University of São Paulo
“Luiz de Queiroz” College of Agriculture

Analysis of the vertical canopy structure in native forest fragments and *Eucalyptus*
plantations to detect edge effects

Thaís Hudari Abib

Dissertation presented to obtain the degree of Master in
Science. Area: Forest Resources. Option in: Silviculture
and Forest Management

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2018

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**Analysis of the vertical canopy structure in native forest fragments and *Eucalyptus*
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DEDICATION

To the reader, by Thaís Hudari Abib.

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RESUMO

Análise da estrutura vertical do dossel em fragmentos de florestas nativas e plantações de *Eucalyptus* para detectar efeitos de borda

Há uma gama de pesquisas detalhadas sobre efeitos de borda usando dados de campo em escalas locais. No entanto, a literatura científica carece de trabalhos que visem compreender suas características em fragmentos florestais utilizando escalas maiores. Além disso, poucos estudos levaram em conta as influências que cada fragmento da paisagem impõe sobre seu vizinho. Uma vez que processos biológicos ligados à fragmentação e degradação geralmente se iniciam pelas bordas e influenciam a dinâmica das comunidades florestais, estudos sobre efeitos de borda são cruciais para o desenvolvimento de planos de manejo e conservação. Tecnologias lidar têm sido usadas em diversos estudos sobre a estrutura de florestas, mas poucos trabalhos investigaram efeitos de borda. Esta dissertação apresenta duas aplicações distintas do lidar para o estudo de bordas criadas pelo homem em diferentes cenários e ecossistemas. No primeiro estudo, efeitos de borda em plantios comerciais de eucalipto e fragmentos de Mata Atlântica, no Estado de São Paulo, foram avaliados por meio da quantificação das diferenças na altura e densidade do sub-bosque na vegetação da borda vs. interior. Buscou-se também compreender as influências que cada tipo de fragmento adjacente (eucalipto, floresta nativa ou pasto) impõe sobre a vegetação vizinha. Os efeitos de borda, em termos de altura e densidade do sub-bosque, em fragmentos de vegetação nativa adjacentes aos plantios de eucalipto e vice-versa foram mais atenuados do que próximo às pastagens. Os resultados indicaram que a proteção de florestas nativas em áreas de silvicultura além de favorecer a manutenção de serviços ecossistêmicos locais (provisão e manutenção do fluxo de água, diversidade de espécies da flora e fauna, controle natural de pragas etc.) poderia ajudar a manter a homogeneidade dos talhões devido à sua capacidade de minimizar os efeitos de borda. Esta proteção poderia favorecer a ocorrência de eucaliptos de borda mais semelhantes aos de interior. No segundo estudo, foram abordados efeitos de borda causados pela abertura de linhas sísmicas durante o processo de exploração de gás e petróleo em áreas de Floresta Boreal, na região central de Alberta. Além da quantificação dos efeitos da distância das linhas sísmicas na altura e cobertura arbórea da vegetação vizinha, foram avaliadas as interações entre tais variáveis e fatores de crescimento primário da vegetação relacionados a posição topográfica, radiação e superfície geológica. Os resultados mostraram que variações significativas na estrutura da vegetação adjacente à borda da floresta ocorrem próximas às linhas sísmicas, incluindo altura e cobertura arbórea reduzidas. Análises por meio de florestas aleatórias (random forest) revelaram que a distância da linha sísmica, a radiação incidente e o potencial de acumulação de água superficial (inferida a partir do índice de posição topográfica) são as variáveis mais importantes para predição de altura e cobertura arbórea. No geral, o lidar se mostrou uma ferramenta robusta para avaliar as dimensões espaciais e ecológicas dos efeitos de borda em diferentes cenários. Com isso em mente, estratégias de manejo e conservação

para áreas fragmentadas poderiam se beneficiar desta tecnologia para redução do impacto de efeitos de borda nos ecossistemas.

Palavras-chave: Efeito de borda; Métricas lidar; Floresta Atlântica; Floresta Boreal; Plantações de eucalipto

ABSTRACT

Analysis of the vertical canopy structure in native forest fragments and *Eucalyptus* plantations to detect edge effects

There is a range of detailed research on edge effects using field data at local scales. However, the scientific literature lacks studies that aim to understand its characteristics in forest fragments using larger scales. Also, few works have considered the influences that each fragment of the landscape imposes on its neighbour. Since biological processes linked to fragmentation and degradation commonly start at edges and influence the dynamics of forest communities, studies on edge effects are crucial for the development of management and conservation plans. Lidar technologies have been used in several studies on forest structure, but few have investigated edge effects. This dissertation presents two distinct applications of lidar for studying anthropogenic-caused edges in different scenarios and ecosystems. In the first study, edge effects in commercial *Eucalyptus* plantations and fragments of the Atlantic Forest, located in the State of São Paulo, were evaluated by quantifying the differences in height and understory density in the edge vegetation vs core. We also sought to understand the influences that each type of adjacent fragment (*Eucalyptus*, native forest or pasture) imposes on the neighbouring vegetation. Edge effects, regarding height and understory density, on fragments of native vegetation adjacent to *Eucalyptus* plantations and vice-versa were more attenuated than nearby pastures. The results indicated that the protection of native forests in silviculture areas besides favouring the maintenance of local ecosystem services (provision and maintenance of water flow, diversity of flora and fauna species, natural pest control, etc.) could help maintain the homogeneity of the stands due to their ability to minimise edge effects. This protection could favour the occurrence of border *Eucalyptus* more similar to the ones in the core. In the second study, edge effects caused by seismic lines, i.e. corridors cut through the forest during the process of exploration of gas and oil, in areas of Boreal Forest in the central region of Alberta is addressed. Besides quantifying the effects of distance from seismic lines over height and fractional cover on the neighbouring vegetation, the interactions between these variables and primary vegetation growth factors related to the topographic position, incident radiation and surface geology were evaluated. The results showed that significant changes in vegetation structure adjacent to forest edge occur close to seismic lines, including reduced tree height and cover. Random Forest analyses revealed that the distance from the seismic line, incident radiation and surface water accumulation potential (inferred from the topographic position index) are the most critical variables for height and fractional cover prediction. Overall, lidar proved to be a robust tool for assessing the spatial and ecological dimensions of edge effects in different scenarios. With this in mind, management and conservation strategies for fragmented areas could benefit from this technology to reduce the impact from edge effects on ecosystems.

Keywords: Edge effect; Lidar metrics; Atlantic Forest; Boreal Forest; *Eucalyptus* plantations

1. INTRODUCTION

Humans have always been dependent on the world's forests and the global environment mainly for the acquisition of raw materials, food, water and energy. Since the beginning of time, they have changed large areas of the Earth. In the early 21st century, they were responsible for modifying in some degree 75% of the Earth ice-free land, being that approximately two-thirds of these areas had their native vegetation completely converted into anthropogenic land uses (Watson et al., 2016). Because of these global land conversion process, a vast area of fragmented native vegetation can be found across the globe.

Activities such as agriculture, livestock, logging and the exploitation of fossil fuels represent different types of land use responsible for the fragmentation of natural vegetation cover and the formation of a mosaic of natural areas adjacent to the production areas, forming patches of irregular geometry (Figure 1). Each patch is inserted into the landscape matrix forming an extensive network of connections. Patches can represent forest remnants, one of the basic units used in the investigation of spatial patterns of ecological phenomena at the landscape level (Gurevitch et al., 2009).

Figure 1. Different landscape boundaries. a) Forest fragments of the Brazilian Atlantic Forest in the North-East of Brazil surround by sugar cane plantations. b) Atlantic Forest fragments nearby pasture fields. c) *Eucalyptus* plantations adjacent to Atlantic Forest fragments. d) Roads created by the exploitation of oil and gas deposits in the Boreal Forest. Images source: Mateus de Dantas de Paula; Dianes G. Marcelino; Clio Luconi and Natural Resources Canada (NRCAN).

Given the need for conservation and wise management of forests and resources in a scenario involving increasing rates of fragmentation, the role of forest ecology becomes increasingly important. The knowledge of ecosystem components and processes combined with the development of tools to describe the ecological variability of forested landscapes, and predict the response of ecosystems to human-caused disturbances will define future strategies for the management of forests.

Historically, much of the early studies in forest ecology aimed at relatively small spatial scales (Forman, 1995). The usual thinking was frequently focused on scales of individual plant growth, relationships between plants and physiological aspects (Forman, 1995). Not long ago, the science of forest ecology has considered studying patterns and processes at larger spatial scales, here referred to as landscape-level studies (Forman, 1995).

A landscape is a mosaic where the mix of local ecosystems or land uses is repeated in similar form over a kilometers-wide area (Forman, 1995). Familiar examples are forested, suburban, cultivated, and dry landscapes. Across the area within a landscape, distinct characteristics tend to be similar and repeated, such as vegetation types, soil types, natural or human disturbances, land uses, etc. Thus, the landscape concept integrates a focus on a) spatial pattern, b) the area viewed from a high point on the land, and c) unity provided by repeated pattern (Forman, 1995).

Landscape-level studies often make use of the so-called landscape ecology, whose origins are rooted in biogeography, i.e. the study of the effects of the physical environment on broad vegetation patterns (Troll, 1939).

