed similar average seasonal variations of ~0.12, while mature black spruce forest exhibited a seasonal variation of ~0.06 (Figure 7).

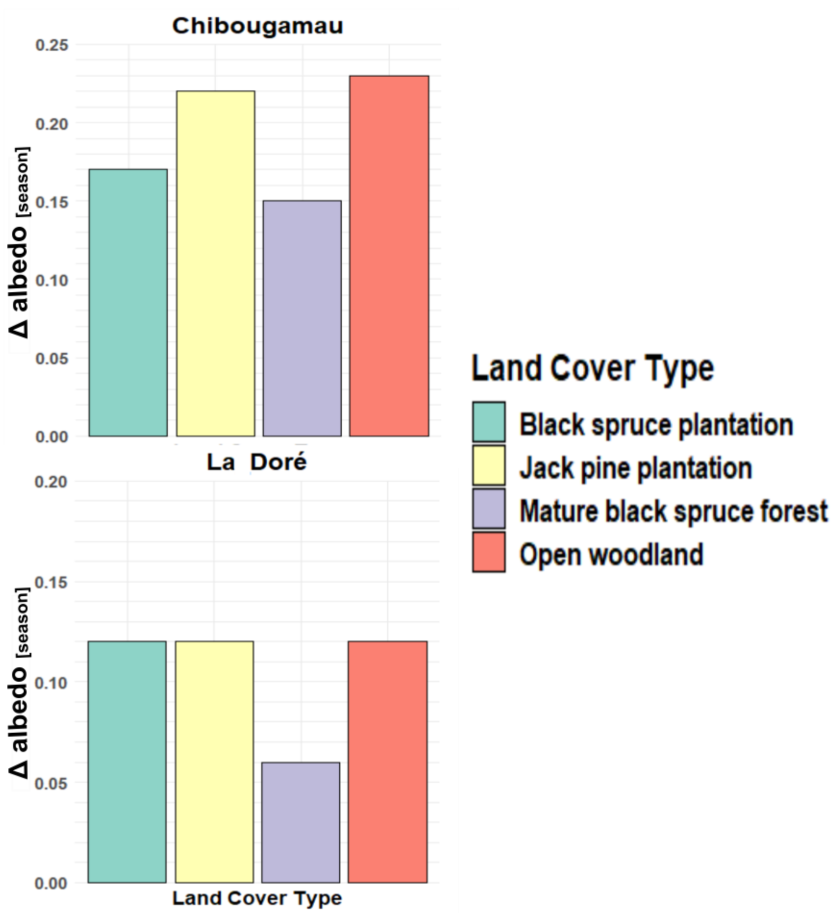

Figure 7. Difference of surface albedo between winter and summer (Δ albedo [season]) for all land cover types at the Chibougamau (top panel) and La Doré (bottom panel) experimental sites.

2.4.4 Spatial variations in albedo

Spatial variation of albedo within each land cover type in winter and summer are presented on orthomosaics in Figures 8 and 9. This visualization scheme represents lower albedo values in blue and higher albedo values in red, and depicts the flight path as a series of points. This allows a detailed observation of the spatial variation of albedo across the study sites.

The Figures 8 and 9 show large spatial variations in albedo within each land cover type. At the Chibougamau site during winter, a large spatial variation in albedo was observed for all land cover types, with values ranging from 0.30 to 0.45, 0.26 to 0.40, and 0.28 to 0.52 in open woodlands and 23-year-old black spruce and jack pine plantations, respectively. Mature forests exhibited an even wider range, due to a lower minimum value compared to the other land cover types (0.13 to 0.40). This is likely due to their dense canopy cover, which limits the exposure of snow-covered ground and results in low surface reflectance. A similar pattern was observed at La Doré, where mature forests showed lower minimum albedo values (0.07) than the other land cover types. However, the spatial variation was slightly lower in the mature forest than in the open woodland and 12-year-old plantations (0.14 to 0.50) likely reflecting a more homogeneous canopy in the mature forest than in the less dense or younger stands.

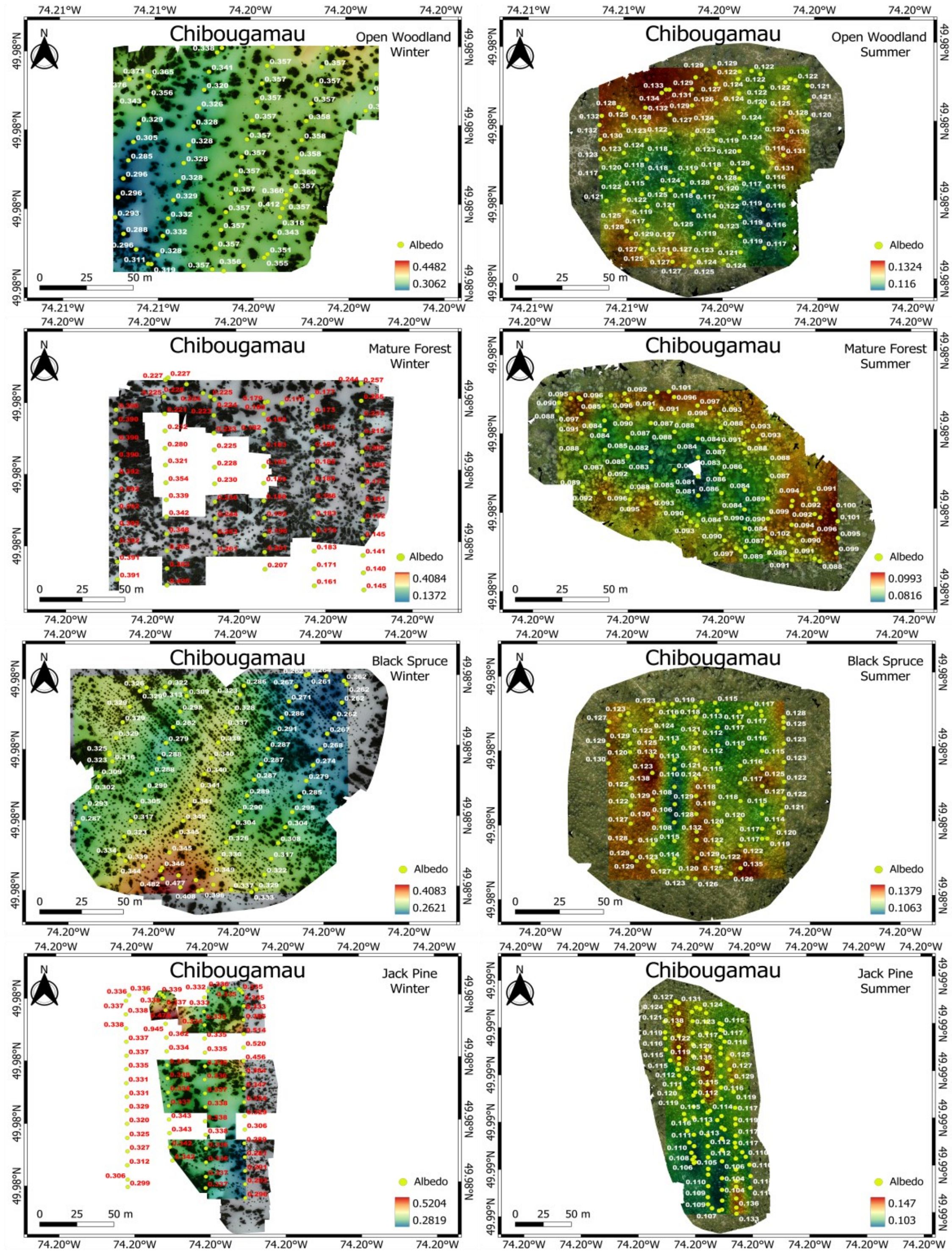

Figure 8. Spatial variation of albedo within four land cover types (open woodland, mature forest, and 23-year-old black spruce and jack pine plantations) in winter and summer at Chibougamau. Albedo values measured during the flights are shown on the orthomosaics.

