UNIVERSITÉ DU QUÉBEC EN ABITIBI-TÉMISCAMINGUE

ESTIMATION DE L'IMPORTANCE RELATIVE DES FACTEURS ABIOTIQUES ET BIOTIQUES INFLUENÇANT LA DISTRIBUTION SPATIALE DE LA PALUDIFICATION DANS LES FORÊTS BORÉALES DU NORD-OUEST DU QUÉBEC

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UNIVERSITÉ DU QUÉBEC EN ABITIBI-TÉMISCAMINGUE

ESTIMATION OF THE RELATIVE IMPORTANCE OF ABIOTIC AND BIOTIC FACTORS INFLUENCING THE SPATIAL DISTRIBUTION OF PALUDIFICATION IN THE BOREAL FORESTS OF NORTHWESTERN QUEBEC

THESIS PRESENTED AS A PARTIAL REQUIREMENT FOR THE MASTER'S DEGREE IN ECOLOGY

BY

CHRISTINE TATIANA CORREDOR DURANGO

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FOREWORD

This Master's thesis consists of three chapters. Chapter I serves as a general introduction to the study, presenting the context, the state of knowledge, objectives, and hypotheses. Chapter II presents all the research carried out in the form of a scientific article, which presents the problem, the methodology and results, as well as a discussion of the results, implications and limitations of the study. The article in Chapter II will be submitted to the open access journal ***Forests*** with Tatiana Corredor, Osvaldo Valeria and Philippe Marchand as authors. I am responsible for the study, data collection, data analysis and writing of the thesis and the article. My director and co-director contributed to the design of the study and assisted me in the interpretation of the results. They also critically and constructively reviewed the content of the thesis and the article. Finally, this master’s thesis concludes with a general conclusion in Chapter III.

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RÉSUMÉ

Les forêts boréales, incluant la ceinture argileuse de l'Ontario et du Québec, soutiennent une importante industrie forestière. Dans cette région, le bois qui est récolté et utilisé pour la production forestière se trouve en partie dans des tourbières et est sujet à un processus naturel appelé paludification. Ce processus conduit progressivement à l'accumulation de tourbe qui commence directement dans le sol minéral sec et implique la formation de conditions saturées en eau. La paludification est influencée par l'interaction de facteurs abiotiques (climatiques et topographiques) et biotiques (type de végétation); elle réduit la température du sol, les taux de décomposition, l'activité microbienne et la disponibilité des nutriments pour la régénération et la croissance des arbres. En conséquence, la paludification entraîne une baisse de la productivité des forêts.

Les paysages paludifiés sont composés d'une mosaïque de fragments, car ils représentent un domaine spatial et temporel de conditions environnementales relativement homogènes. A leur tour, les fragments de ces zones paludifiées sont intégrés dans le paysage et les conditions environnementales qui s'y trouvent sont prédominantes.

Cette étude vise à fournir une meilleure compréhension et de nouvelles connaissances sur la distribution spatiale de l'épaisseur de la couche organique (ECO) en (1) construisant un modèle prédictif de l'épaisseur de la couche organique en utilisant des variables topographiques, climatiques et de type de végétation obtenues à partir du LiDAR, de la base de données Worldclim et de la carte écoforestière du Québec et en (2) déterminant les interactions entre les variables des facteurs abiotiques et biotiques.

Nos résultats montrent que les variables topographiques, principalement la classe de drainage, l'élévation et la pente sont les variables qui influencent le plus l'épaisseur de la couche organique. De plus, il existe une interaction entre les variables parmi les facteurs abiotiques et biotiques. Principalement, entre la classe de drainage, la pente, température minimale, type de végétation et précipitations totales avec ECO, à l'exception de la variable topographique "aspect" dérivée du MNT. Enfin, la distribution spatiale des zones sujettes à la paludification a montré que le type prédominant dans la matrice sont les fragments avec des valeurs < 40cm de l'ECO avec un plus grand indice d'agrégation de 81,5%, tandis que les fragments avec des valeurs plus élevées ≥ 40 cm de l'ECO sont distribués dans cette matrice dans la zone d'étude avec un indice d'agrégation de 44,8%.

Mots clés**:** productivité forestière, analyse des patrons spatiaux, analyse de trajectoire, écologie des paysages

ABSTRACT

Boreal forests, including the clay belt of Ontario and Quebec, support a large forest resource and over important forest industry. In this region, the harvested wood used for forestry production in part is found in peat bogs and prone to a natural process called paludification. This process leads progressively to the accumulation of peat which starts directly in the dry mineral soil and involves the formation of waterlogged conditions. Paludification is influenced by the interaction of the abiotic (climatic and topographic) and biotic (type of vegetation) factors; it reduces soil temperature, decomposition rates, microbial activity, and nutrient availability for tree regeneration and growth. As a result, paludification leads to decreased forest productivity.

Paludified landscapes are composed of a mosaic of patches because they represent a spatial domain and a temporal domain of relatively homogeneous environmental conditions. In turn, the patches of these paludified areas are embedded in a matrix and the species that predominate in the matrix are those that predominate in the landscape.

This study aims to provide a better understanding and knowledge of the spatial distribution of the organic layer thickness (OLT) by (1) constructing of a predictive model of the thickness of the organic layer using topographic, climatic and vegetation type variables obtained from LiDAR, Worldclim database and the ecoforestry map of Quebec and (2) determining the interactions between the variables within the abiotic and biotic factors.

Our results show that topographic variables, mainly drainage class, elevation and slope are the variables that influence the organic layer thickness the most. In addition, there is an interaction between the variables among abiotic and biotic factors. Mainly, OLT is correlated with drainage class, slope, minimum temperature, vegetation type and total precipitation, but not for the topographic variable "aspect" derived from the DTM. Finally, the spatial distribution of areas subject to paludification showed that the predominant type in the matrix are the fragments with values < 40cm of ECO with a greater aggregation index of 81.5%, while the fragments with higher values ≥ 40 cm of ECO are distributed in this matrix in the study area with an aggregation index of 44.8%.

Key words: forest productivity, spatial pattern analysis, path analysis, landscape ecology.

CHAPTER I

GENERAL INTRODUCTION

1.1 Context

The boreal forests of northern Canada, like other forests, are exposed to the effects of climate and natural disturbances, such as decreases or increases in temperature and changes in precipitation patterns that alter the natural cycle of these forests. In these forests, fires are one of the main disturbances and in the absence of these, there is a gradual accumulation of thick layers of organic soil (Kasischke & Turetsky, 2006). Accumulations of organic soil are attributed mainly to a natural process called paludification, which generally creates wetter conditions that decrease soil temperature, decomposition rates, microbial activity, nutrient availability, and increases canopy openings (Crawford et al., 2003; Lavoie et al., 2005). Paludification is the result of the interaction of variables within the abiotic and biotic factors: topography, climate, and vegetation (Fenton et al.,2006). Climate and vegetation actively participate in soil formation (Lopez and Bacilio, 2020). Among the topographical variables we find the superficial deposit, which is the substrate from which the soil develops. The mineral soil is derived directly from the surface deposit and exerts a strong influence on soil texture. This soil texture is determined by the percentage of sand, silt, or clay. Generally, soils are composed of particles of three different sizes. The sands particles are relatively large, the clay particles are very small compared to the sand and silt particles which are medium. Clay and silt retain more water and more plant nutrients than sand particles. This water retention is conducive to poor drainage conditions leading to the appearance of peat over time. Climate influences soil formation through temperature and precipitation regimes, which determine the rate of decomposition of minerals and redistribution of elements, as well as through its influence on vegetation (Fenton et al., 2005). Therefore, the spatial distribution of the organic layer thickness (OLT) depends on the interactions between abiotic and biotic factors. Paludification can cause productivity losses in the boreal forest and, consequently, a reduction in the wood fiber supply that primarily affects forestry companies. Two types of paludification are recognized: permanent paludification, which predominates in depressions, and reversible paludification, which occurs over time after fire or soil management, e.g. mechanical preparation (Laamrani et Valeria, 2020).

Recent advances in remote sensing permit the generation of appropriate data for many mappings and for determining the relationship between the abiotic environment and ecological outcomes at different spatial resolutions. In fact, Light Detection and Ranging (LiDAR) is one of the most effective and reliable active remote sensing technologies that can be used directly or indirectly to assess forest productivity at different spatial scales in boreal forest environments (Laamrani et al., 2014a).

The information available for the study area such as: topographic variables, climatic variables and type of vegetation allows us to create a predictive model and map the spatial distribution of the organic layer thickness (Franklin, 1995; Guisan et Zimmermann, 2000). The indices derived from the Digital Terrain Model (DTM) and LiDAR can therefore be used to elaborate an organic layer thickness prediction map based on the interaction of the abiotic and biotic factors.

1.2 State of knowledge

Paludification is an important ecological process in the Clay Belt region (Fenton et al., 2005; Simard et al., 2009). This process can be initiated or exacerbated due to multiple factors and the interactions of multiple variables. To understand this process, it is necessary to recognize which variables influence the OLT. Previous studies have addressed the individual importance of each one of the following factors: abiotic (topography, climate, drainage class and superficial deposit) and biotic (type of vegetation). All these variables within the factors have an influence on the environment, especially in the soil, being the main drivers of paludification (Fenton et al., 2009).

1.2.1 Abiotic factor

Abiotic factors are all those elements that intervene in the characterization of a given ecosystem, including variables such as superficial deposit, drainage class, topography and climate, which according to previous studies have the greatest influence on the paludification process (Laamrani et al., 2014). The superficial deposit is related to the drainage class (slow, moderate, or fast) and topography (flat or high slope). Clay-dominated superficial deposits reduce runoff by infiltration into the ground; under conditions of poor drainage, the water accumulates due to intense and frequent precipitation and flat and irregular topography (Mesenbet, 2014). The abiotic environment drives tree growth performance, where the mineral soils and well-decomposed organic soils create adequate conditions for tree growth. Tremblay et al. (2006) found that paludification is promoted by the combination of a flat relief with fine superficial deposit and the capacity of the soil to retain water (Barto et al., 2010). This includes the rate at which water can be removed by runoff when rain exceeds the infiltration capacity of the soil. The proportion of water that follows each of these pathways depends on factors such as climate, rock type, or slope of the terrain (Lavoie et al., 2005). For example, in places where there are abundant loose or very porous materials, the percentage of water that infiltrates is very high (Pryor, 1973). Previous studies found that the most important superficial deposits in boreal forests are related to glacial, fluvial and fluvioglacial materials (Paradis, 2006), but paludification is only significant in those with a predominance of compacted soil and poorly drained glaciolacustrine clay deposits that favor water retention (Gauthier et al., 2015).