Ecology is generally defined as the study of the interactions among organisms and their environment (Forman, 1995). Landscape ecology is an area of knowledge that emphasises the relevance of spatial context on ecological processes, and the importance of these relationships regarding biological conservation (Metzger, 2001). The definitions of landscape ecology vary according to the authors. It can be understood as: the study of the structure, function and dynamics of heterogeneous areas composed by interactive ecosystems (Forman and Godron, 1986); an area of knowledge that emphasizes broad spatial scales and the ecological effects of the pattern of spatial distribution of ecosystems (Turner, 1989); a way of considering environmental heterogeneity in spatially explicit terms (Wiens et al., 1993); or research into the structure and functioning of ecosystems on the landscape scale (Pojar et al., 1994).

Regardless of the definition chosen, the focus of landscape ecology analysis is the recognition of the existence of spatial dependence between landscape units, i.e. that the functioning of a unit depends on the interactions it maintains with neighboring units (Metzger, 2001). Thus, landscape ecology applications concerned with the management of spatial heterogeneity, such as that caused by land use change is relevant to forest resource management plans.

1.1. Fragmentation and edges

The fragmentation of natural forest cover in the landscape is an omnipresent phenomenon, (i) with approximately 20% of all remaining forest on the planet found within 100 m of a border, (ii) 50% within 500 m, and (iii) 70% within 1 km (Haddad et al., 2015). Different types of forests around the world are suffering from fragmentation events.

For example, in the Atlantic Forest the majority of fragments are experiencing arrested succession after a range of disturbances (Tabarelli and Gascon, 2005), including selective logging, recurrent fires, cattle grazing, hunting, biological invasions, pollution and severe edge effects (Metzger, 2000; Tabanez and Viana, 2000). Several changes in its plant communities are related to this fragmentation process. Over the short-term, local changes have been reported such as favouring colonization of the canopy by hyperabundant lianas (Laurance et al., 2006) and by pioneer tree species in habitat edges (Laurance et al., 2006; Lôbo et al., 2011); an increase in the levels of floristic homogenization (reduced β -diversity) (Arroyo-Rodríguez et al., 2014); invasion by exotic species (Tabarelli et al., 1999; Benítez-Malvido and Martínez-Ramos, 2003); increase on the vulnerability to extinction in species with low dispersal ability, small population sizes, and specialization to restricted habitats (Henle et al., 2004). Additionally, over the long-term, ecological processes such as pollination, seed dispersal, plant recruitment and animal dispersal throughout the landscape can be strongly affected by fragmentation (Rozza et al., 2007; Guimarães et al., 2008; Lenz et al., 2011).

Another example is the Boreal Forest where industrial activities including logging, mining, hydroelectric development, and oil and gas projects are causing severe impacts on the local ecosystems. There the habitat loss caused by the fragmentation is producing population declines of certain endemic species, such as the woodland caribou (*Rangifer*

tarandus), given the greater number of predators at edges (Bender et al. 1998). Besides that, an increased mortality of trees, ground herbs, and epiphytic lichens at edges have been reported (Schmiegelow and Monkkonen, 2002).

In both cases, the increasing fragmentation of the natural vegetation cover imposed by activities related to the exploitation of natural resources has increased the number of units of the landscape and, consequently, the occurrence of contact regions between patches, called edges (Ries et al., 2004).

A critical comment on edges is that judging them only by the edge's word connotation of line, with different conditions on each side, can commonly lead to a misunderstanding of its ecological meaning. An edge is indeed a boundary, an area of transition, or a gradient between different types of patches.

In a world that is frequently creating edges and regarding that several phenomena are responsible for these creations, if something like an edge taxonomy study field existed, we could be able to classify these edges as natural or anthropogenic-caused. In origin, most edges are anthropogenic (e.g., forestry, agriculture, urbanisation). However, we must not forget that edges are also created due to natural disturbances (e.g., fire, insect outbreaks, windthrow) or natural landscape heterogeneity (e.g., barriers segregating natural vegetation areas such as mountains or lakes).

Additionally, three dimensions of an edge are essential for understanding both its anatomy and functioning, varying widely and influencing nearby ecosystems: a) width between the border and interior, b) vertical including height and stratification, and c) length along the boundary (Forman, 1995).

Also, edges can be identified both qualitatively and quantitatively as transitions between spatially adjacent locations where a key variable (e.g., photosynthetically active radiation, vegetation structure, community composition) shows high levels of contrast (Fortin et al., 2000).

Edge studies are fundamental since the biological processes associated with fragmentation and degradation are mostly initiated by the edge of the fragments, which directly influences the dynamics of forest communities. Thus, the increase of border regions in a landscape is worrisome because of the broad impact of edges on local physical characteristics, flora, and fauna (Wulder et al., 2009).

1.2. Edge effects

Because of edges, marked changes can be observed in the contact regions between forest fragments, known as edge effects (Murcia, 1995; Dantas De Paula et al., 2016). The definition of edge effects can be found in several sources in the literature: generalist books on ecology (Forman and Godron, 1986), scientific reviews (Murcia, 1995; Cadenasso et al., 2003; Ries et al., 2004) and practical guidelines for forest management (Snoeck and Baar, 2001; Gosselin, 2008). In general, edge effects are presented according to a hypothetical spatial pattern that establishes two zones. The core-edge pattern defines an edge zone in which flora and fauna characteristics (e.g., richness, abundance, and composition) vary primarily according to the edge distance, and a core zone where such changes are explained by other factors and not more due to distance from the edge (Alignier and Deconchat, 2011).

Therefore, it is particularly important that edge effects studies identify core, edge, and edge influence habitats (Harris, 1998). Harper and collaborators (2005) define core or interior habitat as a “patch formed by the interior of the forest and outside the zone of edge influence (EI)”. In contrast, EI is the habitat where “the effect of processes (both abiotic and biotic) on the edge results in marked differences in composition, structure, or near-edge function, when compared to neighbouring ecosystems”; and edge would be “the interface between different types of ecosystems” (Harper et al., 2005). Figure 2 illustrates interior/core, edge/border and edge influence habitats of a forest fragment nearby a field.

Figure 2. Relationships between forest interior, edge influence habitat and border of a native fragment nearby a field. Adapted from Forman and Moore (1992).

The effects that the creation of an edge can cause in forest remnants are innumerable, including abiotic effects, involving changes in the physical environment, mainly microclimate (temperature, air humidity, solar radiation, modification of the winds) (Kapos,

1989); and biotic effects, involving changes in populations and community, which may be direct (change in abundance and distribution of species according to edge tolerance) or indirect (changes in the interaction between species, such as predation, parasitism, others) (Murcia, 1995). Areas within the zone of edge influence have been shown to be more susceptible to invasion by exotic species, changes in biodiversity, and climate stress (Harper et al., 2005; Campbell et al., 2009).

Considering that the landscape exists as a mosaic formed by different types of patches, the understanding of edge effects also requires understanding the influences that each adjacent patch imposes on its neighbour. As patches become smaller and more irregular in shape, edge areas predominate over core areas. In this context, the study of edge effects is critical for both landscape ecology and planning of large-scale management and conservation practices involving remnants of native forest adjacent to production areas (Ries et al., 2004).

Because of their importance and ubiquity, edge effects have been extensively researched in ecology. The literature covers several topics including edge identification and measurement (Fortin, 1994; Choesin and Boerner, 2001; Fagan et al., 2003); the impact of edges on species migration (Ries and Debinski, 2001; Schtickzelle and Baguette, 2003); species richness in edge versus interior areas (Marchand and Houle, 2006); dissemination of plant species as weeds in edge environments (Honnay et al., 2002); differences in vegetation composition and structure (Oosterhoon and Kapelle, 2000), among others.

Specifically, for forest communities, edge effects have been studied in different scenarios, climates, and forest types: sub-tropical and tropical (Laurance et al., 1998, Didham and Lawton 1999, Prieto et al., 2014), temperate (Brothers and Spingarn, 1992; MacQuarrie and Lacroix, 2003), sub-boreal (Burton, 2002) and boreal forests (Harper et al., 2004; Gignac and Dale, 2007; Harper et al., 2015), and in different types of edges such as those caused by shallow cutting (Chen Jiquan et al., 1995; Burton, 2002; Dupuch and Fortin, 2013), produced by fire (Harper et al., 2004, 2014), close to lakes (Harper and Macdonald, 2001), plantations (Euskirchen et al., 2001), agriculture and pasture (Gehlhausen et al., 2000), and even linear disturbances such as gas pipelines and power lines (Prieto et al., 2014; Couto-Santos et al., 2015; Eldegard et al., 2015).

To cite some particular effects found in edges that have been described in a specific type of forest ecosystem, let's use as an example an important endangered biome found in Brazil, the Atlantic Forest. There changes such as impoverishment of tree species bearing

large seeds or large fleshy fruits, those pollinated by specialized biotic vectors, those with supra-annual reproduction and those with large adults (i.e. emergent tree species) were reported in edges, whereas a limited number of successional or pioneer taxa tend to proliferate in these habitats (Girão et al., 2007; Oliveira et al., 2008; Tabarelli et al., 2010a,b; Farah et al., 2014). Also, shorter trees (Oliveira et al., 2008), reduction in species richness (Oliveira et al., 2015) and increased density of the understory foliage (Faria, 2002) have been seen.