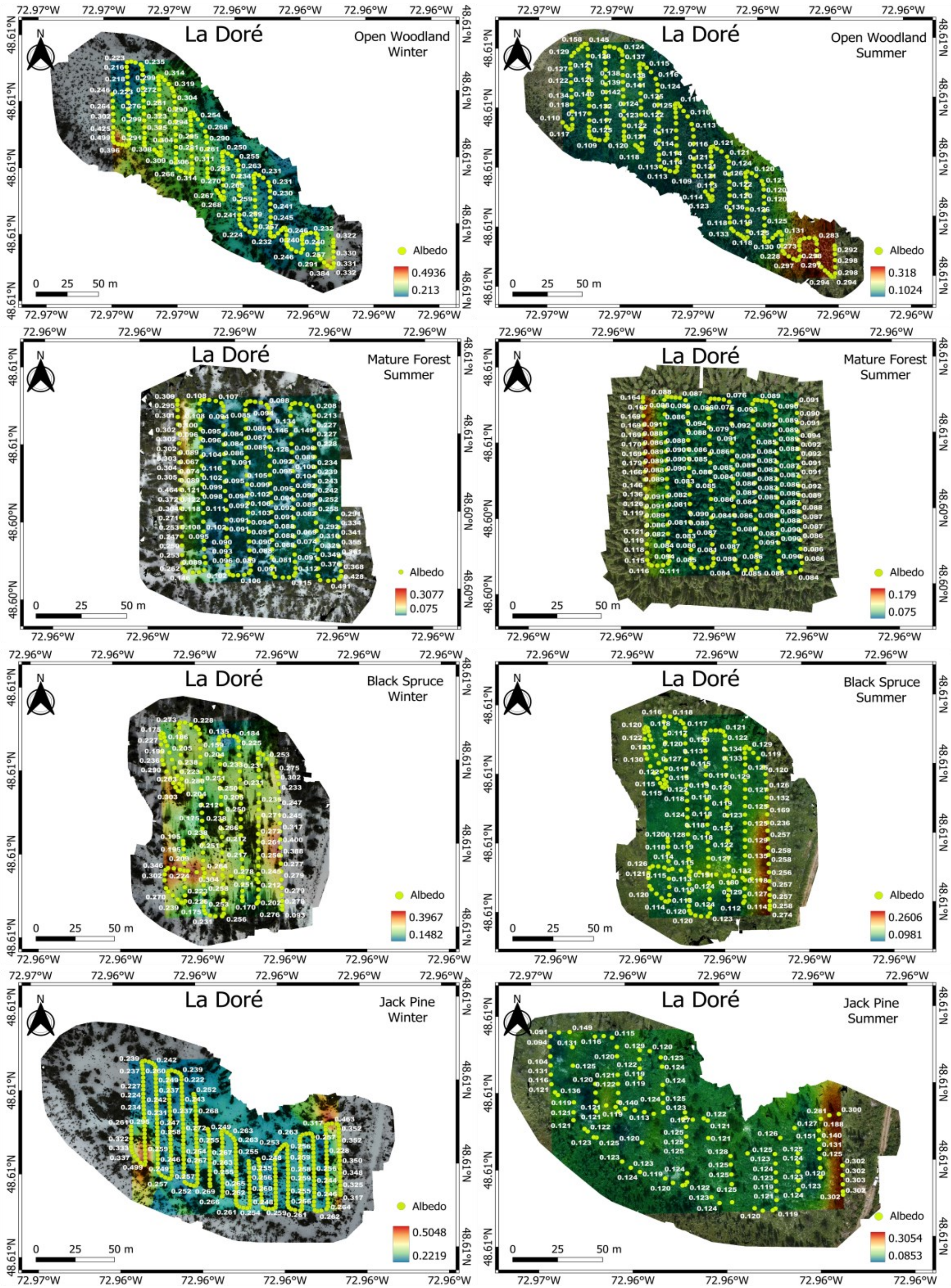

Figure 9. Spatial variation of albedo within four land cover types (open woodland, mature forest, and 12-year-old black spruce and jack pine plantations) in winter and summer at La Doré sites. Albedo values measured during the flights are shown on the orthomosaics.

2.4.5 Impact of tree cover on plantations winter albedo

There was no significant relationship between tree cover and winter albedo (Table 5), which shows that variations in tree cover do not notably affect winter albedo across sites (Figure 10). However, The ANCOVA model revealed a significant site effect (Table 5), indicating notable differences in winter albedo between La Doré and Chibougamau, independently of tree cover. There was no significant effect of species or tree cover (Table 5). The significant intercept in both models indicate that winter albedo was significantly higher than 0 in the absence of tree cover (Table 5).

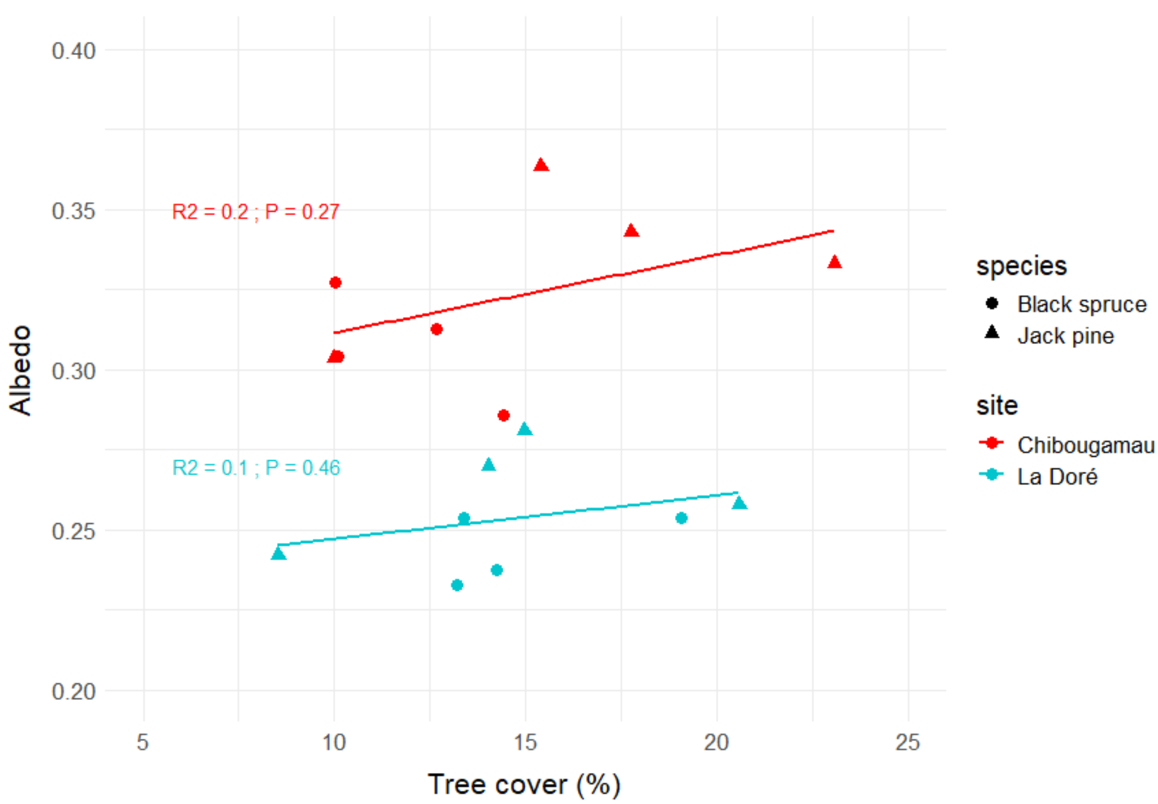

Figure 10. Relationship between albedo and tree cover (%) in black spruce and jack pine plantations at the Chibougamau and La Doré experimental sites in winter.

Table 5.Results of ANCOVA assessing the effects of tree cover, site, and species on albedo.

Term	Estimate	SE	t-value	p-value
Model 1				
Intercept	0.293	0.019	15.002	<0.001
Tree Cover	0.200	0.128	1.562	0.142
Site	-0.069	0.010	-6.875	<0.001
Model 2				
Intercept	0.268	0.039	6.736	<0.001
Tree Cover	0.059	0.276	0.216	0.832
Species	0.021	0.021	1.011	0.330

2.4.6 Impact of lichen cover on plantations' summer albedo

The ANCOVA results showed no significant effects of lichen cover, site, or land cover type on summer albedo (Table 6). The relationship between lichen cover and summer albedo was analyzed for both sites (Figure 11). The regression analysis of both sites revealed low R^2 values (0.08 and 0.04 at Chibougamau and La Doré, respectively), indicating the minimal influence of lichen cover on summer albedo at either site (Figure 11). The non-significant site effect ($p = 0.246$) further confirmed that summer albedo did not significantly differ between sites in plantations in summer.

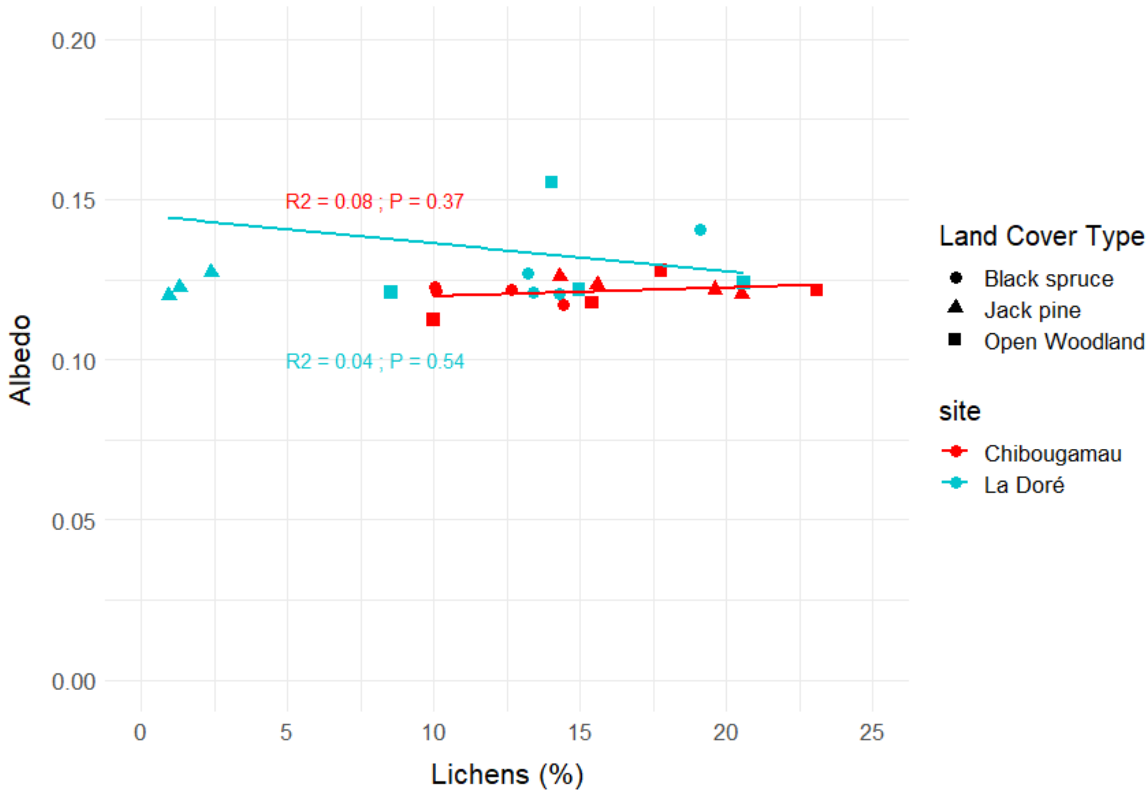

Figure 11. Relationship between albedo and lichen cover (%) in black spruce plantations, jack pine plantations and open woodlands at the Chibougamau and La Doré experimental sites in summer.