Topography plays a fundamental role and is expected to be the variable most correlated with the OLT, because OLT depends on whether the surface is elevated or low. For example, elevated surfaces with sloping or convex relief drain more water through runoff, resulting in a thin organic layer thickness. On the other hand, lower surfaces that are concave accumulate water, promoting the growth of the peat bog. Therefore, elevated surfaces show a lower degree of paludification than lower flatter in humid surfaces (Silva,1998 ; Lavoie et al., 2009).

The water table is formed as a function of the balance between precipitation, evapotranspiration, and groundwater. If groundwater is not lost through evaporation, plant transpiration or runoff, water infiltrates into the soil, causing waterlogging, giving way to the accumulation of organic layer (Lavoie et al., 2005).

Climate affects the formation of the organic layer, as during a long period of precipitation, water accumulates in the soil, saturating it and decreasing the soil temperature (Crespin, 2014). Low temperature and higher precipitation create very high humidity conditions that lead to a decrease in the oxygenation necessary for decomposition and contribute to the growth of moss species (Straková et al., 2012). In particular, the rapidly growing genus *Sphagnum* will establish a slightly decomposed organic layer on the surface (Fenton et al., 2010). On the other hand, precipitation and temperature influence the processes of alteration and mineral transformation, modifying the speed of many chemical reactions that occur in the soil. The temperature conditions the type of weathering, predominantly physical with low temperatures, and chemical with high temperatures (Eberl, 1984). The precipitation conditions, when there is availability of water and its flow, influences a large number of edaphic processes, leaching clay, nutrients, iron and humus (Yi et al., 2010).

1.2.3 Biotic factors

Biotic factors are the living components of an ecosystem such as vegetation. The vegetation and the physical characteristics of the environment with its own disturbance regime drive a particular plant species dynamic (MFFP, 2015). The forests of Quebec have a structure and composition of vegetation that are associated with variation in the environment (i.e., superficial deposit, slope, and drainage), climate and natural disturbances. Together, these natural conditions have created bioclimatic domains that divide the territory and describe the balance between climate and potential vegetation (MRN, 2003). In the northwest of Quebec, mixedwood and hardwood mixed forests dominate the landscape. For example, in the North, conifers dominate the spruce-feather moss domain. In the South, broadleaves dominate the sugar maple domain. Mixed wood stands lie between these extremes and include the balsam fir-white birch and balsam fir-yellow birch domains (MRN, 2013).

1.2.4 Types of paludification

Within the Clay Belt, the topographic variables are the principal drivers of paludification (Fenton et al., 2009). Consequently, two types of paludification, permanent and reversible, are recognised in the study area. Theoretically, these two types occur in different locations across the landscape. Permanent paludification dominates in natural depressions, which have wetter soil conditions favouring organic layer build-up (Laamrani et al., 2015). Reversible paludification occurs on flat or sloping terrain, where feather moss-dominated ground cover is replaced by *Sphagnum* spp. (Fenton and Bergeron, 2006). Reversible paludification may be reversed through natural severe fire or a combination of silvicultural practices such mechanical site preparation. In contrast, permanent paludification is not reversible (Fenton et al., 2009).

In northern forest ecosystems, one cause of productivity decline is the accumulation of a thick organic layer that restricts nutrient mineralization and uptake by plants naturally leads to a strong presence of humid forests (Simard et al., 2009; Prescott et al., 2000). Therefore, it is necessary to know which factors influence paludification to better understand and determine which areas are prone to paludification in the boreal forest. This will be useful to identify productive and non-productive areas.

1.2.5 LiDAR

Until recently, the availability of accurate topographic information at different spatial resolution was a limiting factor in relating these data to forest productivity. This accuracy has improved over time and now there are spatial tools that allow us to work with more detailed, accurate information at a higher spatial resolution, such as digital terrain models (DTM) that allow us to represent (model) the land surface, where a unique elevation value is assigned to each pixel (Mallet et David, 2016). Also, LiDAR is becoming one of the most effective and reliable remote sensing technologies to assess microtopography and will be useful to investigate the factors influencing the spatial distribution of OLT in the boreal forests of Quebec. In this context, LiDAR will be useful to create a DTM mainly to identify topographical features at the landscape scale and to relate them to other variables to determine the areas prone to paludification (Southee et al., 2012).

The spatial distribution of soil properties depends on a complex interaction between factors such as topography, superficial deposits, drainage type and climate (Jenny, 1941; McBratney et al., 2003). Therefore, it is necessary to generate efficient models that allow an accurate prediction of soil properties These include: permeability (porosity), the way individual particles of sand, silt and clay are grouped together; the quality and availability of water and nutrients to plants. Soils retain the mineral substances that plants need for their nutrition and are released by the degradation of organic debris. A soil with favorable conditions is the first condition for forest management since it improves productivity to favor the forest in its survival and subsequent development phases at a stand scale in the boreal forests of Quebec.

1.2.6 OLT spatial distribution

The OLT distribution is tributary to abiotic and biotic factors, their interactions, and the space they occupy in the landscape. The distribution of the OLT varies throughout the landscape due to local environmental and geographical features (Guisan and Thuiller, 2005).

There are three basic types of spatial distribution for a continuous variable like OLT: agglomerated (nearby values more similar), dispersed (nearby values less similar) and random. The spatial distribution of the climate, topography, type of vegetation in the landscape may be assed and delimited by remote sensing. This approach generates soil maps that are the main source of information on the spatial distribution of paludified areas. In the soil, the interaction of abiotic and biotic factors results in more accumulation of organic matter in some areas and not in others. Therefore, in the paludified landscape, OLT values can be agglomerated, dispersed, or spatially random. Aggregation can occur because the climatic and topographic conditions are similar in nearby locations, causing OLT values to be similar as well. Therefore, we would expect agglomerated distribution to be the most common for a variable like OLT that depends on those conditions. A random distribution can occur due to random variation of environmental characteristics at a small scale, where some sites more accumulation of organic matter than other nearby sites. Finally, a dispersed distribution could occur if there were negative feedbacks between OLT values or abiotic and biotic factors influencing OLT at nearby sites, but this is not expected for paludified areas (Dirksen, 2013). The spatial distribution of OLT mapping is also useful for implementing forest management strategies. Such mapping will provide information on paludified-prone areas, allowing the implementation of mitigation measures and forestry operations aimed at reducing the impact of paludification on forest productivity when OLT is high (Henneb et al., 2014).

1.2.7 The patch-corridor-matrix landscape model

One of the most used methodologies in landscape ecology is the patch-corridor-matrix landscape model. The landscape consists of habitat patches, corridors connecting the habitat patches and a surrounding matrix, which is not suitable for habitat species (Keymer et al., 2000). In this simplified conceptual model, the paludified landscape is divided in patches, corridors connecting patches and a matrix, which have different functions in relation to environmental conditions. The paludified areas are divided into patches, depending on the interaction of abiotic or biotic factors and whether they have the same environmental characteristics. Usually in these landscapes, the patches are surrounded by a matrix, which dominates the landscape although they are paludified zones with greater or lesser thicknesses of the organic layer.

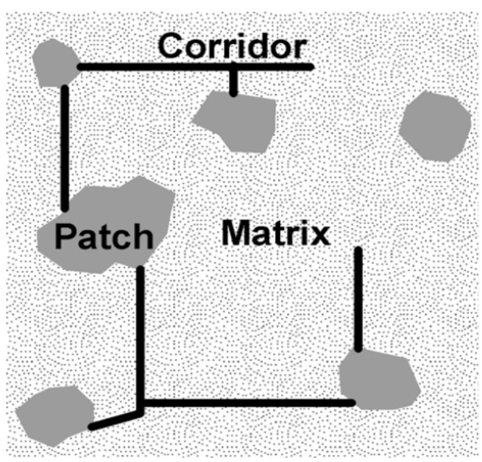

Figure 1.1 The patch-corridor-matrix model. The landscape consists of patches, corridors connecting patches and a matrix (Aminzadeh et Khansefid, 2010)

1.3 General objective

To better understand the spatial distribution of paludification based on the influence of the variables that characterize the selected factors: abiotic (topography, drainage class, superficial deposit, temperature, and precipitation) and biotic (type of vegetation).

Specific objectives and hypothesis

1. Corroborate if the abiotic factor and their variables are the main drivers of the paludification process. It is expected from the literature that topographic variables are the most important variables explaining OLT. Mainly, elevation, a flat slope and poor drainage.

2. Provide a better understanding of the spatial distribution of OLT based on the influence of the variables that characterize the abiotic (topography, drainage class, superficial deposit, temperature, and precipitation) and biotic (type of vegetation) factors. The abiotic factor plays a vital role, as it directly affects OLT and vegetation, since high precipitation and low temperature will be correlated with high OLT in clay flatlands with poor drainage.

3. Determine if there is an interaction between the variables within the two factors that influence the OLT. OLT depends on both abiotic and biotic factors, whereas the factor biotic itself depends on the abiotic factor.

CHAPTER II

INFLUENCE OF BIOTIC AND ABIOTIC FACTORS ON THE SPATIAL DISTRIBUTION OF PALUDIFICATION

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Abstract

In the boreal forest, particularly, in the Clay belt of Northwest Quebec, the low productivity of the forest is influenced by a natural process called paludification. The paludification process is responsible for the long-term decline in forest productivity and is primarily influenced by abiotic and biotic factors (e.g., climate, topography, and vegetation type) and their interaction within a managed forest matrix. Understanding this interaction will provide a better understanding of this process and will be used as a spatial tool to guide forest management decision-making. Organic layer thickness (OLT) is considered a useful indicator of the level of paludification. The objective of this study was to better understand the spatial distribution of paludification as a function of abiotic and biotic factors at a high resolution for a 302 000 km^2 of northwestern Quebec area. The random forest (RF) algorithm was used to develop a spatially explicit predictive model and to generate predictive mapping at a 10 m resolution for the study area. In addition, five metrics (total area, mean area, number of patches, Euclidean distance between nearest neighbors, and aggregation index) were calculated to quantitatively characterize the spatial distribution of low (< 40 cm) and high (≥ 40 cm) OLT patches at the landscape scale. Finally, a path analysis was used to determine how the variables selected for the biotic and abiotic factor analysis correlate with each other and with the OLT. The random forest model explained a significant fraction of OLT at 52%, and abiotic factors, mainly topographic variables appeared systematically as the most important. Also, patches with a low OLT presented a higher aggregation index than those with a high OLT. Finally, there are direct and indirect causal relationships between OLT and the selected variables. These results serve to better understand the areas prone to the process of paludification by locating areas on a 10-meter resolution map that will better guide forest ecosystem management in the Quebec.