1.3. Edge effect analysis for forest management purposes

The type of methodology commonly used in edge effects studies involves the collection of field data and allocation of plots in transects, which may be parallel or perpendicular to the edge, distant at least 5 m apart, and extending to the centre part of the fragment (Figure 3).

In each transect, a series of variables can be collected or measured: temperature and relative air humidity, soil temperature and light intensity (Honnay et al., 2002), species richness (Euskirchen et al., 2001; Eldegard et al., 2015), diameter at breast height, covers of canopy, shrubs and herbaceous strata (Harper and Macdonald, 2001). Subsequently, the collected data are evaluated to verify the differences between their values along the core-edge gradient and thus estimate the edge influence distance, based on a given variable.

Figure 3. Examples of experimental designs commonly applied at edge effect studies. a) Placement of ten transects, each one 5 m wide. b) Plots set up at 0 m, 10 m, 25 m, 40 m, 55 m, 70 m and 85 m from the forest edge. c) Transect sampling using three circular plots at increasing distances from the forest edge (18, 54 and 90). Within each plot, four hemispherical plots were taken 9 m to the North, East, South and West from the plot centre. Source: adapted from Caruso et al. (2011); Arruda and Eisenlohr (2016), and Cayuela et al. (2009), respectively.

There is extensive research on edge effects using field studies at local scales (Cayuela et al., 2009; Caruso et al., 2011; Arruda and Eisenlohr, 2016). However, few studies (Santos et al., 2015; Dantas De Paula et al., 2016) focused on understanding the characteristics of edge effects in forest fragments using larger scales. Besides that, researches that also considered the influences that each adjacent patch imposes on its neighbour (Nascimento et al., 2010) are even more rare. For example, Nascimento and collaborators (2010) studied native forest fragments nearby a barrier formed by three rows of *Eucalyptus* along the edge of a subtropical semi deciduous forest fragment, surrounded by *Eucalyptus* monoculture. They showed that the barrier of *Eucalyptus* mitigated the microclimatic conditions along the edge of forest fragments and could be used as an effective method to minimize the impacts of mechanized forest harvesting operations.

Therefore, finding indicators for edge effect impacts can be crucial to developing management and conservation plans (Dantas De Paula et al., 2016). As the depth of edge influence is site-specific and can be very variable at short intervals of time and distance, estimating it on a landscape scale to identify core areas of the forest can be difficult in the absence of extensive field studies generally time-consuming and costly (MacLean, 2017).

1.4. Edge effect detection with laser remote sensing

Therefore, geographical information systems (GIS) and remote sensing techniques can be useful tools in the identification and evaluation of edge effects in both native and planted forest areas, generating results in a relatively short period and lower monetary investment when compared to field data collection.

GIS are computerised systems that overlay several sorts of spatially explicit information about an area, often a portion of a landscape (Tomlin, 1990). The information presented visually or graphically, may be stored in “raster” form, i.e., cell by cell (pixel by pixel) in a grid, or in “vector” form, i.e., at varying distances and directions from points.

Images from satellites have revolutionised our approaches to understanding landscapes (Forman, 1995). Some studies involving forest fragmentation and edge effects have already used satellite imagery as a source of information. Broadbent and collaborators (2008) utilised a 30-m resolution Landsat Enhanced Thematic Mapper Plus (ETM+) satellite imagery to generate deforestation and logging maps for their area of study. Another work evaluated the spatial and temporal dimensions of edge effects in large areas using LANDSAT Tree Cover (LTC) scenes with 30 m resolution (Dantas De Paula et al., 2016).

As the depth of the edge influence is often associated with local processes such as characterisation of the vertical and horizontal structure of the forest fragment studied, lidar (Light Detection and Ranging) technology can also be a useful tool for analysing edge effects at the landscape scale (MacLean, 2017).

Among remote sensing techniques, lidar has gained popularity in studies on forest structure. This popularity is due to its unique ability to directly estimate the 3D structural characteristics of trees with precision using the emission of laser pulses and reception of the return signals (Lim et al., 2003; Hyypä et al., 2008; White et al., 2016). Also, laser pulses can reach all layers of the vertical structure even in dense forests (Véga et al., 2016).

Lidar systems are based on the principle of constancy of light velocity and laser pulse range. The acronym laser means “amplification of light by stimulated emission of radiation” (Wehr and Lohr, 1999). The laser propagates as a coherent and unidirectional beam because it has a monochromatic characteristic, i.e. it has a well-defined wavelength (Baltsavias, 1999). The main wavelength used in lidar sensors is 1064 nm (near infrared) because of its high reflectance for vegetation. However, there are lidar systems that use other wavelengths, such

as 1550 nm (intermediate infrared) because of its water absorption capacity and 532 nm (near blue/green) for the study of bathymetric surfaces (Hopkinson et al., 2016).

The basic measurement made by a lidar device is the distance between the sensor and the target surface obtained by determining the time elapsed between the emission of a short-duration laser pulse and the arrival of the reflection of that pulse (return signal) at the receiver. Multiplying this time by the speed of light ($3 \times 10^8 \text{ m.s}^{-1}$) and dividing by two results in the estimated distance between the sensor and the target (Petrie and Toth, 2009).

Studies that involve the analysis of the vertical structure of forests in extensive areas make use of Airborne Laser Scanning (ALS), i.e. when the lidar sensor is boarded in an aircraft. The pieces of equipment that compose an ALS system are: a) laser emission and reception unit coupled to the aircraft; b) global positioning units (GPS) in the airplane and in the ground; c) inertial sensor coupled to the laser unit to measure airplane movements (rolling, pitch and yaw) and; d) a computer to control and store survey data (Reutebuch et al., 2005). A geographic coordinate collected through the global positioning equipment (e.g., GPS) present in the aircraft and the ground is attributed to each reflected point. The inertial measurement system (IMU) performs the x, y, and z corrections of the deviations caused by the aircraft's rolling, pitching and yaw movements. As a product of this set, we have the three-dimensional representation of the georeferenced ALS point cloud (Petrie and Toth, 2009).

Lidar technologies have been used in several studies on the structure of forests (Næsset, 1997; Coops et al., 2007; Zonete et al., 2010; Görgens et al., 2016; Palace et al., 2016), including characteristics of edges in forest fragments (Parker et al., 2001; Lefsky et al., 2002; Lesak et al., 2011; Stark et al., 2012), but few studies investigated the depth of the edge influence (dos Santos et al., 2015; MacLean, 2017) or took into account the type of neighbourhood in which the patch is inserted (Wasser et al., 2015), mainly at large scales.

Santos et al. (2015) tested a methodology for quantifying edge effects in degraded areas of the Amazon rainforest using lidar data. To refute or confirm the existence of an edge effect through the analysis of a lidar variable for height, the 95th percentile, data from lidar plots randomly allocated and distributed in different ranges of edge distance from 10 m to 540 m were compared to the core. It was observed the general tendency of the average height of the forest to increase from the edge to the interior.

Wasser and collaborators (2015) used lidar metrics such as the 70th percentile and crown cover percentage to quantify differences in the vegetation structure of riparian forests

in edge environments, according to the type of neighbouring soil. The methodology was based on the identification of sampling transects of 10 m wide by 200 m in length, and perpendicular to the watercourses using an automated algorithm. The results showed that forest cover is often smaller in fragments adjacent to developed areas (urban, commercial or agrarian) compared to undeveloped regions (open fields).

Another study made use of plots arranged every five meters along transects allocated in a Hemlock white pine forest in Petersham, MA, and perpendicular to the edge of an abandoned golf course (MacLean, 2017). Vertical canopy profiles derived from lidar data were used to determine the depth of edge influence. Distances estimated by lidar were not significantly different from those identified in field studies.

In all the mentioned studies, lidar proved to be efficient and sensitive to detect changes in forest height or cover at different edge widths, proving to be a tool with great potential to be used in studies evaluating edge effects.

1.5. Predictive lidar metrics of forest 3D structure

Metrics resulting from the lidar data processing can be used for various purposes such as characterisation of the vertical and horizontal structure of the studied area, parameterisation of the individual tree shape and generation of the digital terrain model (Zhang et al., 2017).

These metrics can be classified into four groups (Table 1): i) counting metrics, ii) elevation or height metrics, iii) return intensity metrics, and iv) topographic metrics (Görgens et al., 2014).

Counting metrics can be used to measure the quality of the point cloud, such as the uniformity of returns per square meter (spatial density of the cloud) (Görgens et al., 2014). Then, elevation or height metrics are those associated with the vertical positioning coordinates of the points in the clouds, such as the average elevation of the returns at a given location. Percentile metrics relate to a given height y in which x % of the total number of returns lie below y (Görgens et al., 2014). In turn, height metrics are divided into position categories (mean, mode, median, minimum, maximum, and percentile), dispersion (standard deviation and height variance), and proportion. This last category has utility in the study of the relationships between the strata of a particular forest, for example, the monitoring of the

understorey and canopy (Görgens et al., 2014). The metrics of the intensity group are related to the electromagnetic energy reflected by the different types of objects intercepted by the laser pulse and can be used, for example, to identify forest species (Görgens et al., 2014). Finally, topography metrics include information on slope, aspect (north, south, east, west) and solar radiation indexes based on the terrain exposure (Görgens et al., 2014).