Table 6. Results of ANCOVA assessing the effects of lichen cover, site, and species on albedo.

Term	Estimate	SE	t-value	p-value
Model 1				
Intercept	0.129	0.014	9.069	<0.001
Lichen cover	-0.056	0.083	-0.672	0.509
Site	0.011	0.010	1.193	0.246
Model 2				
Intercept	0.133	0.014	9.368	<0.001
Lichen cover	-0.074	0.087	-0.857	0.401
Land Cover Type (OW)	0.009	0.012	0.795	0.436
Land Cover Type (JP)	0.002	0. 011	0.239	0.813

2.5 Discussion

Afforestation in the boreal zone has both positive and negative contributions for climate change mitigation. The cooling effect of trees resulting from carbon sequestration can be maintained, balanced or even fully offset for the loss in surface albedo associated with forest cover (Betts 2000, 2011). Boreal forests have a relatively low albedo because the dark canopy of coniferous trees absorb more solar radiation than open areas. The situation is exacerbated in winter, when open areas are usually covered in reflective snow, whereas conifer trees have a much darker colour from the branch and needle masses, thereby absorbing more solar radiation (Anderson et al. 2011; Bright et al. 2017). In some circumstances, this albedo loss may result in a positive radiative forcing that could offset the negative forcing due to carbon sequestration (Bala et al. 2007; Betts 2000). At high latitudes, this albedo effect may be more important than the benefits of carbon storage and may actually accelerate the rate of climate change rather than mitigate it (Betts, 2000). Recent studies emphasize large intercontinental differences in the albedo effect of afforestation between Europe and North America (Asselin et al. 2022). Indeed, regional climate model simulations suggest that the presence of evergreen needle leaf forests masks snow cover, causing a reduction in surface albedo on both continents. However, the resulting warming effect is more pronounced in North America because the dense evergreen forests extend into lower latitudes compared to Europe. Hence, they receive a larger shortwave radiation surplus and associated warming.

Nevertheless, the climate effects of afforestation related to albedo are site-specific. The stand age, tree species, and the length of snow cover are critical for the net impact on climate (Abdul Halim et al. 2019). In the southern areas of the boreal zone, albedo in forests can be enhanced while maintaining a minimal loss of productivity by favouring broadleaved species (Abdul Halim et al. 2019). Strategic afforestation can be beneficial to the climate if thoughtful plans are considered. Considering the albedo changes along with the potential for carbon sequestration allows the identification of such regions where afforestation might result in net-positive climate mitigation outcomes, including the boreal zone. Therefore, there is a need to develop a detailed and location specific assessments considering both carbon and albedo effects when planning afforestation projects in boreal regions (Hasler et al. 2024).

This study aimed to develop a methodology for collecting data using a high spatial resolution RGB digital camera, a set of pyranometers, and a datalogger to measure albedo across four distinct land cover types. This has been made possible by advances in the technology of UAVs that allow the collection of surface topographic and reflectance data in both high spatial and temporal resolutions, as reported in the literature (Bhardwaj et al. 2016; Carrivick et al. 2016). Structure-from-motion software's allow obtaining topographic data using consumer-grade digital cameras (Immerzeel et al. 2014; Ryan et al. 2015; Smith et al. 2016; Tonkin et al. 2014; Westoby et al. 2012; Whitehead et al. 2013). Also, the recent studies have focused on quantifying surface reflectance using cost-effective sensors (Hakala et al. 2010; Mauro 2015; Rippin et al. 2015). The proposed approach greatly improves the conventional methods of orthomosaics generation and albedo variation measurement, particularly in the boreal ecosystem. In the present study, surface albedo seasonal variations were systematically investigated for various land cover types (open woodlands, 12- to 23-year-old plantations, and mature forest stands) by using a UAV. The ability of UAVs to conduct continuous, high-resolution measurements ensures that high-quality reflectance data was obtained regardless of the meteorological conditions, increasing precision and relevance of albedo evaluation in a variety of land cover types and seasons. It also assessed the effects of tree species and stand density on albedo, focusing on the comparison between jack pine and black spruce plantations. We also assessed whether lichen cover in plantations and open woodlands significantly impacts albedo during summer.

2.5.1 Impact of different land cover types on albedo

Surface albedo measurements in boreal environments have long depended mostly on satellite-based remote sensing data, including that of MODIS or Landsat (Hu et al. 2018; Potapov et al. 2008). While such data provides useful coarse-scale measurements, the relatively low spatial resolution limits the ability to detect fine-scale variations within heterogenous forested landscapes, e.g., patchy snow or contrasts between different species and land cover types. Here, we successfully implemented and conducted a UAV-based method for measuring surface albedo with significantly higher resolution, which enabled us to capture high-resolution albedo measurements over different land cover classes and seasons. This approach, in addition to enabling more spatially detailed analysis than satellites, also allows adaptable and targeted data acquisition under varied conditions in the field. Effective development of this UAV method represents an important advancement of the accuracy and resolution of monitoring albedo over complex boreal environments.

Our results show significant differences in albedo between La Doré and Chibougamau and between land cover types, particularly in winter. La Doré's winter albedo values were consistently lower than those of Chibougamau by about 0.05–0.09 for all land cover categories. This pattern suggests that site conditions, in this case, the characteristics of the snowpack played a dominant role in controlling surface albedo variation. According to previous research, snow surfaces are highly reflective, typically ranging from 0.6–0.75 for melting snow to 0.75–0.9 for fresh snow with fine grains (Anderson et al., 2011; Betts & Ball, 1997; Bonan et al., 1992; Sproles et al., 2020; Verro et al., 2025; Warren, 1982). Variations in snow albedo are mainly driven by optical grain size, the presence of impurities, and, to a lesser extent, snowpack thickness (Verro et al. 2025; Warren 1982). Other contributing factors such as snow aging, density, and liquid water content, ultimately influence grain size, which in turn lowers albedo. Solar angle and cloud cover also affect albedo, often increasing reflectance under high zenith angles and cloudy conditions (Warren 1982). The higher winter albedo values observed at Chibougamau may thus be attributed not only to snow properties, but also to the site's slightly higher latitude and increased cloud cover during the flight period, as indicated by lower incoming irradiance measurements (Table 3).

During winter, albedo values were consistent with those reported for the eastern Canadian boreal forest. For example, April albedo values in forests with 10–

25% tree cover, equivalent to the canopy density found in our open woodland plots, were around 0.38 (Bernier et al. 2011; Kalliokoski et al. 2020), closely matching the 0.35 and 0.28 we measured in Chibougamau and La Doré, respectively. Clear-cut areas in the region, with minimal vegetation cover, typically show higher winter albedo values of 0.4 to 0.42 (Bernier et al. 2011; Kalliokoski et al. 2020). These slightly lower albedo values in our study can be explained by the timing of the data collection. Previous research indicates that midwinter albedo values are typically highest in February (Bernier et al. 2011), and since our measurements were taken in April, which was the end of the winter season, the snowpack and surface characteristics may have contributed to the reduction of albedo values in the open woodland. Furthermore, winter albedo was 0.09 higher in Chibougamau's mature forest (0.24) compared to La Doré (0.15). This site-level difference was statistically significant ($p < 0.05$), reinforcing the idea that local forest structure and snow interactions play a crucial role in surface reflectance. One explanation for this pattern was that at Chibougamau, larger amounts of snow could accumulate on the tree branches and canopy surfaces, partially covering the closed canopy. If the canopy completely covered the snowpack, we would not see any difference in albedo between the two sites; along with that, canopy structural differences across the sites could also explain this variation. So the variations in canopy openness, branch density, or tree height might impact ground exposure or snow interception (Bernier et al. 2011; Betts & Ball 1997). Therefore, both snowpack properties and canopy structure together impact winter albedo variation in mature forest between these sites (Bernier et al. 2011; Pomeroy et al. 1998).