Keywords: landscape ecology, landscape metrics, modeling, forest productivity, paludification.

Résumé

Dans la forêt boréale, particulièrement dans la ceinture d'argile du Nord-Ouest du Québec, la faible productivité de la forêt est influencée par un processus naturel appelé paludification. Le processus de paludification est responsable du déclin à long terme de la productivité forestière et est principalement influencé par des facteurs abiotiques et biotiques (par exemple, le climat, la topographie et le type de végétation) et leur interaction au sein d'une matrice forestière aménagée. La compréhension de cette interaction permettra de mieux appréhender ce processus et servira d'outil spatial pour guider la prise de décision en matière de gestion forestière. L'épaisseur de la couche organique (ECO) est considérée comme un indicateur utile, du niveau de paludification. L'objectif de cette étude était de mieux comprendre la distribution spatiale de la paludification en fonction de facteurs abiotiques et biotiques à haute résolution pour une zone de 302 000 km2 du nord-ouest du Québec. L'algorithme de forêt aléatoire (RF) a été utilisé pour développer un modèle prédictif spatialement explicite et pour générer une cartographie prédictive à une résolution de 10 m pour la zone d'étude. De plus, cinq paramètres (superficie totale, superficie moyenne, nombre de taches, distance euclidienne entre les plus proches voisins et indice d'agrégation) ont été calculés pour caractériser quantitativement la distribution spatiale des taches d'ECO faibles (< 40 cm) et élevées (≥ 40 cm) à l'échelle du paysage. Enfin, une analyse des chemins a été utilisée pour déterminer comment les variables sélectionnées pour l'analyse des facteurs biotiques et abiotiques sont corrélées entre elles et avec l'ECO. Le modèle de forêt aléatoire a expliqué une fraction significative de l'ECO, soit 52 %, et les facteurs abiotiques, principalement les variables topographiques, sont apparus systématiquement comme les plus importants. De plus, les parcelles avec une faible ECO présentaient un indice d'agrégation plus élevé que celles avec une ECO élevée. Enfin, il existe des relations causales directes et indirectes entre l'ECO et les variables sélectionnées. Ces résultats permettent de mieux comprendre les zones sujettes au processus de paludification en localisant des zones sur une carte à 10 mètres de

résolution qui permettront de mieux guider la gestion des écosystèmes forestiers au Québec.

Mots clés : écologie du paysage, métrique du paysage, modélisation, productivité forestière, paludification.

2.1 Introduction

Paludification is a natural process that is mainly influenced by abiotic (topography, climate, drainage class and superficial deposit) and biotic (type of vegetation) factors. As a result, the accumulation of the organic layer related to the dominance of *Sphagnum* species in the soil leads to the appearance of microsites poor in nutrients for the regeneration and growth of trees (Van Cleve et al., 1983). This accumulation limits the access of tree roots to the mineral soil necessary for their development, which threatens the provision of ecosystem services and has a significant impact on forest productivity.

Spatial models of forest dynamics have not fully considered how the interactions between these factors affect organic layer thickness (OLT). Understanding these interactions could be relevant because OLT is considered a useful indicator of the level of paludification to predict the loss of productivity of the forest (Laamrani et al., 2015). The abiotic and biotic factors drive complex interactions in the soil environment and vegetation (Yu, 2012) . Also, this interaction favors the growth of the organic layer in certain regions, such as in the Clay Belt of Quebec and Ontario that is an important source of wood supply and also supports a large forest resource (Bergeron et al., 2007; Lavoie et al., 2005). In these areas, decomposition is considerably slower than litter production, due to low temperatures, poor drainage, and the presence of particular recalcitrant substrate in the litter (Prescott et al., 2000). Among the biotic and abiotic factors that are related to the soil environment, previous studies have identified some of the main variables that influence the process of paludification, including temperature, precipitation, topography, superficial deposit, drainage class and type of vegetation (Laamrani et al., 2014).

The climate is determinant because it affects the formation of the organic layer: during a long period of precipitation, water accumulates in the soil especially in flat land due to its high water retention capacity, saturating the soil and affecting the soil temperature. In contrast, sloping sites have greater lateral drainage and lower paludification rates (Simard et al., 2009; Crespin, 2014). Low temperature and higher precipitation create high humidity conditions that result in decreased oxygenation needed for decomposition and contribute to the growth of moss species (Straková et al., 2012). In particular, the fast-growing genus *Sphagnum* will establish a slightly decomposed organic layer on the surface (Fenton et al., 2010).

Previous studies have shown that the most abundant surface deposits in the boreal forests are related to glacial, fluvial, and fluvioglacial materials. In the paludified regions of the Clay belt, when the glacial melting occurred, the lake level dropped and wave action and direction transformed the esker ridges into broad, nearly flat surfaces, while distributing sediments in the form of sand and gravel overlying the fine-grained deep-water deposits (Dionne, 2011). Wind action and fluvial erosion were the main processes determining soil properties in early postglacial times, followed by paludification and vegetation development from the mid-Holocene onward (Banerjee and McDonald, 1975).

The use of statistical models and spatial tools could help us better understand how these factors influence the spatial distribution of OLT (Morgan et al., 1994). Recently, spatial tools have been used to make and update forest management decisions, mainly in landscape ecology. LiDAR is a practical technology for landscape analysis that provides information on surface morphology (flat areas vs. depressions) (Laamrani et al., 2015). This tool generates accurate three-dimensional information and is useful for understanding the shape of the terrain and its surface characteristics (Laamrani et al., 2020). Also, this technology allows the acquisition of topographic data with high accuracy for the creation of maps and terrain models (Sanchez et al.,2012). Therefore, LiDAR will help in the efficient management of forest resources, especially in areas with low productivity due to paludification (Laamrani et al., 2015). This technology is a suitable tool to produce accurate estimates of the spatial distribution of the OLT at a scale of 10 meters resolution, due to allows us measuring the distance of the different layers of vegetation to the ground, which produces an accurate 3D image and allows detecting the microtopography that is hidden by the vegetation.

Our objectives were therefore to: (1) Corroborate if the abiotic factor and their variables are the main drivers of the paludification process; (2) provide a better understanding of the spatial distribution of OLT based on the influence of abiotic (topography, drainage class, superficial deposit, temperature, and precipitation), and biotic (type of vegetation) variables, and (3) determine if there is an interaction between the abiotic and biotic variables that influence the OLT. Based on the literature, our hypotheses regarding each objective are: (1) that the abiotic factor particularly topography are the most important variables explaining OLT; (2) that high ($\geq$ 40 cm) and low (< 40 cm) OLT values are agglomerated, because neighboring locations in the study area have similar conditions due to abiotic factors controlling paludification; (3) that OLT depends on both abiotic and biotic factors, whereas biotic factors themselves depends on abiotic factors. This study will contribute to a better understanding of the spatial distribution of organic layer thickness used as an indicator of paludification. Furthermore, the production of a predictive map of OLT at high resolution will provide information on areas prone to paludification Such spatial tools will provide information on areas prone to paludification.

2.2 Materials and methods

2.2.1 Study area

The study area was chosen based on the availability of a Digital Terrain Model (DTM) (10 m resolution) derived from LiDAR data available obtained from the Ministère des Forêts, de la Faune et des Parcs du Québec (2018) within an area of approximately 302 000 km² (Figure 2.1). This study area overlaps with the Clay Belt zone, a physiographic region created by the deposits left by Lakes Barlow and Ojibway after their maximum extension during the Wisconsonian glaciation (Vincent et Hardy, 1977). The Clay Belt is an area prone to the process of paludification and is also a major source of timber for the forestry industries are also located. This region is dominated by black spruce (*Picea mariana* (Mill.) B.S.P.) and jack pine (*Pinus banksiana Lamb*) followed by trembling aspen *(Populus tremuloides* Michx*),* tamarack (*Larix laricina* [Du Roi] K. Koch*)*, balsam fir (*Abies balsamea [L.]* Miller*)* and white birch (*Betula papyrifera* Marshall*)* (Laamrani et al., 2013; Henneb et al., 2019). The average annual temperature is 0.1 °C and the average annual precipitation is 927.8 mm (Environment Canada, 2020).

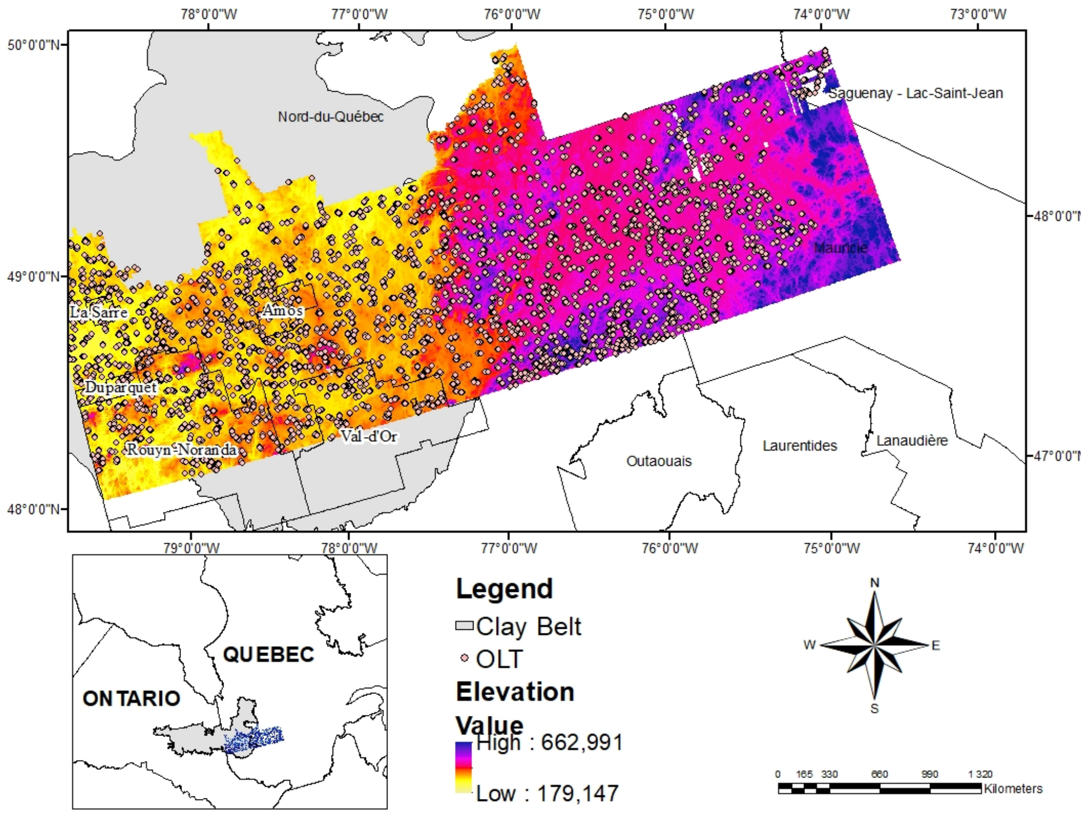

Figure 2.1 Location of the study area in northwest Quebec, Canada, based on LiDAR information (Elevation data, with a resolution of 10 meters). Black dots indicate the OLT sampling sites

2.2.2 Dataset collection

The dataset was obtained by combining OLT measurements from georeferenced plots and transects from several previous projects (1972-2014), with a total of 5627 OLT measurements (in cm) with their respective GPS coordinates (Mansuy et al., 2018).