For example, Melin and collaborators (2018) using lidar technology examined the edge effect on bird diversity and abundance, and the contributory role of vegetation structure. To achieve their goals, they applied lidar metrics of vegetation structure such as maximum and average canopy height and its standard deviation, proportion of vegetation above ground level (defined as > 0.5 m), proportion of vegetation at different height levels of the overstorey (canopy) and understorey (shrub) layers. Then, bird census data were combined with lidar data in mixed models fitted at the whole wood level vs the woodland edges only. Their results showed that bird diversity was maximised by a diverse vegetation structure across the wood and especially a dense understorey along the edge.

Table 1. Acronyms of the most common lidar metrics.

Group	Subgroup	Metric	Description
Count	-	hC.{1}.{2}	Count of points between heights {1} and {2}
Elevation or Height	Position	hMean	Average height of returns
		hMin	Minimum height of returns
		hMax	Maximum height of returns
		avgMaxH	Average maximum height, calculated from the canopy height model of each pixel height
		hQ{1...99}	Height percentiles
	Dispersion	hSd	Height standard deviation
		hSkew	Skewness of the distribution of height points
		hKurt	Kurtosis of the distribution of height points
	Proportion	hD.{1}.{2}	Density of points between heights {1} and {2}
	Intensity	Position	iMean
iQ{1...99}			Intensity percentiles
Dispersion		iSd	Intensity standard deviation
		iSkew	Intensity skewness
		iKurt	Intensity kurtosis
Topography	-	Slope	Terrain slope
		Aspect	Terrain aspect (face direction)

1.6. Overview of the dissertation: Lidar study of the adjacency between forest fragments

This dissertation presents two distinct applications of lidar technology for studying edge effects in different locations and ecosystems: fragments of the Atlantic Forest in Brazil and areas of the Boreal Forest in Canada. Both types of edge effects under study are anthropogenic-caused and represent land use changes typically found in each study site.

The Atlantic Forest and the Boreal Forest have a growing anthropogenic footprint. The Atlantic Forest was one of the largest rainforests of the Americas, originally covering around 150 million ha (Ribeiro et al., 2009). Its geographical characteristics such as wide extension into tropical and subtropical regions, with coastal areas receiving large amounts of rain and large altitudinal range have favoured high biodiversity (Câmara, 2003).

It is considered that the Atlantic Forest flora and fauna may include 1-8% of the world's total species (Silva and Casteleti, 2003). Given its present-day fragmentation, most of the remaining Atlantic Forest is found as small fragments (<100ha; Ranta et al., 1998) isolated from each other and composed by second-growth forests in early to medium stages of succession (Viana et al., 1997; Metzger, 2000; Metzger et al., 2009).

In this context, the biodiversity of the Atlantic Forest is endangered. According to Ribeiro and collaborators (2009), only 11.7% of the original vegetation remains (15,719,337 ha). Of the total forest area remaining, 73% is located less than 250 m from any non-forest area, and 46% is less than 100 m distant from edge. Only 7.7% is located farther than 1000 m from any edge, and 12 km is the maximum distance from any non-forested area in the Atlantic Forest region. Thus, being harshly fragmented in small patches, the remaining Atlantic Forest is subject to strong edge effect influences. Once the majority of the present forest is directly influenced by nearby land use, studies that investigate matrix influences are particularly necessary to conduct management actions properly in the area (Pardini et al., 2009; Vieira et al., 2009).

Chapter 2 explores edges originated through fragmentation processes involving the development of silviculture areas within an Atlantic Forest region in two properties located in the Municipality of Pilar do Sul, SP, Brazil. The region has been undergoing impacts from changes in land use, with the expansion of *Eucalyptus* plantations. The species of the genus *Eucalyptus* are known as the most commonly used for establishing industrial forest

plantations in Brazil (Guerra et al., 2016). Good growth rates and conditions of climate and soil favoured by the genetic improvement of crops have been responsible for the spread of their cultivation across the country (Stape et al., 2010). Thus, natural areas have been replaced by commercial forest plantations, resulting in a landscape composed of native forest fragments and stands.

In this context, we evaluate the edge effects in commercial *Eucalyptus* plantations and Atlantic Forest fragments, by quantifying the differences in the vertical structure (vegetation height and understory density) of the edge vegetation vs core. Additionally, we seek to understand the influences that each type of adjacent soil use (*Eucalyptus*, native forest or pasture) imposes on each kind of neighbouring vegetation.

Despite the ecological relevance of native forest fragments, little is known about their dynamics when they are located within forestry landscapes. Thus, understanding the influences that each patch imposes on its neighbour in silvicultural areas interspersed with native forest fragments can be relevant to the development of management and conservation strategies for *Eucalyptus* and native forest fragments, respectively.

The Atlantic Forest, a biodiversity hotspot, has a long persistent history of deforestation and fragmentation, mainly caused by land use change. Much of its areas have been subject to the complete conversion of previously existing native vegetation into agriculture, pastures, *Eucalyptus* plantations or urban neighbourhoods. Therefore, understanding the edge effect in Atlantic forest fragments found in this context is also crucial to quantify the impacts of environmental changes on this remnant ecosystem, especially because forest remnants play an important conservation role related to the provision of ecosystem services, the support of endemic species and the enhancement of landscape connectivity (Gibson et al., 2013).

Additionally, the analysis of the edge effects in *Eucalyptus* plantations in contact with native forest fragments or pastures is fundamental to evaluate if there is any alteration in the vegetation structure of the stands in each condition. In this context, conservation planning at the landscape level must consider the conservation management of forest fragments combined with the forestry landscape management.

Meanwhile, in a totally different type of forest ecosystem, the Boreal Forest in central Alberta, Canada, a rapidly growing industry for the exploitation and production of gas and oil is being responsible for fragmentation processes across the landscape. Activities

associated with the industrial development are affecting landscape components such as its hydrology and biogeochemistry, with changes to the structure of the forests and impacts on wildlife and ecosystem functioning (Bradshaw et al., 2009; Kuuluvainen et al., 2012; Venier et al., 2014).

Boreal Forests account for approximately one-third of the world's forest cover (UNEP et al., 2009) and have a crucial role in global climate regulation and climate change mitigation (Pan et al., 2011). They also harbor unique biodiversity, and the biome includes some of the world's largest areas of intact primary forest (UNEP et al., 2009). Canada's Boreal Forest is well recognized as one of the largest remaining carbon stores in the world. Also, the Canadian Boreal Forest (270 million hectares) is an important area of forest management for the sustainable production of wood products and for communities supported by these activities (Audet et al., 2015). Additionally, they provide a range of other goods and services that are essential to human well-being (Vanhanen et al., 2012; Brandt et al., 2013; Gauthier et al., 2015).

Chapter 3 addresses the edge effects in this particularly type of forest ecosystem in an area called Oil Sands Region, a place having the largest known crude bitumen deposits worldwide (Audet et al., 2015). This region lies within the boreal plain ecozone, which is characterised by upland forests on gently undulating plains interspersed with vast wetlands (Webber and Flannigan 1997). Biodiversity patterns and biogeochemical cycles are shaped by the region's subhumid and subarctic climate, its predominant brunisol and luvisol soils, and the occurrence and distribution of natural (i.e., wildfire) and anthropogenic disturbances (i.e., exploitation of hydrocarbon resources) (Bergeron et al., 2002; Brandt et al., 2013; Kishchuk et al., 2015; Maynard et al., 2013).

The ecosystems in the area have continuously been threatened over years of anthropogenic activities. Habitat disturbances have occurred mostly caused by the exploitation and production of oil and gas. The oil production from bitumen extraction was initiated in 1967 (Alberta Government 2009) and is expected to more than double (from 1.9 to 4.8 million barrels·day⁻¹) over the next two decades (Canadian Association of Petroleum Producers (CAPP) 2014). To locate oil and gas, explosive charges are initiated along linear corridors known as seismic lines that cut through natural areas (Figure 4). These linear disturbances are responsible for impacting the local biodiversity and surrounding ecosystems, being associated with fragmentation events and edge effects.

Figure 4. a) Seismic lines cut through the Boreal Forest, including a well pad, in Fort McMurray, AB, Canada. b) Recently burned wide seismic line. Note the size of a person compared to that of a seismic line.

In this study, we examine the various interactions that occur between the seismic line environment and ecosystems proximal to seismic lines within the Oil Sands Region. This study is the only so far to use a combination of lidar remote sensing and geospatial analysis applied within a random forest machine learning framework for assessing seismic line impacts on proximal boreal forest environments. In addition, we quantify the effects of distance from seismic line centres on surrounding vegetation height and fractional cover. We also quantify relationships between vegetation structure and spatial variations in height and canopy fractional cover related to the topographic position, radiation, and surface geology. Finally, we provide a random forest model to determine how each of these interact and the dominant drivers of spatial variations in forest/wetland structures adjacent to seismic lines.

In Chapter 4 we finish with a summary of the main results of each application of lidar technology for studying edge effects. Finally, with the knowledge generated in this study, we suggest future researches combining lidar and field data in fragmented landscapes for a better understanding of edge effects both quantitatively and qualitatively.