Lastly, in both sites, 12- and 23-year-old plantations did not impact albedo yet relative to open woodlands, likely due to the low tree density (~ 2000 trees ha^{-1}), the small height of trees and the small surface area of their canopy. However, from a longer-term perspective, a potential difference in albedo might be expected, as shown by our results, showing that the albedo of mature forests was 0.09 lower than that of open woodlands in winter, reflecting the role of canopy density and colour in controlling snow accumulation and surface reflectivity. However, when comparing black spruce and jack pine plantations, black spruce plantations generally exhibited slightly lower albedo values than jack pine, a difference that was particularly evident during winter. This seasonal contrast suggests that the interaction between snow and canopy structure plays a critical role in modulating surface albedo of forest stands (Betts & Ball 1997). Another important factor may be the lighter green foliage of jack pine, which absorbs less shortwave radiation compared to the darker canopy of black spruce, thereby contributing to higher albedo. In addition, the structurally more open jack pine canopy allows greater penetration of sunlight through the trees, enabling more light to reach and reflect off the snow-covered ground beneath (Kuusinen et al. 2012; Webster et al. 2015). Conversely, the denser black spruce canopy tends to obscure the snowpack, diminishing reflectance and lowering albedo under snowy conditions (Bonan 2008). These findings emphasize the role of species-specific traits in modulating forest albedo and highlight the need to consider both snow and canopy structure properties when assessing the radiative impacts of afforestation (Bernier et al. 2011).

In summer, La Doré exhibited marginally higher albedo in open woodlands and jack pine plantations than Chibougamau, whereas black spruce plantations and mature forests showed similar values between the two sites. This indicates that plant canopy structure, density, and species, which vary with site, are all factors influencing albedo. The albedo of jack pine plantations, black spruce plantations, and open woodlands at both study sites was quite similar, ranging from 0.12 to 0.15; this similarity is likely because these land cover types have similar structural properties that facilitate moderate reflection of solar radiation. Mature forests of conifers hosted a continually reduced albedo (~0.09) because their denser canopies absorbed more incoming of solar energy. The findings confirm previous evidence that mature boreal forests retain an albedo between 0.09 and 0.15 during the summer due to their high capacity of sunlight absorption (Bernier et al. 2011). Our results indicate that the role of species-specific traits in modulating forest albedo and highlight the importance of selecting tree species for afforestation projects in boreal regions not only based on their ecological characteristics or productivity, but also on their canopy structure and spectral properties.

2.5.2 Seasonal effect on surface albedo

As expected, our results showed that for both experimental sites and land cover types, the variation in delta albedo among land cover types is obvious, with open woodland showing the highest seasonal change, especially in Chibougamau, where Δ albedo $_{[season]}$ reached 0.24 vs. 0.13 at La Doré. On the other hand, the lowest Δ albedo $_{[season]}$ was observed in mature black spruce forests, being about 0.14 at Chibougamau and 0.07 at La Doré. These differences in Δ albedo $_{[season]}$ between open woodland and mature forests mostly resulted from differences in winter albedo because of the presence of snow, which enhances surface reflectance in open woodlands, whereas in dense forests, snow that falls through the canopy accumulates mostly on the shaded forest floor, where it has limited influence on albedo due to low light penetration (Bernier et al. 2011; Pomeroy et al. 2002). This trend is consistent with research that demonstrated that increases in forest cover are associated with large reductions in albedo, such that values drop from 0.58 at 0–10% forest cover to around 0.3 at 40–60% forest cover (Bernier et al. 2011). These findings highlight the complex interplay between forest succession, seasonal variability, and boreal ecosystem energy balance.

2.5.3 Impact of vegetation on surface albedo

In contrast with our hypothesis, the albedo-tree cover relationship in winter was not significant in plantations at both sites. We expected a decrease in albedo with increasing tree cover as tree canopy is less reflective than snow. This indicates that other variables, such as snowpack or canopy properties may be influencing how much light the surface reflects (Betts et al., 2007).

Moreover, the interaction between species and tree cover approached significance ($p = 0.085$), indicating that species-specific traits may affect how albedo responds to tree cover. Specifically, black spruce and jack pine differ in canopy structure, canopy density, needle density, and snow interception, all of which could affect surface reflectance (Randerson et al. 2006). In our study, jack pine stands tended to exhibit slightly higher albedo values than black spruce stands despite having similar or even higher tree cover. This trend is consistent with findings from Finland, where jack pine plantations showed higher albedo in both winter and summer compared to black spruce (Kalliokoski et al. 2020; Kuusinen et al. 2012; Webster et al. 2015). At Chibougamau, for instance, jack pine may cause higher snow accumulation compared with black spruce. The consequence of these species-specific differences is significant for afforestation and climate feedback. The higher albedo of jack pine stands means that jack pine-supported afforestation might help lessen the warming impacts typically associated with increased forest cover by reflecting additional solar radiation under snow conditions. On the other hand, black spruce plantations could enhance solar energy absorption, triggering quicker local warming. This highlights the necessity of selecting tree species not only with regard to growth and ecological suitability but also based on their influence on surface energy balance and climate via albedo effects (Betts & Ball 1997; Hollinger et al. 2010; Ollinger et al. 2008). In contrast, tree cover at La Doré may exhibit less species-dependent differences because of reduced snowfall and snow retention, hence weakening the interaction with albedo. These results suggest that the relationship between tree cover and albedo is strongly dependent on regional climatic parameters, including snowpack and temperature.

Contrary to our hypothesis, no relationship was found between lichen cover and summer albedo at both sites, suggesting that under summer conditions, lichen cover does not contribute significantly to the increase in surface albedo at the study sites. This absence of a statistically significant relationship may however be due to the low range of lichen cover at our sites (2 to 23%). The limited impact of lichen cover on albedo may be due to the presence of other understory elements, including soil, mosses, shrubs, and small trees, which collectively influence surface reflectance and play a significant role in regulating albedo. Therefore, the mixed composition of low-reflectance ground cover can diminish the specific effect of lichens (Bernier et al. 2011; Kuusinen et al. 2014).

These findings suggest that even the presence of lichen cover does not mean that there will be an increase in surface albedo because it also depends on the interaction of various ecological factors, which plays an important role in controlling albedo dynamics in the boreal zone even in the presence of lichen cover.

2.5.4 Conclusion

Our findings reveal a consistent seasonal pattern where winter albedo is significantly greater than summer albedo across all land cover types. Seasonal variation is most prominent in open woodlands and young black spruce and jack pine plantations, where a greater portion of the ground is exposed to snow. In contrast, mature black spruce forests exhibited lower seasonal variation due to greater absorption of solar radiation as well as minimal exposure to snow under the canopy.

Comparison among land cover types also indicated the temporal effects of afforestation. The short-term effect on albedo, when comparing open woodlands to

12- to 23-year-old plantations, resulted in a slight decrease in winter albedo (~0.01–0.03), indicating limited radiative change during early post-afforestation periods. However, comparing open woodlands to mature forests indicates that a long-term effect might be a more significant decline in albedo (~0.11–0.12), highlighting the increased climate feedback of more mature forest development. However, this difference was not as high as previously observed, likely due to an early snow melting. Consequently, future changes in snow regimes may diminish this effect, and the use of fast-growing, more reflective species such as jack pine could help improve the net balance between biochemical and biophysical effects.

These findings emphasize the importance of long-term, high-resolution observations of data along spatial gradients in order to enhance climate models and the accuracy of radiative forcing estimates. As climate change progresses, future conditions are expected to bring less snowfall and earlier snowmelt (Ouranos 2015), which could shift the seasonal peak of albedo contrast between open woodlands and mature forests to earlier in the spring, likely in March rather than April. As solar irradiance is lower in March, this shift might lead to a reduction in the amount of positive radiative forcing that is truly associated with afforestation-driven changes in albedo. Therefore, it is important to understand the impact of forest management on surface reflectance to determine whether or not the cooling benefits of carbon sequestration can still offset the warming effect of reduced albedo, particularly in boreal afforestation strategies.