LiDAR Processing and Topographic Variable Measurements

A digital terrain model (DTM) at 10 m resolution was generated to obtain elevation. From this DTM, we used the Spatial Analyst Tools (Esri) to generate topographic variables, such as: slope, aspect (compass direction of the slope in degrees) and curvature (Mansuy et al., 2011).The aspect, being a circular variable, was converted into two linear variables representing the northness and eastness of the slope, obtained respectively from the cosine and sine of the aspect. Table 2.1 provides a detailed description of each of these topographic variables. The topographic variables chosen were useful for the spatial estimation of the distribution of OLT because the topographic lows/depressions are associated with an accumulation of organic matter and an increase in the water table (Laamrani et al., 2014).

Processing ecoforestry data

A single layer in a raster format (10m x 10m) was generated by joining the spatial entities of different layers of the Quebec ecoforestry map, such as: superficial deposit, type of vegetation and drainage class using ArcGIS v.10 (ESRI, 2016) . The extracted values were classified for each OLT sampling point (Table 2.1). We obtained three class of superficial deposits (C, clay; Sa, sand; SaS, Sand-Stone). The nature of the deposit is assessed from the shape of the land, its position on the slope and the texture of the soil. Also, six classes of drainage classes (1, fast; 2, good; 3, moderate; 4, imperfect; 5, bad and 6, very bad) defined by their rock fraction and texture and linked to the drying potential of the superficial deposits (Mansuy et al., 2012).

For the type of vegetation cover, we classified according to MFFP (2015): if softwoods represent more than 75% of the basal area of the stand, it is considered a softwood (class 1); if softwoods constitute 50 to 75% of the basal area of stand it is considered mixed stand predominantly resinous (class 2); if softwoods represent less than 25% of the stand basal area, it is considered hardwood (class 3).

Processing climatic variables

Climate data (historical climate data from 1972 to 2014) were extracted from the Worldclim database with a resolution of 1 km² (Table 2.1). We used the raster calculator to obtain the mean maximum monthly temperature, the mean minimum monthly temperature and the total precipitation from April to June (spring) and from June to September (summer), since these climatic variables are determinant for the paludification process (Lavoie, 2005). These variables were resampled at 10 m resolution.

These environmental variables were grouped into two factors: the abiotic factor (climatic variables including temperature and precipitation, as well as topographical variables including aspect, curvature, slope, elevation, drainage class and superficial deposit) and the biotic factor (type of vegetation cover). Specific variables were chosen due to the important link between these variables and the organic layer thickness in the northwest boreal forest of Quebec (Mansuy et al., 2014; Vijayakumar et al., 2015).

Table 2.1 Description of the variables, units, and source. More details available in (Mansuy et al., 2014; Vijayakumar et al., 2015)

Variables	Names	Description	Source	Resolution
Climatic	Maximum temperature (°C)	The mean of the monthly maximum temperature	Worldclim	~1 km² (30 s)
	Minimum temperature (°C)	The mean of the monthly minimum temperature	Worldclim	~1 km² (30 s)
	Total precipitation (mm)	The sum of all the monthly precipitation estimates	Worldclim	~1 km² (30 s)
Topographic	Slope (%)	The rate of maximum change in z-value from each cell	LiDAR	10 m
	Elevation (m)	Digital terrain model (DTM).	LiDAR	10 m
	Aspect (0 to 360°)	Aspect is related to the slope direction and is expressed in degrees.	LiDAR	10 m
	Curvature (<0 to >0)	The mean curvature in the direction of the maximum slope.	LiDAR	10 m
Ecoforestry	Superficial deposit (Class)	The most recent of geological formations; rock sediment unconsolidated lying on or near the surface (MFFP, 2015)	Ecoforestry map	10 m
	Drainage (Class)	Soil drainage; faster or slower evacuation of water by surface runoff and deep infiltration.	Ecoforestry map	10 m
	Type of vegetation cover (Class)	Three main types of forest cover; hardwood, softwood and mixed.	Ecoforestry map	10 m

2.2.3 Data analysis

Analysis of direct and indirect causal relationship

All analyses were conducted in the R software environment version 4.0.3 (R Core Team, 2018). To reveal the relationships among environmental variables that are within the biotic and abiotic factors and OLT (See Figure 2.2), we used a path analysis (lavaan package in R) (Rosseel, 2012). Path analysis is an extension of the regression model, used to test the fit of the correlation matrix against two or more causal models which are being compared (Garson, 2013). We fit the model using the « sem » function in lavaan. We used two metrics to measure the path analysis model fit: the Comparative Fit Index (CFI) that compares the fit of a target model to the fit of an independent, or null, model (≥90) and the Root Mean Square Error of Approximation (RMSEA) for which values closer to 0 represent a better fit of the model.

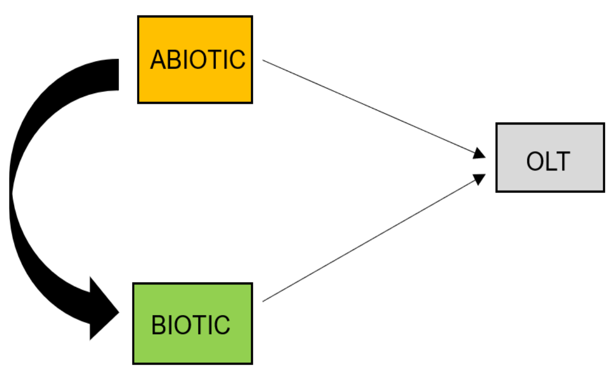

Figure 2.2 Path analysis diagram of organic layer thickness

Prediction model

A total of 11 potential environmental variables were selected (those in Table 2.1, with aspect transformed into eastness and northness). Then, to determine which variables of the factors best explain the OLT, we proceeded to make an elimination of the explanatory variables that was conducted through a wrapper method from the Boruta package v7.0.0 (Kursa et Rudnicki, 2010), which determined the relevance of each explanatory variable, classifying them as important. To complement the final selection of variables, the Pearson's product-moment correlation was used to eliminate environmental variables such as: westness, southness that were highly correlated with each other ($r > |0.7|$) and avoid the inclusion of redundant variables in the model.

Random forest (RF) is an appropriate tool for exploring remote sensing and geographic variables. Also, RF is useful to make predictions of a response variable based on complex (interacting, non-linear) relationships of explanatory variables. (Gislason *et al.*, 2006). We used a RF model from the randomforest package v4.6 (Liaw et Wiener, 2002) considering that the analysis was successful used in the past to predict the organic layer thickness as a response variable base on the explanatory variables (minimum and maximum temperature, total precipitation, slope, elevation, aspect, curvature, type of vegetation, superficial deposit, and drainage class). RF are a set of hierarchically organized conditions or restrictions which are sequentially applied from a root (Cardinael et al., 2015) node to a terminal leaf of a tree to make continual predictions of the phenomenon represented by training data (Breiman, 2001).

The data were randomly split into a calibration (70%) and a validation dataset (30%) using the sample.split() function from the caTools package v.1.17.1.1 (Tuszynski, 2018). The RF algorithm was first tuned to optimize the values of the parameters ntree (5000) and mtry (1). The importance of each predictor (%IncMSE) is estimated by calculating, tree by tree, the deterioration of the predictive ability of the model when each predictor is replaced in turn by randomly permuted values. Higher %IncMSE indicates greater variable importance (Liaw et Wiener, 2002). Subsequently, we generated a predictive cartography at 10 m resolution of the organic layer thickness for the whole study area using the "predict" function with the RF model and the multi-layer Raster object containing the predictor values for the study area.

Landscape pattern analysis for the spatial distribution of OLT

To determine the spatial distribution of the OLT, we used the raster version of the spatial pattern analysis software Fragstats v 4.2, developed by McGarigal et Cushman (2002), which allowed us to develop a Patch Corridor Matrix Model to compute different metrics and to quantify the structure (composition and configuration) (Forman, 1995) of the paludified landscape. The following changes were applied prior to this analysis:

(1) The raster of the predicting mapping was changed from 10 meters to 100 meters due to computational limitations, using the Resample (Data Management) tool in ArcGIS. The resampling technique used was Nearest-Neighbor. It is mainly used for discrete data, such as a land use classification since it will not change the cell values.

(2) The organic layer thickness values were converted into high and low OLT classes (OLT ≥ 40 cm and < 40 cm). These classes were chosen according to Henneb et al. (2015) and Mansuy et al. (2018) where that those studies showed that 40 cm is a good threshold to predict areas prone to paludification. Also, these classes allowed our models to have a better accuracy to identify the spatial distribution of highly paludified areas.

To quantitatively characterize the paludified landscape, a set of spatial analysis metrics have been selected from the existing metrics in Fragstats. Table 2.2 presents a description of the selected metrics, according to McGarigal et Cushman (2002). The selected metrics, including the total area (TA), number of patches (NP), mean area of patches (AREA_MN), Euclidian distance to nearest neighbour (ENN) and aggregation index (AI), provided information about the configuration of patches in the landscape, which of the patches shared the same class and how the OLT classes are distributed in the study area (Botequilha et al., 2006; Leitao and Ahern, 2002). We used a 8 cell neighborhood rule to define patches: two or more pixels are said to be 8-connected if they are 8-adjacent with each others

Table 2.2 Description of metrics used in Fragstats to quantify the paludified landscape in northwest Quebec

Metrics	**Abbreviation**	**Description**
Total area	TA	Total landscape area (m^2).
Euclidian distance to nearest neighbour	ENN	The sum of the distance (m) to the nearest neighbouring patch of the same type, based on the nearest edge to edge distance, for each patch of the corresponding patch type, divided by the number of patches of this same type.
Number of Patches	NP	The total number of patches at the landscape and class levels. The landscape level includes all patches of all classes. The class level includes all patches within a specified Landscape Character Types LCT.
Mean area of patches	AREA_MN	MN (Mean) equals the sum, across all patches of the corresponding patch type, of the corresponding patch metric values, divided by the number of patches of the same type. MN is given in the same units as the corresponding patch metric.
Aggregation Index	AI	AI equals 0 when the focal patch type is maximally disaggregated (i.e., when there are no like adjacencies); AI increases as the focal patch type is increasingly aggregated and equals 100 when the patch type is maximally aggregated into a single, compact patch.