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2. LIDAR REMOTE SENSING: A TOOL TO CHARACTERIZE EDGE EFFECTS IN TROPICAL FORESTS AND *EUCALYPTUS* PLANTATIONS

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ABSTRACT

Fragmentation of native forests is an omnipresent phenomenon caused mostly by anthropogenic land-use changes. Edge effects are directly linked to fragmentation and known to affect the dynamics of forest communities. Studying local structural variations in edge habitats has been widely explored through field surveys. However, few works have investigated edge effects at landscape level using lidar remote sensing. We aimed to study different responses of forest structure based on vegetation height and understory density in fragments of the Atlantic Forest and *Eucalyptus* plantations depending on the distance from an edge and the type of adjacent land use. Height and understory density differences were detected between edge and core areas, especially up to 10 m distance from the edge within pasture fields. In this case, *Eucalyptus* plantations adjacent to pasture displayed trees 3.62 % shorter and understory 69.60 % less dense than the core habitat. Next to riparian pasture, trees were 5.72 % taller with understory 59.20 % less dense. Native and riparian native fragments at the same distance from pasture, displayed edge trees between 27.49 % and 37.27 % shorter than the core and an increased understory density of 400 % and 244.44 %, respectively. Edge effects in stands next to native or riparian native remnants and vice-versa displayed the lowest influences on both variables studied and were seen up to 10 m, however, if adjacent to pasture, they extended to distances further than 40 m. Edge effects, in terms of height and understory density, in native fragments adjacent to stands and vice-versa were less intense than next to pasture. Thus, it seems that the protection of native forests in silviculture areas besides favouring the maintenance of local ecosystem services could help maintain the homogeneity of the stands due to their ability to minimise edge effects. This protection could favor the occurrence of border *Eucalyptus* more similar to the ones in the core. Overall, lidar proved to be a useful tool to evaluate the spatial and ecological dimensions of edge effects.

Keywords: Fragmentation; Atlantic forest; Vegetation structure; Height; Understory density; Light detection and ranging (lidar); Remote sensing

2.1. Introduction

Anthropogenic disturbances have led to the fragmentation of habitat, a widely spread phenomenon, where a continuous habitat is divided into smaller isolated patches, immersed into a matrix of land converted to anthropogenic land-uses (Wu 2013, Haddad et al. 2015). Edge effect is one of the primary sources of disturbance caused by fragmentation, being responsible for changes in the quality of the remaining vegetation (Pardini et al. 2017). Abiotic (e.g., light, temperature, wind and humidity), and biotic factors (e.g., an abundance of species and competition) in the ecosystem can be altered in habitat edges (Murcia 1995, Kunert et al. 2015).

Studying edge effects usually involves the identification of the habitat edge in contrast to its (nearly) unaltered core. Habitat edge constitutes the contact zone with the matrix and represents the interface between forested and nonforested ecosystems or between two forests of contrasting composition or structure (Fahrig 2003, Harper et al. 2005). An edge is usually characterized by depth of edge influence (EI) (Chen et al. 1993, Euskirchen et al. 2001, MacLean 2017). EI is the distance from the border into the forest patch's core over which there is a significant effect of processes (both abiotic and biotic) that result in a detectable difference in composition, structure, or function near the edge when compared with the core's ecosystem (Harper et al. 2005). Thus, the core (also referred as interior) is the habitat where no detectable edge influence is shown (Harper et al. 2005).

Once the landscape exists as a mosaic formed by different types of patches, the understanding of edge effects also requires understanding the influences that each adjacent patch imposes on its neighbour (Ries et al. 2004). Thus, quantifying variability in the structure of forests in edge versus core vegetation, as with variation in adjacent land, might be crucial to developing management and conservation strategies (Vidal et al. 2015). The Atlantic Forest, considered one of the top five global biodiversity hotspots (Myers et al. 2000), is a highly diverse tropical forest that has been threatened by fragmentation (Joly et al. 2014) as land use change keeps happening in the region, with much of the natural areas being

converted into *Eucalyptus* plantations, pastures or urban neighbourhoods (d'Albertas et al. 2018). Understanding the edge effect in Atlantic forest fragments adjacent to *Eucalyptus* or pasture areas is fundamental to quantify the impacts of environmental changes on this remnant ecosystem. On the other side, the analysis of the edge effect in *Eucalyptus* areas in contact with native forest fragments or pasture might help us evaluate if there is any alteration in the vegetation structure of the stands.

As the edge's depth influence is continuously changing in size over time, the analysis of structural variations at landscape level turns out a difficult task without extensive field surveys. According to Hummel and collaborators (2011), lidar data can provide information across a much larger area than field surveys alone, and its cost can be comparable to traditional stand assessments for structural attributes. Remote sensing is a useful tool to evaluate the extent of edge effect and to generate results in a short time at increasingly affordable costs compared to field data collection. Lidar remote sensing can measure the 3D vertical structure of terrestrial ecosystems directly across landscapes (Lefsky et al. 2002, Wasser et al. 2015). It has been applied to quantify and characterise different forest 3D structural traits, such as height, biomass, canopy and understory cover (Popescu et al. 2003, Hopkinson and Chasmer 2009, Martinuzzi et al. 2009, Wing et al. 2012, Cao et al. 2016). However, mapping edge effects using lidar data has been done in few studies (dos Santos et al. 2015, MacLean 2017) but remains virtually underexplored in tropical forests. This study advances in the use of lidar remote sensing data for studying edge effects on areas of mixed land cover. We predicted different responses of forest structure depending on the distance from an edge and the type of adjacent land use. Focusing on the edge effects on the forest structure we aimed to a) quantify the effects of distance from edge on surrounding vegetation height and understory density, and b) examine the combined effects of adjacent patch type and distance from the edge over vegetation height and understory density.

2.2. Methods

2.2.1. Study area

Data collection was carried out in a forest production area with clonal *Eucalyptus grandis* x *Eucalyptus urophylla* plantations six years old. The area was selected because it

presents the group of eucalypts in contact with different types of patches, including native forest fragments and pasture lands. For all the *Eucalyptus* plantations under study, the spacing was 3 x 2 m. The area covers two farms of Suzano Pulp and Paper Company, which together totalize 1,347.2 hectares. The properties are in the municipality of Pilar do Sul, state of São Paulo (Fig. 1).

Figure 1. (a) São Paulo State. (b) Properties in the municipality of Pilar do Sul (southwest of the São Paulo state). (c) Categories of land use type found in the study area.

Vegetation is classified as Ombrophilous Dense Forest or Pluvial Forest, biome Atlantic Forest (IBGE, 2012). The Atlantic Forest mainly covers low altitudes (≤ 1000 m elevation) of the eastern mountain range that runs along the coast, from south to northeast of Brazil, with hot and humid climate without a dry season (Morellato and Haddad, 2000). Both farms are a mosaic of *Eucalyptus* plantations, fragments of Atlantic Forest in different successional stages and pasture areas (Ditt et al. 2008, Ribeiro et al. 2009, Teixeira et al. 2009). Climate is humid subtropical, with dry winters and hot and humid summers. Annual rainfall is around 1,293.2 mm, and the mean annual temperature ranges between 16.5 and 23.6 °C (www.cpa.unicamp.br). The relief is of wide hills (wide interfluves) where low slopes predominate, and altitudes vary from 650 to 980 meters. Pilar do Sul is inserted in the Alto Paranapanema Hydrographic Basin, with soils classified as red-yellow latosols, recognised as clayey, deep, low acid, cohesive and of relatively homogeneous red-yellow colour (Pfeifer et al. 1986). The study area is next to the largest Atlantic forest continuum in São Paulo state, comprised by various protected areas, the APA (Environmental Protection Area) of Serra de Tapiraí, Carlos Botelho State Park and Intervalos State Park (www.iflorestal.sp.gov.br).

2.2.2. Remote sensing data

The flight for lidar data collection was carried out in July 2014 with a Trimble lidar Harrier 68i sensor. Survey parameters included a flying altitude of approximately 1000 m above ground, pulse repetition frequency of 100 kHz, and an average point density of 10.8 points per square meter.

2.2.3. Data processing and statistical analysis

The lidar data was processed using LasTools (RapidLasso, Germany) and lidR package (Roussel et al. 2018) in the R language (R version 3.5.0, R Foundation for Statistical Computing). To determine the vegetation height, a canopy height model (CHM) was computed at 1 m spatial resolution. To include shrubs and short vegetation the point cloud processing was based on a minimum height cutoff of 0.2 m. Then, to convert the elevation of the highest point attributed to each pixel into the average maximum height on a 3 m grid, we aggregated and computed the mean of all 1 m grid pixels within a 3 m pixel radius. The cell

size choice was based on the *Eucalyptus* planting spacing used in the study area (3 x 2 m) so that each pixel would be able to contain all the lidar returns from at least one tree. The understory density was determined by the count of points whose heights fell into the interval 0.2 m to 1.3 m. The counts were divided by the total number of points inside the pixel and scaled to a percentage. We performed a buffer analysis to quantify the effects of distance from the edge on surrounding vegetation height and understory density. A multiple ring buffer approach containing 10 m wide contour lines was used to split the patches into concentric buffers from the edge up to 50 m into the forest (Fig. 2).