2.6 Supplementary materials

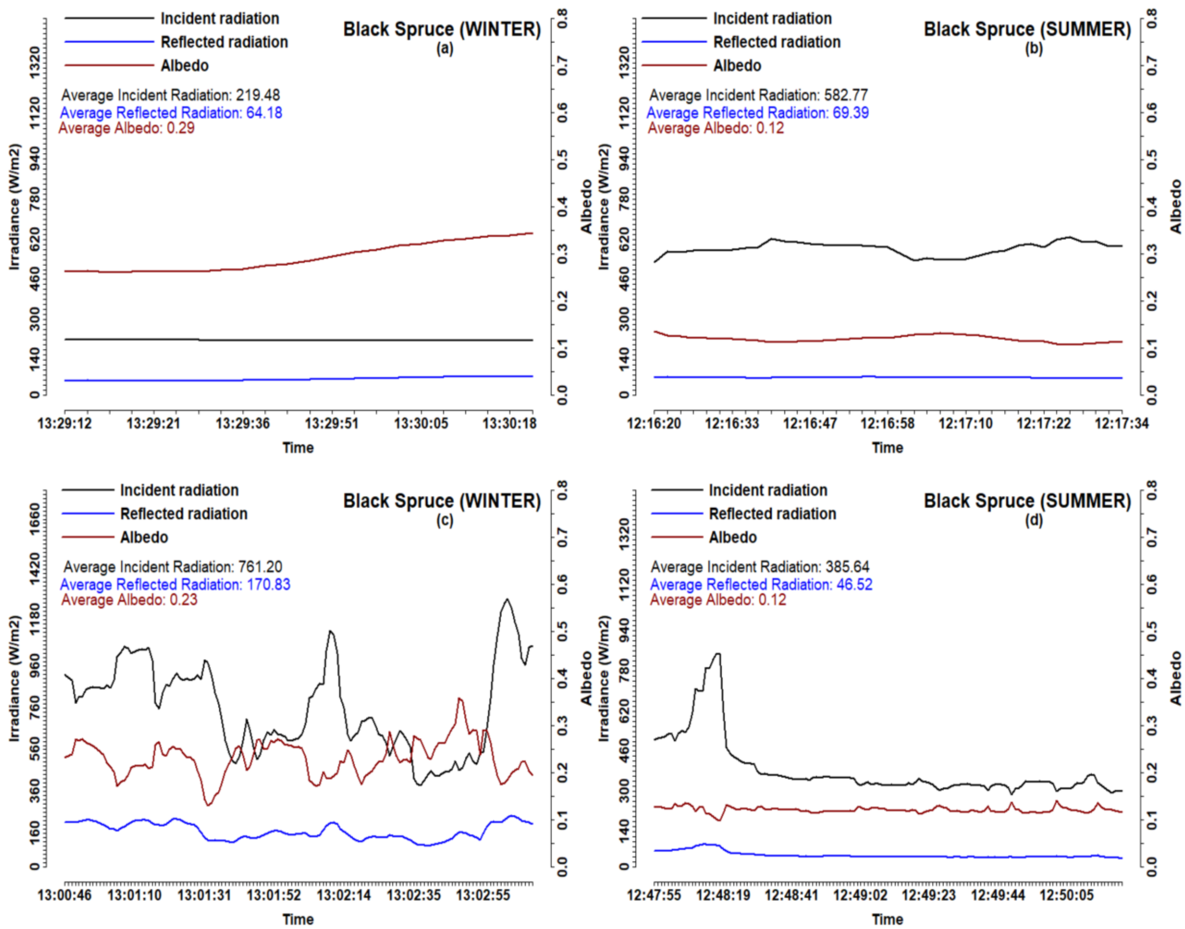

Figure 12. Incident radiation, reflected radiation and albedo values measured during the flights in black spruce plantations in both the winter and summer seasons at Chibougamau (a and b) and at La Doré (c and d).

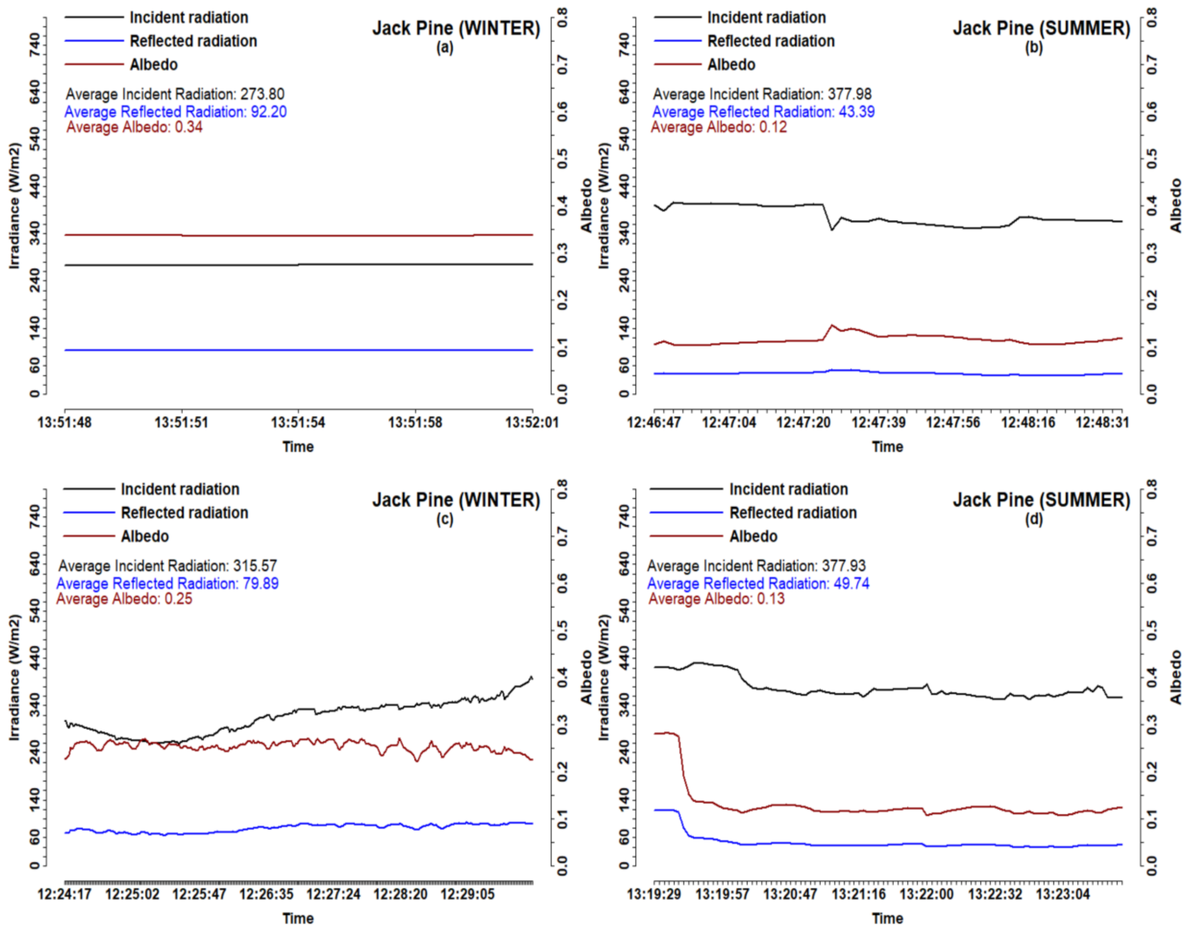

Figure 13. Incident radiation, reflected radiation and albedo values measured during the flights in jack pine plantations in both the winter and summer seasons at Chibougamau (a and b) and at La Doré (c and d).

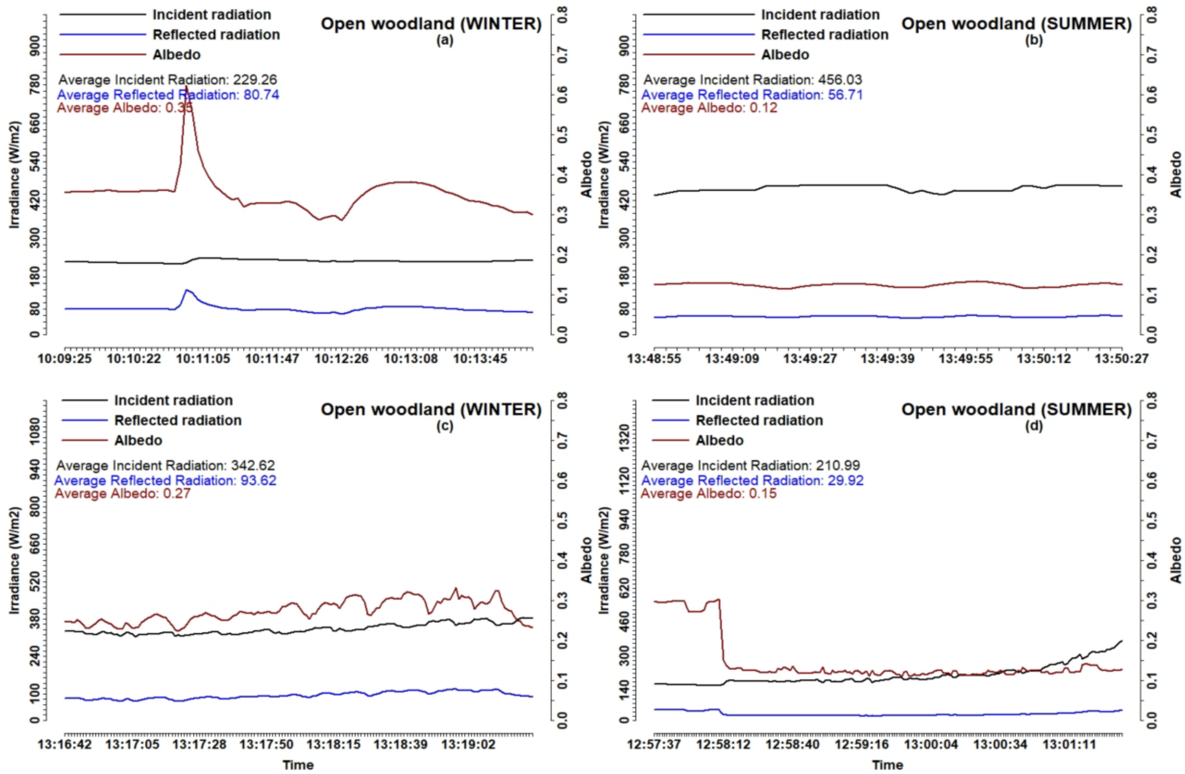

Figure 14. Incident radiation, reflected radiation and albedo values measured during the flights in open woodlands in both the winter and summer seasons at Chibougamau (a and b) and at La Doré (c and d).