2.3 Results

2.3.1 Path Analysis and direct and indirect causal relationships that influence OLT

Figure 2.3 shows the significant correlations found by the path analysis from a total of 114 potential correlations of the environmental variables (Table 2.1). The analysis shows the direct and indirect correlations between the abiotic, biotic factors and OLT. The aspect variable did not appear to significantly affect the OLT. In contrast, the drainage class, slope, minimum temperature, type of vegetation and total precipitation all showed a strong correlation with the OLT. The metrics used to measure model fit were the Root Mean Square Error of Approximation (RMSEA) of 0.05, the Comparative Fit Index (CFI) with a value of 0.870 and the R^2 of 32% respectively.

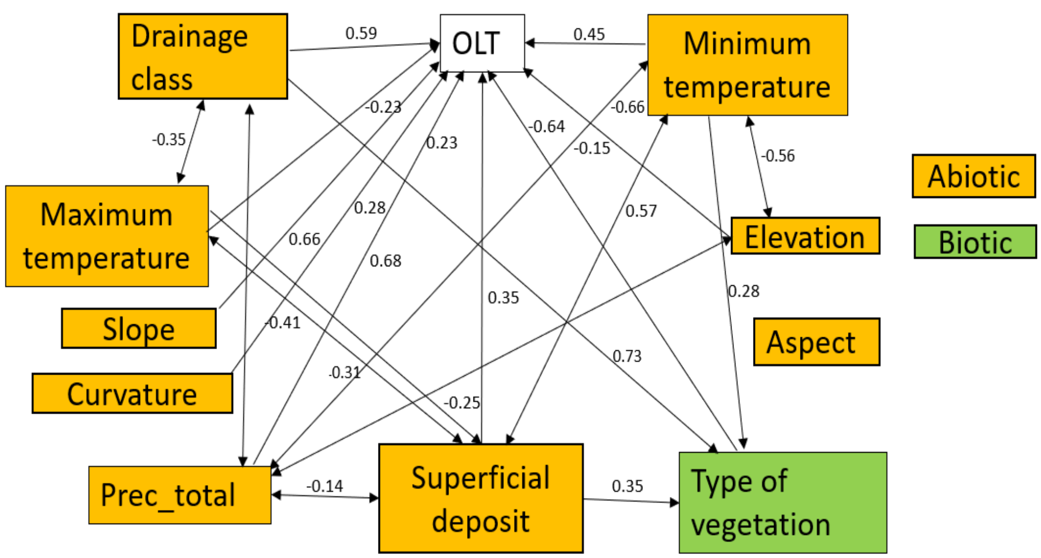

Figure 2.3 Direct and indirect correlations between the variables within the biotic and abiotic factor and OLT. The yellow color corresponds to variables within the abiotic factor and the green color to variables within the biotic factor

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2.3.2 Random forest regression model

The average variance explained by the random forest model was 52% (Figure 2.4), with a root mean square residual error (RMSE) of 15 cm.

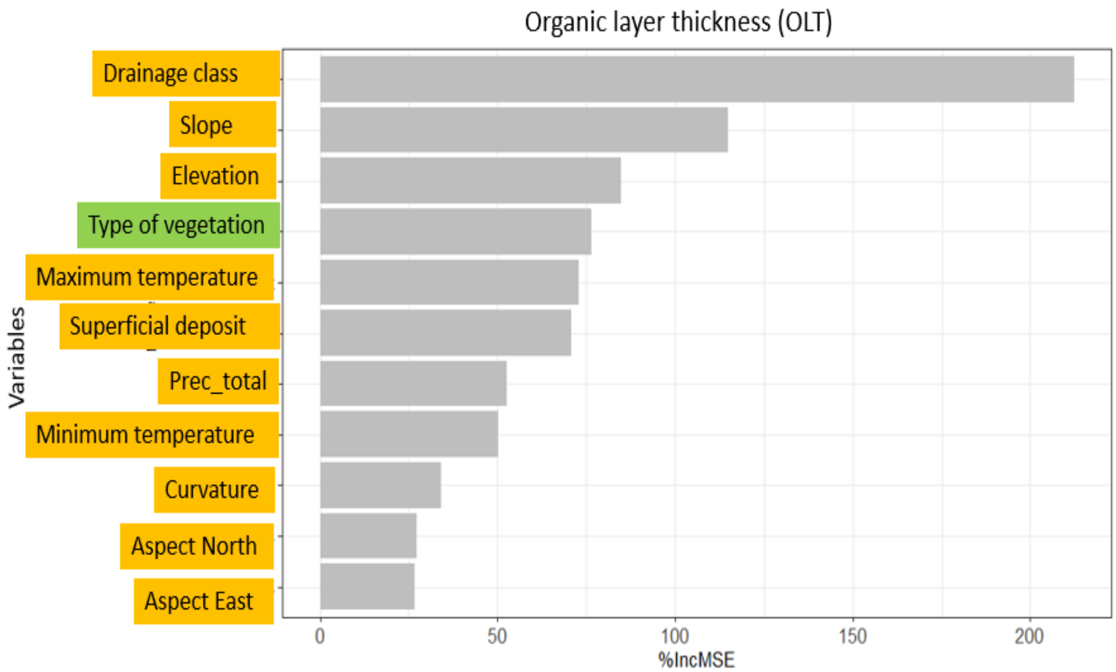

Figure 2.4 Variable importance (%IncMSE) for the organic layer thickness random forest regression model

According to the variable importance results (Figure 2.4), the abiotic factor has the greatest influence on the OLT. Within this factor, the most important variables are topographic variables such as: drainage class, with a value > 200% on average, followed by the slope and elevation with >100% and >75%. For the biotic factor, the type of vegetation variable shows a value of ~75%. The climatic variables show %IncMSE values between 50% and 75%. The least important variables are the curvature and the aspect with less than 40%.

Our model shows better predictive performance for low levels of organic layer thickness and less accuracy when the observed OLT is high (Figure 2.5).

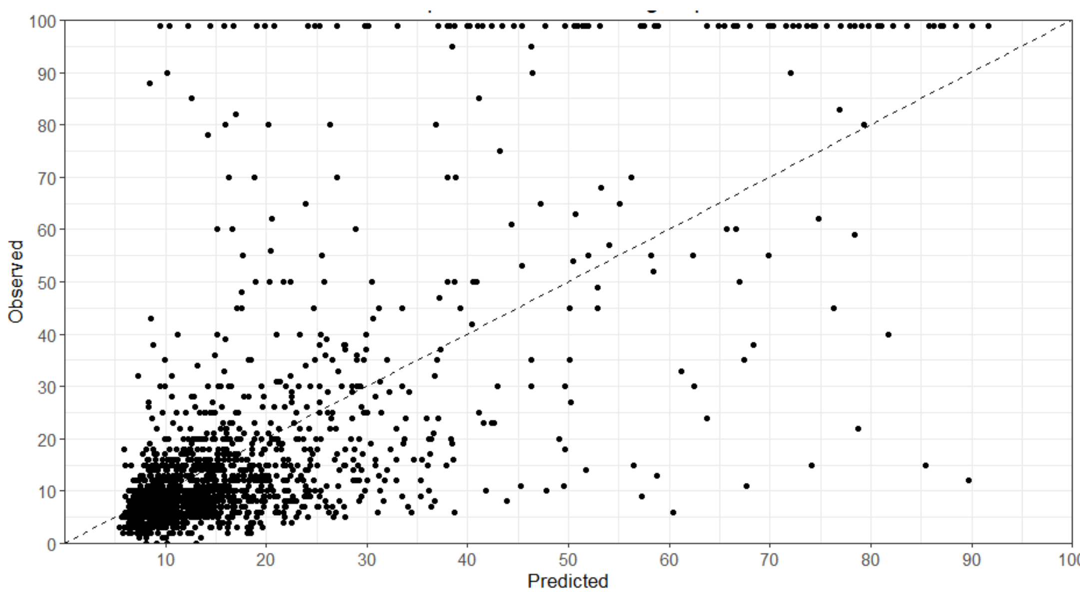

Figure 2.5 Observed organic layer thickness values vs. values predicted by the random

2.3.3 Predictive mapping

The results from our model allowed us to obtain a predictive map (Figure 2.6) for the study area at a 10 m resolution. The green colors correspond to areas predicted to have high values, reaching a maximum value of 96 cm of organic layer thickness, while the orange-red colors correspond to low values, reaching a minimum value of 3 cm of organic layer thickness. White areas within the study area correspond to water zones. The highest values of OLT are concentrated in the southwest of the study area, while the low values are present in all the zone.