Figure 2. (a) Types of interfaces analysed according to the vegetation studied and its adjacent patch. (b) Schematic representation of a buffer with 10 m wide contour lines from the edge to the patch's core.

The maximum edge distance was determined following a study of edge effects in the Atlantic Forest that suggests the depth-of-edge influence was limited to 50 m into the forest (d'Albertas et al. 2018). We selected study sites in 84 patches of Atlantic forest (42 of riparian native and 42 of non-riparian native), and 52 *Eucalyptus* stands that were large enough to include core habitat at distances from the edge greater than 50 m. Each patch was classified according to its land use type (Atlantic forest = native fragments, *Eucalyptus* plantations, pasture) and the proximity to water streams (riparian = within a 30-m buffer on either side of a stream; not riparian = outside). Hereafter, native fragments, *Eucalyptus* plantations and pasture patches mean fragments not considered next to a stream.

In addition, to avoid areas where there could be water accumulation, we applied a Topographical Position Index (TPI) methodology to exclude locations that were lower than the average of their surroundings, as defined by the neighbourhood. The Topographic Position Index compares the elevation of each cell in a digital elevation model (DEM) to the mean elevation of a specified neighborhood around that cell. Positive TPI values represent locations that are higher than the average of their surroundings, as defined by the neighborhood, and were considered as areas without water favouring. Negative TPI values represent locations that are lower than their surroundings, thus, being regions considered with water favouring. The TPI raster layer was created based on a DTM at 3 m resolution obtained by interpolating ground points by Delaunay triangulation and circular windows of 12 m.

We developed an automated algorithm to classify each pixel inside a buffer ring according to its nearest adjacent land use type. A Euclidean distance algorithm was applied to calculate the shortest distances from a pixel's centre to pixels belonging to the other land use classes surrounding the patch. The pixels were then classified according to their closest neighbour (*Eucalyptus*, riparian native, native, riparian pasture or pasture). We carried out all GIS analyses in ArcGIS 10 (ESRI, 2017).

The statistical analyses were performed in R (R Development Core Team, 2017). Due to the nonnormality of data under study, to determine whether there was an edge effect on vegetation height and understory density and whether these parameters were, consequently, greater or smaller near the forest edge compared to the core habitat, pairwise comparisons using the Wilcoxon rank sum test were performed between each transect and its core. The Bonferroni correction method was used to adjust P-values for multiple comparisons (Wright, 1992). Unless otherwise noted, variations in height and understory density are expressed as medians.

2.3. Results

2.3.1. Influence of edge distance and adjacent patch type on vegetation

Eucalyptus plantations reached peak height (27.36 m) within 10 m of the riparian pasture edge ($p = 0.0010$) (Fig. 3a). This represents an increase in the height of 5.72 % when compared to *Eucalyptus*'s core habitat (25.88 m). At the same distance from the edge, stands

nearby native or riparian native fragments did not have a significant influence on *Eucalyptus* height (25.02 m; 25.89 m, respectively). We found the lowest heights (24.94 m) across *Eucalyptus* adjacent to pasture, 3.62 % less than the value observed for the core habitats. At the 40-50 m buffer, vegetation heights become similar to the core's heights for all adjacent patch types.

Up to 10 m distance from the edge, riparian native fragments next to pasture had the lowest heights (pasture = 9.83 m; riparian pasture = 8.86 m) compared to the natural forest's core (15.67 m), indicating a height decrease of 37.27 % and 43.46 %, respectively. Meanwhile, when nearby *Eucalyptus* plantations those fragments showed greater heights (14.84 m) in comparison to the other groups. However, it represented a reduction in the height of 5.30 % when compared to the core habitat. At the farthest distances from the edge significant height differences ($p < 0.0001$) from the core habitats were still found (Fig. 3b).

Native fragments adjacent to pasture and up to 10 m distance from the edge also displayed lower heights (pasture = 9.18 m; riparian pasture = 5.44 m) than their cores (12.66 m). These were equivalent to a reduction in the height of 27.49 % and 57.03 %, respectively. On the other hand, at the same distance from the edge, the proximity to *Eucalyptus* plantations resulted in 13.59 % taller trees (14.38 m). Within the 40-50 m buffer, the only interface type that did not show significant differences ($p = 1.00$) in comparison to core habitat was native fragments next to pasture (Fig. 3c).

Figure 3. Average max height values (m) versus buffer distance from patches' edges split by neighbourhood composition. Dotted line represents the median value of the interior group.

With regards to understory density, *Eucalyptus* plantations within 10 m from the edge showed greater point densities when adjacent to native fragments (native = 7.40 %; riparian native = 8.80 %) than to pasture (pasture = 3.80 %; riparian pasture = 5.10 %). Within the 10-20 m buffer, no significant differences ($p = 1.00$) were found between edge and interior for the *Eucalyptus* and native fragments interface, irrespectively to the presence of water. However, stands next to riparian pasture and pasture showed significant differences on understory point density up to 20-30 m and 40-50 m buffers, respectively. Irrespectively to the adjacent patch type, reduced understory density was found in the edge compared to the interior habitat (12.5 %) (Fig. 4a).

Figure 4. Understory point density (%) versus buffer distance to edge, according to neighbourhood type. Dotted line represents the median value of the interior group.

Within 10 m from the edge, the understory density on riparian native vegetation adjacent to stands (1.60 %) was lower than to pasture (pasture = 3.10 %; riparian pasture =

6.50 %). Both native and riparian native fragments next to riparian pasture were the only type of interface to show significant differences between edge and core up to the 40-50 m buffer ($p < 0.0001$) (Figs. 4b and 4c).

Up to 10 m distance from the edge within native fragments next to stands, the understory density was also lower (1.30 %) than to pasture (pasture = 6.00 %; riparian pasture = 16.90 %). Independent of the edge distance, no significant differences were found between edge and interior habitats on the native and *Eucalyptus* plantations interface. Within the 30-40 m buffer, no significant differences ($p = 1.00$) were found between native edge and core adjacent to pasture. Irrespectively to the adjacent patch type, greater understory density was found in the edge compared to the native core habitat (native = 1.20 %; riparian native = 0.90 %) (Figs. 4b and 4c).

2.4. Discussion

Height and understory density differences were detected between edge and core areas. Our results showed that edges with pasture fields, a relatively inhospitable matrix, might help to magnify edge effects. For instance, the greatest differences between edge and core were found in situations where the adjacent patch was pasture (Figures 3 and 4). Fragments surrounded by a matrix of low biomass and structural complexity (Murcia 1995), such as pastures, allow more solar radiation to reach the ground during the day and higher reradiation to the atmosphere at night (Geiger 1965). Thus, daily temperatures in pastures tend to be higher and fluctuate more widely (Fetcher et al. 1985). On the other hand, the forest fragment provides a cooler, moister and more uniform environment (Geiger 1965, Fletcher et al. 1985). According to Murcia (1995), the difference in microclimate between forested areas and pastures might create a gradient of temperature and moisture running inwards from the edge.

Our results revealed that *Eucalyptus* stands adjacent to riparian pasture had taller trees, as opposed to fragments close to pasture, and reduced understory density than stands near native fragments (Figures 3a and 4a), which could indicate an environment without limitation of sunlight or moisture. *Eucalyptus* species are predominantly shade-intolerant compared to other genera (Montagu et al. 2003), as indicated by a significant drop in the photosynthetic rate of *Eucalyptus* leaves when they lose light saturation (Sands 1996). Thus,

the opening created by an adjacent pasture patch might result in greater light penetration and wind exposure to the border trees (Stueve et al. 2011). Although, airflow across the surface of leaves can facilitate transpiration and the exchange of carbon dioxide and oxygen between the leaf and the atmosphere (Mitchell 2013). Thus, increasing evapotranspiration, the available water in the soil of riparian pasture due to the proximity to water bodies might contribute to avoiding moisture stress. Therefore, it could provide conditions to maintain *Eucalyptus* optimal growth. Although the percentage of increase in height has been low ($\sim 6\%$), it is essential to consider that changes within a population belonging to clonal stands, i.e. forests that tend to be remarkably homogeneous, are mostly limited by environmental constraints (such as incoming light, vapour pressure deficit, supplies of nutrients and water) (Stape et al. 2010). Thus, it would be expected that changes in forest growth manifest in percentages considered small in other realities such as seminal plantations or natural forests. However, this interface type does not seem to favour the understory development compared to the native-*Eucalyptus* interface. Indeed, fragments such as stands and pastures near native forest edges probably receive greater propagule dispersal (termed seed rain) from surrounding areas (Grau 2004, Dodonov et al. 2014, Charles et al. 2017).