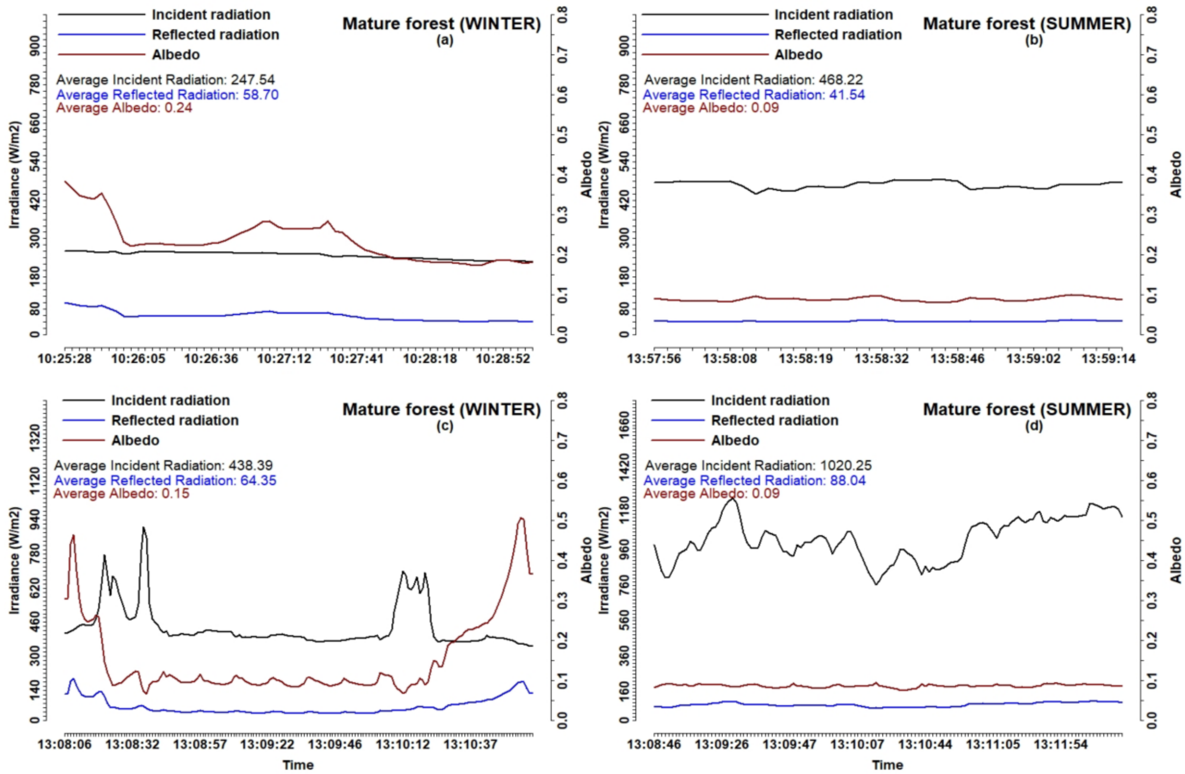

Figure 15. Incident radiation, reflected radiation and albedo values measured during the flights in mature forest in both the winter and summer seasons at Chibougamau (a and b) and at La Doré (c and d).

CHAPTER III

GENERAL CONCLUSION

This study further improves the application of UAV-based albedo measurements, addressing the scaling gap between in-situ and satellite-based data. Our research has provided an approach for the use of UAV platforms to get accurate seasonal albedo measurements in boreal forests, considering the impact of plantation attributes such as age, species, and density on albedo.

Our results showed that winter surface albedo was significantly higher than summer albedo across both study sites (Chibougamau and La Doré) and land cover types. The seasonal variation was more pronounced in open woodlands and plantations (jack pine and black spruce), which have more exposed ground and greater snow cover. In contrast, mature black spruce forests exhibited lower albedo and smaller seasonal differences due to their dense canopies and reduced snow exposure.

We also observed that canopy cover, snowpack characteristics, lichen cover and the timing of observations influenced albedo variations. Therefore, from a surface energy perspective, afforesting open woodlands will reduce albedo and increase the absorption of incoming shortwave radiation. This highlights the need for long-term, high-resolution monitoring across spatial scales to improve the precision of radiative forcing estimates. This will enable us to enhance boreal climate models by offering more responsive and spatially explicit albedo estimates that mirror forest management practices.

Despite the valuable insights obtained, several limitations should be acknowledged. First, the research plots utilized for field measurements were not very large; each one covered less than or equal to one hectare. This size was good for looking at small areas, but it might not show the entire range of spatial differences in boreal forest landscapes. Second, due to limited accessibility of the experimental sites during peak winter, logistical problems limited the number of observations for each kind of land cover types in April. Third, it was hard to accurately compare albedo measurements taken in the field with those taken by satellites. Satellites commonly used for albedo measurements, such as Sentinel-2 and MODIS, could not be used to match field data collected on specific dates because their temporal resolution was too coarse. This challenge was further compounded by frequent cloud cover over the study areas, particularly during winter. Since clouds are highly reflective, their presence in satellite imagery increases the measured surface albedo values compared to UAV-based measurements, which directly capture true surface albedo at the ground level without atmospheric interference. As a result, many of the satellite images for the study period were unusable. Moreover, clear-sky conditions were rare, making it difficult to obtain reliable satellite observations that corresponded to the same dates as UAV flights. Together, these limitations prevented the use of satellite products for accurate validation of field-measured albedo.

Lastly, while pyranometers are widely used to measure solar radiation on surfaces, it's still hard to figure out exactly how much ground area they cover in their conical field of view, which might lead to imprecision in albedo measurements.

Future climate projections suggest that diminished snowfall and earlier snowmelt could shift the peak albedo contrast between open woodlands and mature forests from April toward March. This shortening of the snow season is expected to result from both a delayed onset of snowfall and earlier snowmelt, driven by rising temperatures. Since solar irradiance is lower in March, this seasonal shift may reduce the positive radiative forcing currently associated with afforestation-induced albedo change (Bernier et al. 2011). As a result, the long-term cooling benefit of high winter albedo in open woodlands may diminish. These reductions in snow amount and duration will further limit the impact of afforestation on surface albedo during winter and early spring, and planting jack pine rather than black spruce may amplify this effect.

Therefore, it is important to quantify how forest management affects surface reflectance under current and future climate conditions. Understanding this relationship is crucial to determining whether the cooling benefit of carbon sequestration can continue to outweigh the warming effect of reduced albedo, particularly in boreal afforestation plans. In this context, species selection, such as preferring jack pine over black spruce, emerges as a key management decision influencing the balance between carbon and albedo effects.

REFERENCES

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

Anderson, R. G., Canadell, J. G., & Randerson, J. T. (2011). Biophysical considerations in forestry for climate protection. *Frontiers in Ecology and the Environment*, *9*(3), 174–182. https://doi.org/10.1890/090179

Antonio Pacheco Gil, H., & De Jesús Montilla Pacheco, A. (2021). Rgb spectral indices for the analysis of soil protection by vegetation cover against erosive processes. In A. Vieira & S. Carlos Rodrigues (Eds.), *Soil Erosion—Current Challenges and Future Perspectives in a Changing World*. IntechOpen. https://doi.org/10.5772/intechopen.95055

Antonucci, S., Rossi, S., Deslauriers, A., Morin, H., Lombardi, F., Marchetti, M., & Tognetti, R. (2017). Large-scale estimation of xylem phenology in black spruce through remote sensing. *Agricultural and Forest Meteorology*, *233*, 92–100. https://doi.org/10.1016/j.agrformet.2016.11.011

Asselin, O., Leduc, M., Paquin, D., Winger, K., Di Luca, A., Bukovsky, M., Music, B., & Giguère, M. (2022). *Climate response to severe forestation: A regional climate model intercomparison study*. https://doi.org/10.5194/egusphere-2022-291

Bala, G., Caldeira, K., Wickett, M., Phillips, T. J., Lobell, D. B., Delire, C., & Mirin, A. (2007). Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences*, *104*(16), 6550–6555. https://doi.org/10.1073/pnas.0608998104

Barazzetti, L., Brumana, R., Oreni, D., Previtali, M., & Roncoroni, F. (2014). True-orthophoto generation from UAV images: Implementation of a combined photogrammetric and computer vision approach. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *II–5*, 57–63. https://doi.org/10.5194/isprsannals-II-5-57-2014

Beaury, E. M., Smith, J., & Levine, J. M. (2024). Global suitability and spatial overlap of land-based climate mitigation strategies. *Global Change Biology*, *30*(9), e17515. https://doi.org/10.1111/gcb.17515

Bernier, P. Y., Desjardins, R. L., Karimi-Zindashty, Y., Worth, D., Beaudoin, A., Luo, Y., & Wang, S. (2011). Boreal lichen woodlands: A possible negative feedback to climate change in eastern North America. *Agricultural and Forest Meteorology*, *151*(4), 521–528. https://doi.org/10.1016/j.agrformet.2010.12.013

Betts, A. K., & Ball, J. H. (1997). Albedo over the boreal forest. *Journal of Geophysical Research: Atmospheres*, *102*(D24), 28901–28909. https://doi.org/10.1029/96JD03876