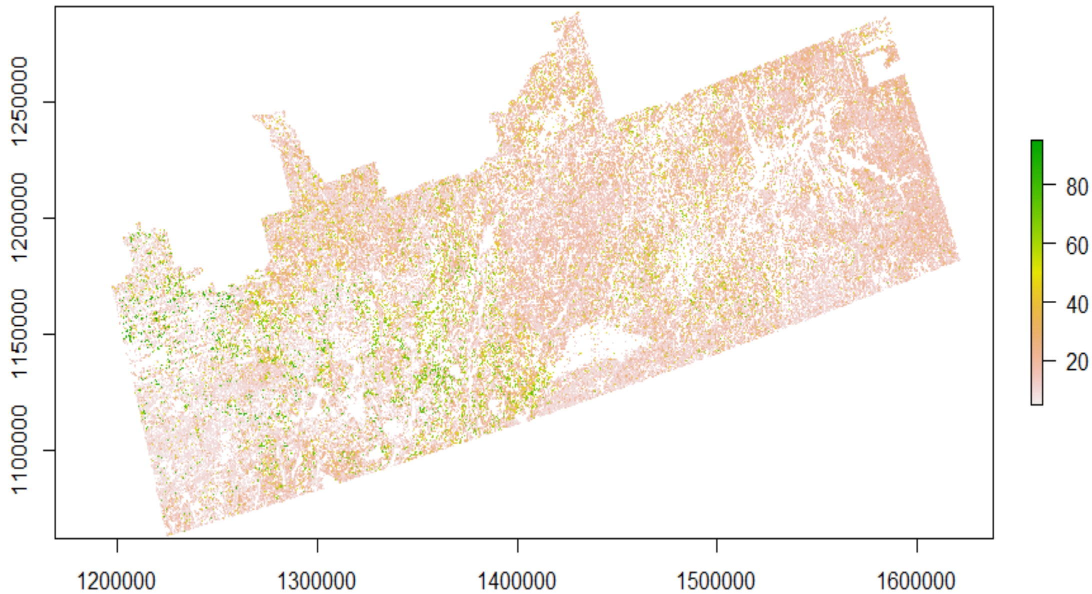

Figure 2.6 Organic layer thickness prediction map in the study area at 10 m resolution

2.3.4 Analysis of Landscape Pattern

Our results showed that the composition of the paludified landscape was quantified by the percentage of area occupied by each organic layer thickness class, where there are 6700 patches of low OLT values (<40cm) and 2600 for the high OLT values (≥ 40 cm) with a 8 cell neighborhood rule. The mean area of the patches (AREA_MN) was 1010 km² for the low values was and 50 km² for the high values. The Euclidian distance to nearest neighbour (ENN) between patches we obtained for the low values was 200 km, compared with 300 km for the high values. Finally, the aggregation index (AI) was 81.5% for low OLT patches (< 40 cm) and 44.8% for high OLT patches (≥ 40 cm) (Figure 2.7). The AI is a metric that equals 0 when the focal patch type is maximally disaggregated (i.e., when there are no like adjacencies) and equals 100 when the patch type is maximally aggregated into a single, compact patch. Therefore, the patches with low OLT values are more aggregated that the high values of OLT. Also, we can observe that the predominant type (matrix) of our model are the patches with low values and the high values are the individual landscape elements (patches) integrated into the matrix.

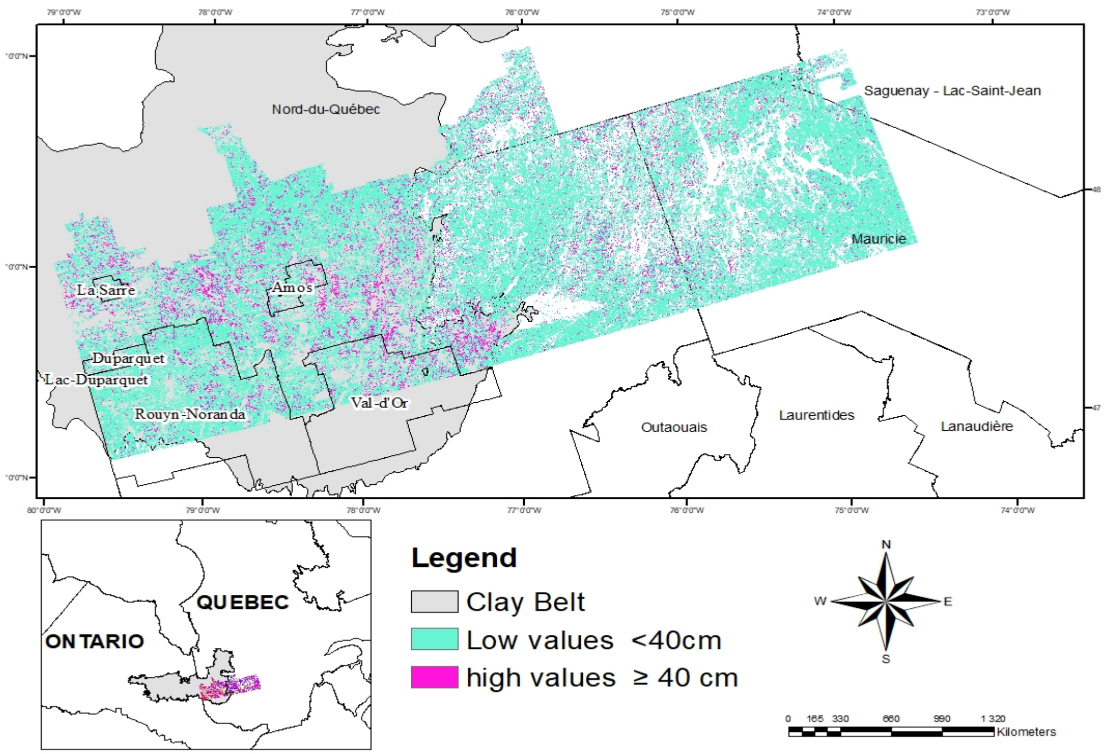

Figure 2.7 The spatial distribution of the low (<40 cm) and high (≥40 cm) organic layer thickness

2.4 Discussion

2.4.1 Performance and limitations of the model

Our RF prediction model allowed us with 11 environmental variables to map predicted values of OLT in a raster format at a resolution of 10 m. Also, we were able to test the hypothesis that among the 11 variables chosen, the abiotic factor, mainly the topographic variables were the most important in explaining the OLT. Primarily, the drainage class has the highest influence the OLT followed by slope and elevation. This result is consistent with previous studies in the Clay Belt, which revealed that paludification is influence by topographic variables (Laamrani et al., 2020; Simard et al., 2009). Our model explained a significant fraction of the variation of the predicted organic layer thickness with a R^2 of 52%, in comparison to other results available for the Northern Quebec territory with a R^2 of 41% for the model in Mansuy et al. (2018) and 63% for the model in Laamrani et al. (2014). However, for our model, a substantial part of the variation remained unexplained, which can be due to several causes: i) missing topographic variables such as those proposed by Laamrani et al. (2015), like the topographic position index (TPI) and topographic wetness index (TWI) generated from a LiDAR DTM, which are important as predictors of surface morphology (i.e., depressions vs. flat areas) and wetness conditions (i.e., wet vs. dry). These variables were not considered because the most representative variables for each of the factors were chosen to determine their correlation with the OLT and among themselves; (ii) Vegetation variables, such as: The normalized difference vegetation index (NDVI), were not included in this study. Although, NDVI allows us to define and visualize photosynthetic activity in land cover, but less sensitive to the biomass of tree species that are associated to slow down the paludification process, such as hardwood species. So, only the type of vegetation related to the forest cover: hardwood, softwood and mixed was taken into account; (iii) variables that included information on forest fires, which strongly influence the dynamics of the boreal forest. For the study area, there was not much information on forest fires: due to environmental conditions in the Clay Belt, fires are not as frequent as in the eastern part of the study area, where environmental conditions are more prone to forest wildfires.

The type of vegetation related to the forest cover showed to be important in predicting the thickness of the organic layer, this may be because the interception implies that part of the precipitation falling on a given area is retained by the vegetation surface, causing a decrease in the amount of water reaching the soil (Bonan et al., 1989).

Climatic variables, especially mean maximum temperature and total precipitation, were moderately important in OLT prediction. In our study area, we observe higher precipitation in the eastern part than in the Clay belt (west) Figure 2.8, as was also observed by Henneb et al (2020). However, in the Clay belt the drainage class is slow, but the precipitation is lower. At the same time, we observed that the low values of organic layer thickness in the whole area <40 cm are found in the areas with higher total precipitation as in the east. We also note that the mean maximum temperature was higher in the western part of the study zone than in the east (Figure 2.9). Although the effect of the variation of these variables in the warmer months has not been considered, it can influence the accumulation of the organic layer by evaporation. Solar radiation is the cause of water at the surface changing to the vapor state in a process known as evaporation. Plant transpiration is a similar process in which water is absorbed from the soil by the roots and transported by the stem to the leaves from where it passes - is transpired - in the form of water vapor to the atmosphere. once rainfall reaches the soil surface it can infiltrate, flow over the soil surface, and give way to waterlogging.

On the contrary, the aspect variable appeared to be the least important with respect to the others explained by the model. This result may agree with the fact that the direction of the slope (aspect) is not that important in the process of paludification. Most of the area under study was classified as flat surfaces, which is not surprising given the predominance of flat ground (Veillette, 1994).