In the case of *Eucalyptus* plantations, greater understory density was found in the core habitats compared to the edge irrespective to the adjacent patch type. This behaviour might be associated with silvicultural treatments (site preparation, fertilisation and control of leaf-cutting ants and weed) and litter biochemical characteristics (Wu et al. 2011, Zhao et al. 2013). Also, it is possible that the control of the understory has been limited to the edge of stands. Time since fragmentation disturbance which could be related to the age of trees might be another plausible explanation, indicating that understory plants had a longer time to develop in the core of the patch than at the edges (Dodonov et al. 2014). On the other hand, native fragments had shorter trees and denser understory when adjacent to pasture, irrespective to the amount of water available, than next to *Eucalyptus* (Figs. 3b, 3c, 4b and 4c). Lower tree heights at edges have already been reported in the Amazonian due to road-associated edge effects (Kunert et al. 2015) and fragments of the Brazilian Atlantic forest surrounded by pasture (d'Albertas et al. 2018). For example, a study in a hyper-fragmented landscape of the Atlantic Forest showed native fragments nearby sugar-cane fields containing trees 30 % shorter in edges when compared to areas with non-edge-effects (Oliveira et al. 2008).

In the forest edge, vegetation is under different disturbance regimes, and local abiotic factors are altered creating a particular habitat and changes in the community and the ecological and ecosystem processes (de Paula et al. 2016). Drought and higher temperatures are considered the main drivers of structural changes in forest edges, being capable of altering tree allometry and carbon storage (Oliveira et al. 2008, de Paula et al. 2011). In case of native vegetation, it appears that relaxing of competition for light in edges might reduce tree height (Osuri et al. 2014), avoiding the need to trespass the canopy to receive light (d'Albertas et al. 2018). In addition, it has been shown that short duration displacements of branches and leaders by wind, another primary disturbance agent in forest edges, can lead to thigmomorphogenic responses such as formation of flexure wood, increased secondary thickening of stems and structural roots, and reduced shoot extension (Telewski 1995, Coutts et al. 1999). Thereby, shorter, thicker and, less slender, trunks and branches which better resist deflection (Wood 1995) and improve root anchorage (Nicoll et al. 2006) would be produced by these growth responses.

Moreover, pioneer species, lianas, shrubs and herbaceous plants adapted to the edge conditions may proliferate in the native fragment edge and dominate this region (Gascon et al. 2000, Laurance et al. 2001, Oliveira et al. 2004). It could indicate that successional, exotic, and invasive plant species are gradually replacing old-growth forest species, thus, impacting the local biodiversity (Benítez-Malvido and Martínez-Ramos 2003, Laurance et al. 2006). Meanwhile, the forest core could be holding a rich assemblage of tree species consisting mostly of shade-tolerant canopy and emergent species (Oliveira et al. 2004). Indeed, windthrow at the patch-level is known to damage the overstory and make light and soil resources available to subcanopy and understory plants, deposit pulses of foliage, branch and stem material on or near the ground, and invert and expose soil profile (Stueve et al. 2011). Also, an edge effect study by de Melo and collaborators (2006) in a large fragment of the Brazilian Atlantic forest, revealed at habitat level the occurrence of biased seed rain in forest edge that appears to be particularly impoverished in terms of: (1) large-seeded species (large plus very large seed species); (2) large-seeded species showing vertebrate seed-dispersal attributes; and (3) species handled by vertebrates.

Overall, the understory density was more sensitive to alterations in environmental structure than height, a pattern already observed in a previous study (Mendes et al. 2016). For *Eucalyptus* plantations within 10 m from pasture, edge trees were 3.62 % shorter than the

interior, meanwhile, based on understory density the reduction was 69.60 %. Native and riparian native vegetation at the same distance from pasture displayed edge trees between 27.49 % and 37.27 % shorter than the interior and an increased understory density of 400 % and 244.44 %, respectively.

As we initially predicted, forest structure showed different responses about the distance from the edge and the type of adjacent land use. Our results highlight that the edge effect and the adjacent land use type affected the vegetation height and its understory density. Matrix vegetation that is more structurally different to the forest (*Eucalyptus* or native fragments) can significantly impact the vegetation characteristics on a higher scale than a matrix more similar (Fillooy et al. 2010). Native fragments or *Eucalyptus* stands in contact with pasture displayed the greatest differences on vegetation height and understory density between the edge and core habitats. It was possible to use a lidar approach, combined with other remote sensing techniques and geographic information systems, as a powerful tool in the study of edge effects on native forest and silviculture. Here, we focused on a large scale of edge effects on the mixed types of land uses. However, future studies combining lidar and ground data in the edge and core habitats can be useful to better understand, qualitatively and in a fine scale, how structural changes can alter forest composition.

2.4.1. Considerations of the adjacency between forest fragments

In *Eucalyptus* next to native fragments, regardless of proximity to water, showed a depth of edge influence of 10 m in terms of height and understory density. Conversely, native and riparian native fragments adjacent to stands revealed the same pattern. However, when stands and native fragments were found next to pasture or riparian pasture, the depth of EI could be extended to further distances than the 40-50 m buffer for both variables under study. Indeed, the occurrence of significant differences in height and understory density between the 40-50 m band and the interior were still observed as in the case of *Eucalyptus* next to pasture and native fragments adjacent to riparian pasture. It suggests that in some situations the remaining forest, at distances greater than 50 m, should be assigned as forest edge habitat instead of core habitat, even if we conservatively assumed that edge effects penetrate only 50 m into forest fragments.

Our results also showed that edge effects, regarding vertical growth and understory density, in native fragments adjacent to *Eucalyptus* stands were more attenuated compared to situations in which they were found next to pasture. In addition, stands next to native fragments displayed the lowest influences on both variables studied. Priority has been given to restoring native forests in silviculture properties with the purpose of protecting springs. Moreover, native forests within silviculture properties help to maintain ecosystem services, such as provision and maintenance of water flow throughout the year (Little et al. 2015, Christina et al. 2018, Dresel et al. 2018), diversity of local flora and fauna species, crop pollinators and natural pest control (Zanuncio et al. 1998, 2016). With our findings, we emphasise another reason to protect native forests in silviculture areas given their capacity to minimise edge effects: assist in maintaining the stand homogeneity, guaranteeing border *Eucalyptus* more similar to the ones in the core.

The present study emphasises that lidar technology is a useful tool to analyse edge effects and to support forest managers on monitoring forest structure at large scales. As edges are dynamic, multitemporal lidar monitoring of forest fragments could be the focus of future studies.

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3. SEISMIC LINE IMPACTS ON PROXIMAL BOREAL FOREST WETLAND ENVIRONMENTS IN ALBERTA

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ABSTRACT

Seismic lines are corridors cut through forest and wetland land covers for geophysical exploration of oil and gas deposits. The linear extent of seismic lines in Alberta, Canada exceeds 1.5 million km, sometimes with a density greater than 10 linear km per km². Here we present a localised case study of the impacts of seismic lines on proximal boreal forest and wetland ecosystem vegetation structural characteristics. The study concentrates on a relatively undisturbed area of the Oil Sands Region of the Boreal zone in north central Alberta using airborne multi-spectral lidar and publically available geospatial data. The results of this study indicate that significant variations in adjacent forest/wetland edge vegetation structure occurs proximal to 30 seismic lines identified within the study area. The variations observed in this area depend on the environmental characteristics of the seismic lines. Often taller trees and greater fractional cover extends to a distance of up to 55 m from the seismic line, especially in land covers adjacent to wider seismic lines. Random forest analysis of spatial correspondence between environmental and proximity-based variability associated with seismic lines indicates that distance, incident radiation and the potential for accumulation of surface water based on local geomorphology (inferred from topographic position) are the most important variables affecting height and fractional cover of proximal vegetation. Combined variables including distance from the seismic line, width of the seismic line, cardinal direction and incident radiation, topographic position and underlying surface geology may be used to predict spatial variability of vegetation height to an accuracy of 70% (adjusted (adj.) R²). From this research, we suggest continued sampling/testing of lidar/high resolution optical imagery and geospatial data to examine the impacts of seismic lines in other parts of the Oil Sands Region using the methods developed in this case study. Reclamation management plans for oil and gas exploration areas should focus on reclaiming

wider seismic lines first as these have the greatest impact on proximal ecosystems.

Keywords: Linear disturbance; Seismic line; Edge effects; Lidar; Vegetation structure; Oil sands

3.1. Introduction

Despite being considered one of the largest remaining carbon stores of the world (Pimm et al., 2009; Warkentin and Bradshaw, 2012), Canada's Boreal Forest has been threatened by habitat disturbances due in part to exploration and production of hydrocarbon resources (Tigner et al., 2015). Western Canada's Boreal region contains at least 10% of the Earth's proven oil reserves, making Canada third only to Venezuela and Saudi Arabia (Alberta Energy, 2017). To locate oil and gas deposits, explosive charges are initiated along linear anthropogenically modified corridors or 'seismic lines' that cut through natural ecosystems. Seismic lines represent the most frequent linear disturbances related to the energy sector in Boreal Canada (Chen et al., 2017). Due to their total length in Alberta, estimated to be between 1.5 - 1.8 million km (in 2001; Timoney and Lee, 2001), and high density of up to 10 km per km² (Lee and Boutin, 2006). Seismic lines have therefore had an extensive impact on local ecosystems and biodiversity (van Rensen et al. 2015). These features are also responsible for reducing habitat area and increasing ecosystem fragmentation (Linke and McDermid, 2012), thus enlarging the ratio of edge to interior habitats. For example, one of biodiversity's boreal icons, the woodland caribou (*Rangifer tarandus caribou*), has been threatened by rapid land use change and seismic line development over its natural habitat (Hebblewhite, 2017). Considering the rapid change of these sensitive ecosystems and in an effort to mitigate post-seismic line habitat fragmentation, the Government of Alberta developed the Draft Provincial Woodland Caribou Range Plan, which aims to restore 10,000 linear km of land previously cleared for seismic lines within the Little Smoky and A La Pêche caribou ranges (Pyper et al., 2014). Public concern related to seismic lines demonstrates the importance of studies aimed at understanding the effects of linear corridors on within seismic line and adjacent ecosystems, allowing the development of better restoration plans and management actions.