Betts, A. K., Desjardins, R. L., & Worth, D. (2007). Impact of agriculture, forest and cloud feedback on the surface energy budget in BOREAS. *Agricultural and Forest Meteorology*, *142*(2–4), 156–169. https://doi.org/10.1016/j.agrformet.2006.08.020

Betts, R. A. (2000). Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature*, *408*(6809), 187–190. https://doi.org/10.1038/35041545

Betts, R. A. (2011). Afforestation cools more or less. *Nature Geoscience*, *4*(8), 504–505. https://doi.org/10.1038/ngeo1223

Bhardwaj, A., Sam, L., Akanksha, Martín-Torres, F. J., & Kumar, R. (2016). UAVs as remote sensing platform in glaciology: Present applications and future prospects. *Remote Sensing of Environment*, *175*, 196–204. https://doi.org/10.1016/j.rse.2015.12.029

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, *320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121

Bonan, G. B., Pollard, D., & Thompson, S. L. (1992). Effects of boreal forest vegetation on global climate. *Nature*, *359*(6397), 716–718. https://doi.org/10.1038/359716a0

Boucher, J.-F., Tremblay, P., Gaboury, S., & Villeneuve, C. (2012). Can boreal afforestation help offset incompressible GHG emissions from Canadian industries? *Process Safety and Environmental Protection*, *90*(6), 459–466. https://doi.org/10.1016/j.psep.2012.10.011

Bounoua, L., DeFries, R., Collatz, G. J., Sellers, P., & Khan, H. (2002). Effects of land cover conversion on surface climate. *Climatic Change*, *52*(1), 29–64. https://doi.org/10.1023/A:1013051420309

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

Burton, P.J., Messier, C., Weetman, G.F., Prepas, E.E., Adamowicz, W.L., & Tittler, R. (2003). The current state of boreal forestry and the drive for change. Chapter 1. In Towards Sustainable Management of the Boreal Forest. Edited by P.J. Burton, C. Messier, D.W. Smith, and W.L. Adamowicz. NRC Research Press, Ottawa, Ontario, Canada. pp. 1–40.

Cao, C., Lee, X., Muhlhausen, J., Bonneau, L., & Xu, J. (2018). Measuring landscape albedo using unmanned aerial vehicles. *Remote Sensing*, *10*(11), 1812. https://doi.org/10.3390/rs10111812

Carrivick, J. L., Smith, M. W., & Quincey, D. J. (2016). *Structure from Motion in the Geosciences*. John Wiley & Sons.

Chapin, F. S., Sturm, M., Serreze, M. C., McFadden, J. P., Key, J. R., Lloyd, A. H., McGuire, A. D., Rupp, T. S., Lynch, A. H., Schimel, J. P., Beringer, J., Chapman, W. L., Epstein, H. E., Euskirchen, E. S., Hinzman, L. D., Jia, G., Ping, C.-L., Tape, K. D., Thompson, C. D. C., … Welker, J. M. (2005). Role of land-surface changes in arctic summer warming. *Science*, *310*(5748), 657–660. https://doi.org/10.1126/science.1117368

Chen, Y., Briese, C., Karel, W., & Pfeifer, N. (2014). True orthophoto generation using multi-view aerial images. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL–3*, 67–71. https://doi.org/10.5194/isprsarchives-XL-3-67-2014

Faubert, P., Ribeiro Paula, R., Bouchard, S., Marty, C., Fradette, O., & Villeneuve, C. (2023). Funding research using climate change mitigation: The case of the Carbone boréal research infrastructure. *PLOS Climate*, *2*(6), e0000232. https://doi.org/10.1371/journal.pclm.0000232

Fradette, O., Marty, C., Tremblay, P., Lord, D., & Boucher, J.-F. (2021). Allometric equations for estimating biomass and carbon stocks in afforested open woodlands with black spruce and jack pine, in the eastern canadian boreal forest. *Forests*, *12*(1), 59. https://doi.org/10.3390/f12010059

Gaboury, S., Boucher, J.-F., Villeneuve, C., Lord, D., & Gagnon, R. (2009). Estimating the net carbon balance of boreal open woodland afforestation: A case-study in Québec's closed-crown boreal forest. *Forest Ecology and Management*, *257*(2), 483–494. https://doi.org/10.1016/j.foreco.2008.09.037

Girard, F., Payette, S., & Gagnon, R. (2008). Rapid expansion of lichen woodlands within the closed-crown boreal forest zone over the last 50 years caused by stand disturbances in eastern Canada. *Journal of Biogeography*, *35*(3), 529–537. https://doi.org/10.1111/j.1365-2699.2007.01816.x

Girard, F., Payette, S., & Gagnon, R. (2009). Origin of the lichen–spruce woodland in the closed-crown forest zone of eastern Canada. *Global Ecology and Biogeography*, *18*(3), 291–303. https://doi.org/10.1111/j.1466-8238.2009.00449.x

Hakala, T., Suomalainen, J., & Peltoniemi, J. I. (2010). Acquisition of bidirectional reflectance factor dataset using a micro unmanned aerial vehicle and a consumer camera. *Remote Sensing*, *2*(3), 819–832. https://doi.org/10.3390/rs2030819

Hasler, N., Williams, C. A., Denney, V. C., Ellis, P. W., Shrestha, S., Terasaki Hart, D. E., Wolff, N. H., Yeo, S., Crowther, T. W., Werden, L. K., & Cook-Patton, S. C. (2024). Accounting for albedo change to identify climate-positive tree cover restoration. *Nature Communications*, *15*(1), 2275. https://doi.org/10.1038/s41467-024-46577-1

Hollinger, D. Y., Ollinger, S. V., Richardson, A. D., Meyers, T. P., Dail, D. B., Martin, M. E., Scott, N. A., Arkebauer, T. J., Baldocchi, D. D., Clark, K. L., Curtis, P. S., Davis, K. J., Desai, A. R., Dragoni, D., Goulden, M. L., Gu, L., Katul, G. G., Pallardy, S. G., Paw U, K. T., … Verma, S. B. (2010). Albedo estimates for land surface models and support for a new paradigm based on foliage nitrogen concentration. *Global Change Biology*, *16*(2), 696–710. https://doi.org/10.1111/j.1365-2486.2009.02028.x

Hu, X., Cherubini, F., Vezhapparambu, S., & Strømman, A. H. (2018). From remotely-sensed data of norwegian boreal forests to fast and flexible models for estimating surface albedo. *Journal of Advances in Modeling Earth Systems*, *10*(10), 2495–2513. https://doi.org/10.1029/2018MS001403

Immerzeel, W. W., Kraaijenbrink, P. D. A., Shea, J. M., Shrestha, A. B., Pellicciotti, F., Bierkens, M. F. P., & De Jong, S. M. (2014). High-resolution monitoring of Himalayan glacier dynamics using unmanned aerial vehicles. *Remote Sensing of Environment*, *150*, 93–103. https://doi.org/10.1016/j.rse.2014.04.025

Jasinski, J. P. P., & Payette, S. (2005). The creation of alternative stable states in the southern boreal forest, québec, canada. *Ecological Monographs*, *75*(4), 561–583. https://doi.org/10.1890/04-1621

Johnson, E. A., & Miyanishi, K. (1999). Subarctic lichen woodlands. In J. S. Fralish, J. M. Baskin, & R. C. Anderson (Eds.), *Savannas, Barrens, and Rock Outcrop Plant Communities of North America* (pp. 421–436). Cambridge University Press. https://doi.org/10.1017/CBO9780511574627.027

Kalliokoski, T., Bäck, J., Boy, M., Kulmala, M., Kuusinen, N., Mäkelä, A., Minkkinen, K., Minunno, F., Paasonen, P., Peltoniemi, M., Taipale, D., Valsta, L., Vanhatalo, A., Zhou, L., Zhou, P., & Berninger, F. (2020). Mitigation impact of different harvest scenarios of finnish forests that account for albedo, aerosols, and trade-offs of carbon sequestration and avoided emissions. *Frontiers in Forests and Global Change*, *3*, 562044. https://doi.org/10.3389/ffgc.2020.562044

Klassen, S., & Bugbee, B. (2015). Shortwave radiation. In J. L. Hatfield & J. M. Baker (Eds.), *Agronomy Monographs* (pp. 43–57). American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. https://doi.org/10.2134/agronmonogr47.c3

Kristensen, J. Å., Barbero-Palacios, L., Barrio, I. C., Jacobsen, I. B. D., Kerby, J. T., López-Blanco, E., Malhi, Y., Le Moullec, M., Mueller, C. W., Post, E., Raundrup, K., & Macias-Fauria, M. (2024). Tree planting is no climate solution at northern high latitudes. *Nature Geoscience*, *17*(11), 1087–1092. https://doi.org/10.1038/s41561-024-01573-4

Kuusinen, N., Kolari, P., Levula, J., Porcar-Castell, A., Stenberg, P., & Berninger, F. (2012). Seasonal variation in boreal pine forest albedo and effects of canopy snow on forest reflectance. *Agricultural and Forest Meteorology*, *164*, 53–60. https://doi.org/10.1016/j.agrformet.2012.05.009

Kuusinen, N., Tomppo, E., Shuai, Y., & Berninger, F. (2014). Effects of forest age on albedo in boreal forests estimated from MODIS and Landsat albedo retrievals. *Remote Sensing of Environment*, *145*, 145–153. https://doi.org/10.1016/j.rse.2014.02.005

Levy, C. R., Burakowski, E., & Richardson, A. D. (2018). Novel measurements of fine-scale albedo: Using a commercial quadcopter to measure radiation fluxes. *Remote Sensing*, *10*(8), 1303. https://doi.org/10.3390/rs10081303

Li, J. and Heap, A.D., 2008. A Review of Spatial Interpolation Methods for Environmental Scientists. Geoscience Australia, Record 2008/23, 137 pp.