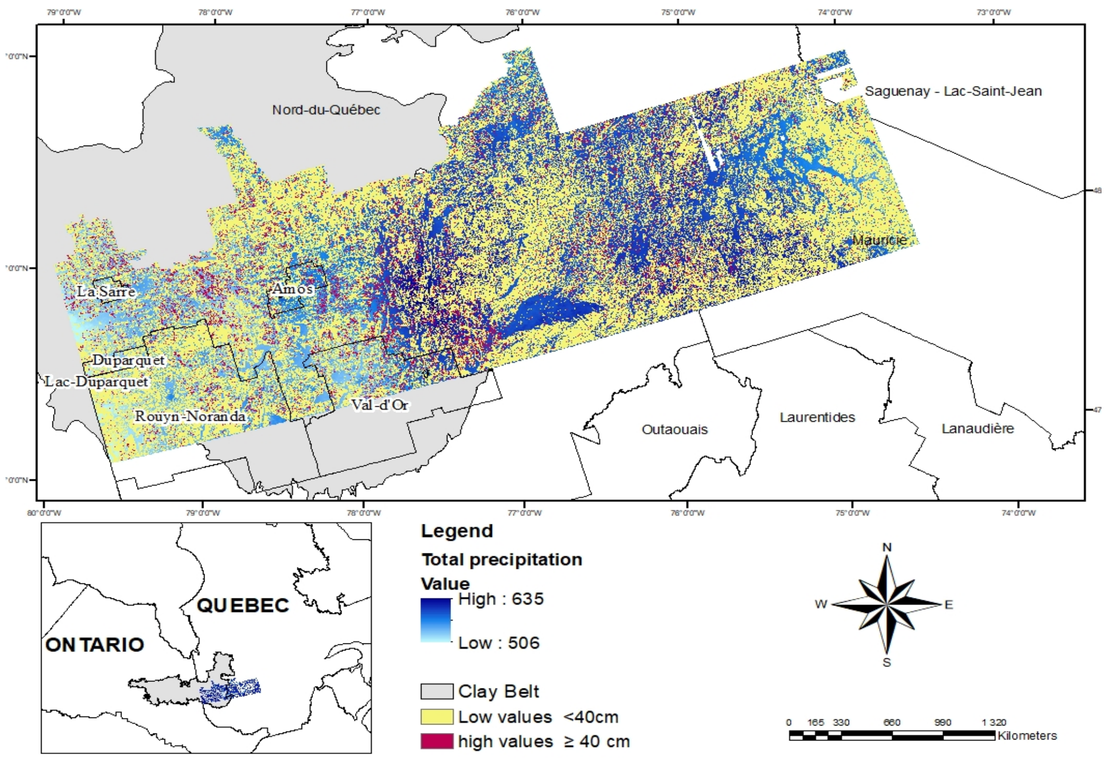

Figure 2.8 Total precipitation in mm for the study area

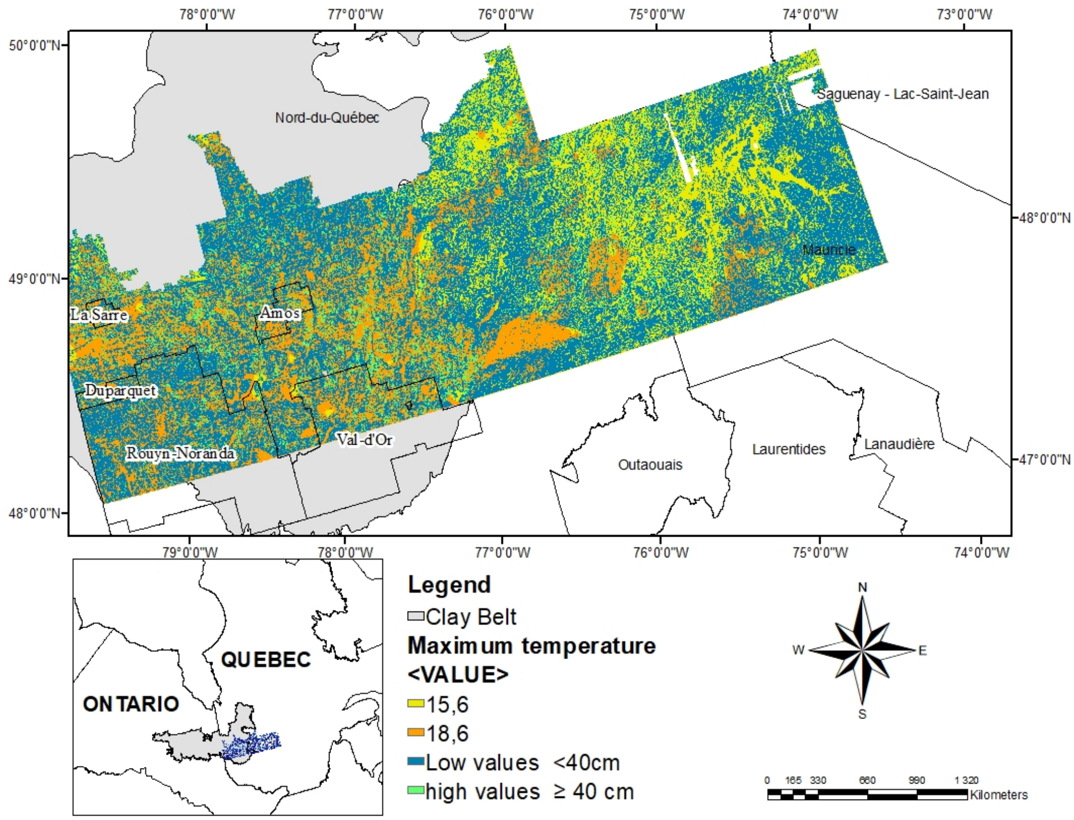

Figure 2.9 Mean maximum temperature in C° for the study area

2.4.2 Analysis of the spatial distribution of the organic layer thickness

Our results are consistent with the hypothesis that high and low OLT values are agglomerated. However, as mentioned in the results, the predominant type of our matrix are patches with < 40 cm OLT values throughout the study area. This can be explained by the fact that paludification is a slow process that depends on the interactions of abiotic and biotic factors and landscape patterns, such as natural depressions (e.g. reversible or permanent paludification). In some areas we observed that there is a permanent paludification, which spatially shows that patches are agglomerated because they have similar environmental characteristics and dominate in natural landscape depressions, and in other areas there is a reversible paludification, which spatially shows that patches are more dispersed throughout the study area because they occur over time following fire or mechanical land preparation. (Fenton et al., 2009, Lavoie et al., 2007, Simard et al., 2007). Finally, the patches of OLT <40 cm are less distant from each other, with a nearest-neighbor distance of 200 km, this shorter distance is consistent with their higher percentage of aggregation.

2.4.3 Relationships among the variables that influence the organic layer thickness

According to our analyses, the path analysis has allowed us to test the hypothesis that OLT is directly influenced by abiotic and biotic factors, and that biotic factors are also influenced by abiotic factors. This means that the abiotic and biotic factors and the OLT are interdependent and that their interaction is determinant; if one variable among these factors is removed or modified, it will affect the whole process. For example, climate is an important variable; in cases of high precipitation, the temperature decreases, and water accumulates in the soil causing waterlogging, mainly in the plains where clayey soils predominate making drainage slow. On paludified sites, the drainage class is significantly correlated with OLT; this variable has an indirect influence on the process of paludification because flat areas, topography and poor drainage are the main drivers of the paludification process (≥ 40 cm) (Mansuy et al., 2018). In contrast to previous studies, the aspect variable did not show high significance in the interaction with other variables and OLT.

In general, we can conclude that random forests produce better results than path analysis, because although path analysis (based on multiple linear regression) allows examining the interaction of a set of variables on multiple dependent variables, RF can reproduce complex non-linear relationships with enough input data, thus they work well with large datasets. However, they pose a major challenge in that they cannot extrapolate away from unseen data. Also, one disadvantage of the RF compared to regression methods is that only gives you a prediction, it doesn't show the positive or negative of each variable. In our study we had a large database with information on climate and OLT variables; topographic and vegetation type information over a large area that the RF regression method showed an acceptable result for the prediction model at a resolution of 10 meters.

2.4.4 Implications for forest management

The purpose of the current study was to increase the precision of mapping of OLT distribution in space by considering the interaction between the variables among the factors. This will allow paludification to be linked with forest productivity in a future project. Fine-scale OLT mapping, at 10-m resolution, is another step-in helping foresters and land managers to mitigate the high risk of paludification and increase tree productivity. Our results coincide with those previously reported by Laamrani et al. (2015). Those authors have mapped paludified areas in northwestern Quebec by incorporating LiDAR measurements of the topography at 10-m and 30-m resolution on a much smaller study area than ours (7.5 km2, 180 000 km^2 versus 302 000 km^2).

From the point of view of management implications, the results of this study are important for landscape management for several reasons. We have better understood that topographic variables are related to OLT accumulation such as drainage class, elevation, and slope, which is an important step towards forecasting and mapping productivity through paludification of landscapes. This finding would be particularly useful for implementing sustainable management strategies in paludified boreal forests that consider the importance of topographic variables. For example, forest managers can make decisions based on the OLT map where the patches are visible, and they can identify the areas more susceptible to paludification, with high values of OLT ($\geq$ 40cm), to determine what treatments are needed to mitigate this process, such as regeneration following a mechanical site treatment.

2.5 Conclusion

This study allowed us to map an area of 302 000 km^2 at a resolution of 10 meters using the RF prediction model for the organic layer thickness. The RF had an acceptable proportion of variance explained with R2: 52%, and corroborated that topographic variables, type of vegetation and climatic variables were the main drivers of the paludification process. Also, we can conclude that the 6700 patches of OLT values <40 cm are agglomerated. This occurs because neighboring locations in the study area have similar conditions due to the abiotic factors controlling paludification. These low OLT patches also have a smaller distance between them compared with high OLT patches. Finally, we were able to confirm the interaction of the study variables. Principally, the topographic variables included in the abiotic factor are the most important influencing the process of paludification in the boreal forests of northwestern Quebec.

CHAPTER III

GENERAL CONCLUSION

This study aimed to observe the interactions between the topographic, climatic and vegetation type variables of abiotic and biotic factors that influence the spatial distribution of paludification using remote sensing tools. We determined that the inclusion of all the variables and their interactions that influence this process determine a spatial distribution agglomerated by the short distance between OLT patches and by the similar conditions that represent. These tools allowed us to create a numerical terrain model using LiDAR and other environmental variables. Therefore, the combination of topographic information from remotely sensed LiDAR data is a useful tool to define promising and vulnerable areas for forest management, including areas prone to paludification. Also, we were able to develop a predictive model using the RF classification model where we obtained a 10 m resolution map of the areas that will be prone to this process. In addition, with this study we were able to quantitatively characterize our study area using Fragstats software, where we obtained that the predominant matrix type were the OLT values < 40 cm with 6700 patches, and that OLT values ≥ 40 cm with 2600 patches are within this matrix. These various analyses of paludification at the regional level allowed us to distinguish the spatial patterns of OLT and that the risk of paludification was much more marked towards the northwest of the study area than in the east. Although more accurate and reliable predictive models could be developed in the future using high-resolution data, this study clearly underlines the potential of remote sensing tools, mainly LiDAR, in the field of predictive modeling of organic layer thickness

REFERENCES

Aminzadeh, B. et Khansefid, M. (2010). A case study of urban ecological networks and a sustainable city: Tehran's metropolitan area. *Urban ecosystems*, *13*(1), 23-36.

Banerjee, I. et McDonald, B. C. (1975). Nature of esker sedimentation.

Barto, E. K., Alt, F., Oelmann, Y., Wilcke, W. et Rillig, M. C. (2010). Contributions of biotic and abiotic factors to soil aggregation across a land use gradient. *Soil Biology and Biochemistry*, *42*(12), 2316-2324.

Bergeron, Y., Drapeau, P., Gauthier, S. et Lecomte, N. (2007). Using knowledge of natural disturbances to support sustainable forest management in the northern Clay Belt. *The Forestry Chronicle*, *83*(3), 326-337.

Boudreault, C., Bergeron, Y., Gauthier, S. et Drapeau, P. (2002). Bryophyte and lichen communities in mature to old-growth stands in eastern boreal forests of Canada. *Canadian Journal of Forest Research*, *32*(6), 1080-1093.

Breiman, L. (2001). Random forests. *Machine learning*, *45*(1), 5-32.

Cardinael, R., Chevallier, T., Barthès, B. G., Saby, N. P., Parent, T., Dupraz, C., . . . Chenu, C. (2015). Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon—A case study in a Mediterranean context. *Geoderma*, *259*, 288-299.

Cerrejón, C., Valeria, O., Mansuy, N., Barbé, M. et Fenton, N. J. (2020). Predictive mapping of bryophyte richness patterns in boreal forests using species distribution models and remote sensing data. *Ecological Indicators*, *119*, 106826.

Crawford, R., Jeffree, C. et Rees, W. (2003). Paludification and forest retreat in northern oceanic environments. *Annals of botany*, *91*(2), 213-226.

Crespin, P. (2014). *Dynamique holocène de la paludification des forêts de la ceinture d'argile*. Université du Québec en Abitibi-Témiscamingue.

Dionne, J.-C. (2011). *Troisième bibliographie sur le glaciel couvrant principalement la période de 1974 à 2010* Département de géomatique appliquée, Université de Sherbrooke.

Dirksen, J. W. (2013). *Modelling presence of swamp forest and forest dwelling birds in a boreal forest reserve using airborne laser scanning*. Doctoral Dissertation. Norwegian University of Life Sciences, Department of ….

Eberl, D. (1984). Clay mineral formation and transformation in rocks and soils. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *311*(1517), 241-257.

Environment Canada, 2010. https://climate.weather.gc.ca/climate_normals/ (accessed 11 March 2020).

Fenton, Bergeron, Y. et Paré, D. (2010). Decomposition rates of bryophytes in managed boreal forests: influence of bryophyte species and forest harvesting. *Plant and soil*, *336*(1-2), 499-508.

Fenton, Simard, M. et Bergeron, Y. (2009). Emulating natural disturbances: the role of silviculture in creating even-aged and complex structures in the black spruce boreal forest of eastern North America. *Journal of Forest Research*, *14*(5), 258-267.

Fenton, N., Lecomte, N., Légaré, S. et Bergeron, Y. (2005). Paludification in black spruce (Picea mariana) forests of eastern Canada: potential factors and management implications. *Forest Ecology and Management*, *213*(1-3), 151-159.

Fenton, N. J. et Bergeron, Y. (2006). Facilitative succession in a boreal bryophyte community driven by changes in available moisture and light. *Journal of Vegetation Science*, *17*(1), 65-76.

Forman, R. T. (1995). Some general principles of landscape and regional ecology. *Landscape ecology*, *10*(3), 133-142.

Franklin, J. (1995). Predictive vegetation mapping: geographic modelling of biospatial patterns in relation to environmental gradients. *Progress in physical geography*, *19*(4), 474-499.

Garson, G. D. (2013). *Path analysis* Statistical Associates Publishing Asheboro, NC.

Gauthier, S., Bernier, P., Kuuluvainen, T., Shvidenko, A. et Schepaschenko, D. (2015). Boreal forest health and global change. *Science*, *349*(6250), 819-822.

Gislason, P. O., Benediktsson, J. A. et Sveinsson, J. R. (2006). Random forests for land cover classification. *Pattern recognition letters*, *27*(4), 294-300.

Guisan, A. et Thuiller, W. (2005). Predicting species distribution: offering more than simple habitat models. *Ecology letters*, *8*(9), 993-1009.

Guisan, A. et Zimmermann, N. E. (2000). Predictive habitat distribution models in ecology. *Ecological modelling*, *135*(2-3), 147-186.

Henneb, M., Valeria, O., Fenton, N. J., Thiffault, N. et Bergeron, Y. (2015). Mechanical site preparation: Key to microsite creation success on Clay Belt paludified sites. *The Forestry Chronicle*, *91*(2), 187-196.

Henneb, M., Valeria, O., Thiffault, N., Fenton, N. J. et Bergeron, Y. (2019). Effects of mechanical site preparation on microsite availability and growth of planted black spruce in Canadian paludified forests. *Forests*, *10*(8), 670.

Jenny, H. (1941). Factors of soil formation. 281 pp. *New York*.

Keymer, J. E., Marquet, P. A., Velasco-Hernández, J. X. et Levin, S. A. (2000). Extinction thresholds and metapopulation persistence in dynamic landscapes. *The American Naturalist*, *156*(5), 478-494.

Kursa, M. B. et Rudnicki, W. R. (2010). Feature selection with the Boruta package. *J Stat Softw*, *36*(11), 1-13.

Laamrani, A. et Valeria, O. (2020). Ranking Importance of Topographical Surface and Subsurface Parameters on Paludification in Northern Boreal Forests Using Very High Resolution Remotely Sensed Datasets. *Sustainability*, *12*(2), 577.

Laamrani, A., Valeria, O., Bergeron, Y., Fenton, N. et Cheng, L. Z. (2015). Distinguishing and mapping permanent and reversible paludified landscapes in Canadian black spruce forests. *Geoderma*, *237*, 88-97.

Laamrani, A., Valeria, O., Fenton, N. et Bergeron, Y. (2014). Landscape-scale influence of topography on organic layer accumulation in paludified boreal forests. *Forest Science*, *60*(3), 579-590.

Laamrani, A., Valeria, O., Fenton, N., Bergeron, Y. et Cheng, L. Z. (2014). The role of mineral soil topography on the spatial distribution of organic layer thickness in a paludified boreal landscape. *Geoderma*, *221*, 70-81.

Lavoie, M. (2005). *Paludification and Forest Management in the Northern Clay Section: A Literature Review* Lake Abitibi Model Forest.

Lavoie, M., Filion, L. et Robert, É. C. (2009). Boreal peatland margins as repository sites of long-term natural disturbances of balsam fir/spruce forests. *Quaternary Research*, *71*(3), 295-306.

Lavoie, M., Paré, D., Fenton, N., Groot, A. et Taylor, K. (2005). Paludification and management of forested peatlands in Canada: a literature review. *Environmental reviews*, *13*(2), 21-50.

Liaw, A. et Wiener, M. (2002). Classification and regression by randomForest. *R news*, *2*(3), 18-22.

Lopez, B. R. et Bacilio, M. (2020). Weathering and soil formation in hot, dry environments mediated by plant–microbe interactions. *Biology and Fertility of Soils*, *56*(4), 447-459.

Mallet, C. et David, N. (2016). Digital terrain models derived from airborne lidar data. Dans *Optical Remote Sensing of Land Surface* (p. 299-319). Elsevier.

Mansuy, Gauthier, S., Robitaille, A. et Bergeron, Y. (2011). The effects of surficial deposit–drainage combinations on spatial variations of fire cycles in the boreal forest of eastern Canada. *International Journal of Wildland Fire*, *19*(8), 1083-1098.

Mansuy, Thiffault, E., Paré, D., Bernier, P., Guindon, L., Villemaire, P., . . . Beaudoin, A. (2014). Digital mapping of soil properties in Canadian managed forests at 250 m of resolution using the k-nearest neighbor method. *Geoderma*, *235*, 59-73.

Mansuy, N., Valeria, O., Laamrani, A., Fenton, N., Guindon, L., Bergeron, Y., . . . Légaré, S. (2018). Digital mapping of paludification in soils under black spruce forests of eastern Canada. *Geoderma Regional*, *15*, e00194.

McBratney, A. B., Santos, M. M. et Minasny, B. (2003). On digital soil mapping. *Geoderma*, *117*(1-2), 3-52.

McGarigal, K. et Cushman, S. A. (2002). Comparative evaluation of experimental approaches to the study of habitat fragmentation effects. *Ecological applications*, *12*(2), 335-345.

Ménard, S., Darveau, M., Imbeau, L. et Lemelin, L.-V. (2006). Méthode de classification des milieux humides du Québec boréal à partir de la carte écoforestière du 3 e inventaire décennal. *Québec, Canards Illimités Canada*.

Mesenbet, Y. S. (2014). Water balance of the Juba and Shabelle Rivers in Ethiopia-Somalia. *International Research Journal of Agricultural Science and Soil Science*, *4*(4), 65-75.

Morgan, J., Knight, W., Dudley, L. et Hunt, H. (1994). Enhanced root system C-sink activity, water relations and aspects of nutrient acquisition in mycotrophic Bouteloua gracilis subjected to CO 2 enrichment. Dans *Belowground Responses to Rising Atmospheric CO2: Implications for Plants, Soil Biota, and Ecosystem Processes* (p. 139-146). Springer.

Paradis, Y. (2006). *Facteurs déterminant la répartition spatiale et l'abondance des stades larvaire et juvénile de la perchaude dans l'écosystème fluvial du Lac Saint-Pierre (Québec)*. Université du Québec à Trois-Rivières.

Prescott, C. E., Maynard, D. G. et Laiho, R. (2000). Humus in northern forests: friend or foe? *Forest ecology and management*, *133*(1-2), 23-36.

Pryor, W. A. (1973). Permeability-porosity patterns and variations in some Holocene sand bodies. *AAPG Bulletin*, *57*(1), 162-189.

Rosseel, Y. (2012). Lavaan: An R package for structural equation modeling and more. Version 0.5–12 (BETA). *Journal of statistical software*, *48*(2), 1-36.

Sánchez Lopera, J. et Lerma García, J. L. (2012). Actualización de cartografía catastral urbana mediante LiDAR y SIG. *GeoFocus*, *12*, 53-70.

Silva, A. (1998). La materia orgánica del suelo. *Montevideo: Facultad de Agronomía. 34p*.

Southee, F. M., Treitz, P. M. et Scott, N. A. (2012). Application of Lidar terrain surfaces for soil moisture modeling. *Photogrammetric Engineering & Remote Sensing*, *78*(12), 1241-1251.

Straková, P., Penttilä, T., Laine, J. et Laiho, R. (2012). Disentangling direct and indirect effects of water table drawdown on above-and belowground plant litter decomposition: consequences for accumulation of organic matter in boreal peatlands. *Global Change Biology*, *18*(1), 322-335.

Team, R. (2018). *Core. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2014*.

Tremblay, S., Périé, C. et Ouimet, R. (2006). Changes in organic carbon storage in a 50 year white spruce plantation chronosequence established on fallow land in Quebec. *Canadian journal of forest research*, *36*(11), 2713-2723.

Veillette, J. (1994). Evolution and paleohydrology of glacial lakes Barlow and Ojibway. *Quaternary Science Reviews*, *13*(9-10), 945-971.

Vijayakumar, D. B. I. P., Raulier, F., Bernier, P. Y., Gauthier, S., Bergeron, Y. et Pothier, D. (2015). Lengthening the historical records of fire history over large areas of boreal forest in eastern Canada using empirical relationships. *Forest Ecology and Management*, *347*, 30-39.

Vincent, J.-S. et Hardy, L. (1977). L'évolution et l'extension des lacs glaciaires Barlow et Ojibway en territoire québécois. *Géographie physique et Quaternaire*, *31*(3-4), 357-372.

Yi, S., McGuire, A. D., Kasischke, E., Harden, J., Manies, K., Mack, M. et Turetsky, M. (2010). A dynamic organic soil biogeochemical model for simulating the effects of wildfire on soil environmental conditions and carbon dynamics of black spruce forests. *Journal of Geophysical Research: Biogeosciences*, *115*(G4).

Yu, Z. (2012). Northern peatland carbon stocks and dynamics: a review. *Biogeosciences*, *9*(10), 4071-4085.