Marty, C., Fradette, O., Faubert, P., Bouchard, S., & Villeneuve, C. (2023). Performance of seedlings of four coniferous species planted in two boreal lichen woodlands with contrasting soil fertility. *Forest Ecology and Management*, *527*, 120601. https://doi.org/10.1016/j.foreco.2022.120601

Di Mauro, B., Fava, F., Ferrero, L., Garzonio, R., Baccolo, G., Delmonte, B., & Colombo, R. (2015). Mineral dust impact on snow radiative properties in the European Alps combining ground, UAV, and satellite observations. *Journal of Geophysical Research: Atmospheres*, *120*(12), 6080–6097. https://doi.org/10.1002/2015JD023287

Ollinger, S. V., Richardson, A. D., Martin, M. E., Hollinger, D. Y., Frolking, S. E., Reich, P. B., Plourde, L. C., Katul, G. G., Munger, J. W., Oren, R., Smith, M.-L., Paw U, K. T., Bolstad, P. V., Cook, B. D., Day, M. C., Martin, T. A., Monson, R. K., & Schmid, H. P. (2008). Canopy nitrogen, carbon assimilation, and albedo in temperate and boreal forests: Functional relations and potential climate feedbacks. *Proceedings of the National Academy of Sciences*, *105*(49), 19336–19341. https://doi.org/10.1073/pnas.0810021105

Ouranos, H. C. (2015). Vers l’adaptation. Synthèse des connaissances sur les changements climatiques au Québec. *Ouranos Consortium on Regional Climatology and Adaptation to Climate Change*, 415.

Özyeşil, O., Voroninski, V., Basri, R., & Singer, A. (2017). A survey of structure from motion. *Acta Numerica*, *26*, 305–364. https://doi.org/10.1017/S096249291700006X

Pan, Y., Birdsey, R. A., Phillips, O. L., Houghton, R. A., Fang, J., Kauppi, P. E., Keith, H., Kurz, W. A., Ito, A., Lewis, S. L., Nabuurs, G.-J., Shvidenko, A., Hashimoto, S., Lerink, B., Schepaschenko, D., Castanho, A., & Murdiyarso, D. (2024). The enduring world forest carbon sink. *Nature*, *631*(8021), 563–569. https://doi.org/10.1038/s41586-024-07602-x

Payette, S., & Delwaide, A. (2018). Tamm review: The North-American lichen woodland. *Forest Ecology and Management*, *417*, 167–183. https://doi.org/10.1016/j.foreco.2018.02.043

Pomeroy, J. W., Gray, D. M., Hedstrom, N. R., & Janowicz, J. R. (2002). Prediction of seasonal snow accumulation in cold climate forests. *Hydrological Processes*, *16*(18), 3543–3558. https://doi.org/10.1002/hyp.1228

Pomeroy, J. W., Parviainen, J., Hedstrom, N., & Gray, D. M. (1998). Coupled modelling of forest snow interception and sublimation. *Hydrological Processes*, *12*(15), 2317–2337. https://doi.org/10.1002/(SICI)1099-1085(199812)12:15<2317::AID-HYP799>3.0.CO;2-X

Potapov, P., Hansen, M. C., Stehman, S. V., Loveland, T. R., & Pittman, K. (2008). Combining MODIS and Landsat imagery to estimate and map boreal forest cover loss. *Remote Sensing of Environment*, *112*(9), 3708–3719. https://doi.org/10.1016/j.rse.2008.05.006

Randerson, J. T., Liu, H., Flanner, M. G., Chambers, S. D., Jin, Y., Hess, P. G., Pfister, G., Mack, M. C., Treseder, K. K., Welp, L. R., Chapin, F. S., Harden, J. W., Goulden, M. L., Lyons, E., Neff, J. C., Schuur, E. A. G., & Zender, C. S. (2006). The impact of boreal forest fire on climate warming. *Science*, *314*(5802), 1130–1132. https://doi.org/10.1126/science.1132075

Rippin, D. M., Pomfret, A., & King, N. (2015). High resolution mapping of supra-glacial drainage pathways reveals link between micro-channel drainage density, surface roughness and surface reflectance. *Earth Surface Processes and Landforms*, *40*(10), 1279–1290. https://doi.org/10.1002/esp.3719

Roberts, G. C., Ramana, M. V., Corrigan, C., Kim, D., & Ramanathan, V. (2008). Simultaneous observations of aerosol–cloud–albedo interactions with three stacked unmanned aerial vehicles. *Proceedings of the National Academy of Sciences*, *105*(21), 7370–7375. https://doi.org/10.1073/pnas.0710308105

Roujean, J.-L., Olioso, A., Ceschia, E., Hagolle, O., Weiss, M., Tallec, T., Brut, A., & Ferlicoq, M. (2019). A surface albedo product at high spatial resolution from a combination of sentinel-2 and landsat-8 data: The role of surface radiative forcing from agriculture areas as a major contributor to an abatement of carbon emission. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-3/W6*, 59–61. https://doi.org/10.5194/isprs-archives-XLII-3-W6-59-2019

Ryan, J. C., Hubbard, A. L., Box, J. E., Todd, J., Christoffersen, P., Carr, J. R., Holt, T. O., & Snooke, N. (2015). UAV photogrammetry and structure from motion to assess calving dynamics at Store Glacier, a large outlet draining the Greenland ice sheet. *The Cryosphere*, *9*(1), 1–11. https://doi.org/10.5194/tc-9-1-2015

Schaepman-Strub, G., Schaepman, M. E., Painter, T. H., Dangel, S., & Martonchik, J. V. (2006). Reflectance quantities in optical remote sensing—Definitions and case studies. *Remote Sensing of Environment*, *103*(1), 27–42. https://doi.org/10.1016/j.rse.2006.03.002

Smith, M. W., Carrivick, J. L., & Quincey, D. J. (2016). Structure from motion photogrammetry in physical geography. *Progress in Physical Geography: Earth and Environment*, *40*(2), 247–275. https://doi.org/10.1177/0309133315615805

Sproles, E. A., Mullen, A., Hendrikx, J., Gatebe, C., & Taylor, S. (2020). Autonomous aerial vehicles (Aavs) as a tool for improving the spatial resolution of snow albedo measurements in mountainous regions. *Hydrology*, *7*(3), 41. https://doi.org/10.3390/hydrology7030041

Tonkin, T. N., Midgley, N. G., Graham, D. J., & Labadz, J. C. (2014). The potential of small unmanned aircraft systems and structure-from-motion for topographic surveys: A test of emerging integrated approaches at Cwm Idwal, North Wales. *Geomorphology*, *226*, 35–43. https://doi.org/10.1016/j.geomorph.2014.07.021

Trenberth, K. E., Fasullo, J. T., & Kiehl, J. (2009). Earth's global energy budget. *Bulletin of the American Meteorological Society*, *90*(3), 311–324. https://doi.org/10.1175/2008BAMS2634.1

Santamouris, M. (Ed.). (2013). *Energy and climate in the urban built environment* (0 ed.). Routledge. https://doi.org/10.4324/9781315073774

Verro, K., Äijälä, C., Pirazzini, R., Dadic, R., Maure, D., Van De Berg, W. J., Traversa, G., Van Dalum, C. T., Uotila, P., Fettweis, X., Di Mauro, B., & Johansson, M. (2025). *How well do the regional atmospheric and oceanic models describe the Antarctic sea ice albedo?* https://doi.org/10.5194/egusphere-2025-386

Wang, X., & Xie, J. (2012). A method for true orthophoto generation based on projection and iteration strategy. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *I–4*, 311–314. https://doi.org/10.5194/isprsannals-I-4-311-2012

Warren, S. G. (1982). Optical properties of snow. *Reviews of Geophysics*, *20*(1), 67–89. https://doi.org/10.1029/RG020i001p00067

Webster, C., Rutter, N., Zahner, F., & Jonas, T. (2016). Modeling subcanopy incoming longwave radiation to seasonal snow using air and tree trunk temperatures. *Journal* *of Geophysical Research: Atmospheres*, *121*(3), 1220–1235. https://doi.org/10.1002/2015JD024099

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. (2012). ‘Structure-from-Motion’ photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, *179*, 300–314. https://doi.org/10.1016/j.geomorph.2012.08.021

Whitehead, K., Moorman, B. J., & Hugenholtz, C. H. (2013). Brief Communication: Low-cost, on-demand aerial photogrammetry for glaciological measurement. *The Cryosphere*, *7*(6), 1879–1884. https://doi.org/10.5194/tc-7-1879-2013

Zhang, X., Jiao, Z., Zhao, C., Qu, Y., Liu, Q., Zhang, H., Tong, Y., Wang, C., Li, S., Guo, J., Zhu, Z., Yin, S., & Cui, L. (2022). Review of land surface albedo: Variance characteristics, climate effect and management strategy. *Remote Sensing*, *14*(6), 1382. https://doi.org/10.3390/rs14061382