Fragmentation, caused by the establishment of a seismic line, creates an interface between the area of disturbance (the seismic line) and adjacent vegetation. Boundaries (edges) between habitat types creates environmental gradients (Chen et al., 1993; Caruso et al., 2011), known as edge effects, which cause abiotic and biological changes in and near edges (Murcia, 1995). Research related to edge effects relies on an edge-interior pattern defined as an edge zone, where vegetation attributes (i.e. height, basal area, composition) vary mainly with the distance from the edge, and an interior zone, where the edge no longer impacts the interior and therefore varies according to other factors (Alignier and Deconchat, 2011). Across fragmented landscapes, information on the effective edge widths (i.e. depth of edge influence, DEI) is important for the planning of different management projects in and near the edges with a view to controlling their effects on the adjacent environment (Alignier and Deconchat, 2011).

Numerous studies have examined the impacts of edge effects on adjacent ecosystems and across a range of boreal ecosystems (Harper et al., 2004, 2005; Hylander, 2005; Gignac and Dale, 2007; Dennis and Dale, 2009; Baltzer et al., 2014; Barry et al., 2015; van Rensen et al. 2015; Reinmann and Huttyra, 2017). Despite this, the methods used to examine the impacts from seismic lines are variable and may not be spatially distributed (Revel et al., 1984; Bella, 1986; MacFarlane, 2003; Dabros et al., 2017). Other studies have focused on the impacts of seismic lines on local micro-meteorology, including light variations, wind intensity, air temperature, vapor pressure, and hydrology (Lee and Boutin, 2006; Pohlman et al., 2007; van Rensen et al. 2015; Braverman and Quinton, 2016). For example, increased soil temperature and light/wind intensity are important influences on ecosystems proximal to seismic lines (Dabros et al., 2017). The influence of edge effects, including warmer soils and increased light and wind intensity may alter conditions beyond the threshold to which the natural ecosystem is not easily able to regenerate. Lee and Boutin (2006) and van Rensen et al. (2015) further examined the impacts of ground compaction and altered local hydrology caused by mechanical damage during the construction of seismic lines on vegetation regeneration. While driving mechanisms and edge effects are important, Revel et al. (1984) found that regenerating vegetation on seismic lines is different to that of adjacent ecosystems, even 30 - 50 years post-disturbance.

Despite ongoing research of the impacts of seismic lines on proximal ecosystems, studies are often based on discrete measurements and do not consider variations across broader areas. The assessment and quantification of seismic line regeneration is also difficult due to the often remote nature of these northern environments and the extent of disturbance. Quantifying disturbance regeneration often includes measuring the height and density of vegetation species several times over a period of years. This procedure can be prone to subjective errors and difficulties associated with scaling to the broader environment due to the localized nature of the measurements (Chen et al., 2017). To improve the scalability of field data and the application to broad, remote regions, remote sensing data can be used as an attractive alternative to, or in combination with, field data for the monitoring of seismic lines (Linke and McDermid, 2012). Various remote sensing technologies have been used to collect data related to seismic lines. Among the variety of passive optical and active remote sensing technologies available, lidar (light detection and ranging) has the advantage of characterizing both horizontal and vertical structures within forested environments (Sumnall et al., 2017). Airborne lidar is an active remote sensing technology that measures the time of flight of laser pulses, which can be used to determine the elevation of the Earth's surface and overlying vegetation structure (Lim et al., 2003; Evans et al., 2009; Mora et al., 2013; Doyle and Woodroffe, 2018). A few studies have developed and evaluated methods for estimating vegetation height and impacts from linear disturbances in the Boreal region using point clouds and images from unmanned aerial vehicle (UAV) photogrammetry (e.g. Chen et al. 2017). Another study by Bayne et al. (2011) used lidar data to analyse and correlate the behavioural responses of ovenbirds and marten to linear disturbance characteristics. Further, modelling of local vegetation regeneration on seismic lines used lidar-derived data products to understand factors affecting patterns of vegetation recovery in northeast Alberta (van Rensen et al., 2015). Optical imagery estimates indicators of ecosystem structure using absorbed and reflected electromagnetic radiation. For example, Dickie et al. (2017) evaluated the functional habitat recovery along seismic lines for threatened woodland caribou using 2012 SPOT imagery (2-m resolution) and Valtus Views (0.5-m resolution), while He et al. (2009) used SPOT 5 imagery to classify small disturbances such as cut blocks, trails and linear features. Lidar is therefore useful for the study of seismic lines because it enables a more holistic investigation into linear disturbances, spatial variations in post-disturbance vegetation

height and canopy cover, and the derivation of data products as proxy indicators for local ecosystem processes (e.g. topography and accumulation of surface water).

While the impact of seismic lines on regenerating ecosystems is fairly well-known (Bayne et al., 2011; van Rensen et al., 2015; Paulson and Thomson, 2016; Pigeon et al., 2016; Finnegan et al., 2018), less is understood about the combined interactions between seismic lines and proximal ecosystems. Numerous complex and non-linear interactions influence the condition of ecosystems within and beyond seismic lines, which are differentially affected by limitations to growth including variations in soil moisture and incident solar radiation (Gallardo-Cruz et al., 2009; Méndez-Toribio et al., 2016). Further, seismic line attributes such as width, time since disturbance and orientation (van Rensen et al. 2015) can complicate soil moisture/radiation relationships. The following study focuses on a relatively small, heterogeneous region of upland forest and wetland crossed by a range of seismic lines of different ages found in the Central Mixedwood ecoregion of the Boreal Plains ecozone of central Alberta (Downing and Pettapiece, 2006). Here we examine the various interactions that occur between the seismic line environment and those ecosystems proximal to the seismic line using a combined lidar remote sensing and geospatial approach applied within a random forest machine learning framework (Breiman, 2001). The objectives of this study are to: a) quantify the effects of distance from seismic line centres on surrounding vegetation height and fractional cover; b) assess interactions between vegetation structure and primary drivers of growth related to topographic position, radiation, and surface geology, which can be estimated using geospatial data; and c) provide a random forest model to determine how each of these interact and the dominant drivers of spatial variations in forest/wetland structures adjacent to seismic lines.

3.2. Materials and methods

3.2.1. Study site

The area of study is situated within the Central Mixedwood subregion in the Boreal Plains ecozone (Figure 1). Vast expanses of upland forests and wetlands are found within gently undulating plains (Natural Regions Committee, 2006), with elevation ranging from 200 to 1,050 m above sea level (Devito et al., 2017). The climate of the area is sub-humid,

consisting of short, warm summers and long, cold winters (Downing and Pettapiece, 2006). Mean annual air temperature is approximately 0.2 °C and mean cumulative annual precipitation is 478 mm (Devito et al., 2017). The surficial geology of the Central Mixedwood subregion is roughly equal portions of fine-textured glacio-lacustrine deposits, hummocky clay-rich glacial till moraines, and coarse-textured glacio-fluvial and aeolian deposits (Fenton et al., 2013). Luvisolic soils are typical of uplands and organic soils are dominant in wet, poorly drained areas. Vegetation in the region is dominated by pure and mixed forests of *Populus tremuloides* (trembling aspen), *Picea glauca* (white spruce), and *Populus balsamifera* (balsam poplar) on luvisolic mineral soils (e.g. found nearby in Wells et al. 2017). Shrublands and transition zones between landcover types are dominated by various willows, alder, birch, and other shrubs, while meadows comprise of various sedges and may persist in some disturbed areas (Smerdon, et al. 2005). Wetland forests are often extensive and contain dominantly *Picea mariana* (black spruce) and open fens and bogs. *Pinus banksiana* (Jack pine) with reindeer lichen and bearberry groundcover are found in well-drained, coarse textured glaciofluvial or eolian deposits (Goetz and Price, 2015; Wells et al. 2017). On coarse textured deposits, jack pine, trembling aspen and white spruce are found in both pure and mixed stands. Different types of land uses permeate the Central Mixedwood including forestry operations, intensive petroleum exploration (tar sands extraction, oil and gas production), hay crops, and native pasture/domestic livestock grazing (Timoney, 2003).

Figure 1. a) Province of Alberta, Canada and the location of the survey polygons, with inset example sub-area; b) Outline of the full survey polygon area running adjacent to the Athabasca River, southwest of Fort McMurray, Alberta; c) Subset of broader survey polygon showing a false color composite image derived using multispectral lidar data including seismic lines and a well pad cut.

3.2.2. Data collection

The multispectral airborne lidar dataset was planned and collected by the authors at three wavelengths (band 3: 532 nm, band 2: 1064 nm, and band 1: 1550 nm) utilizing a Teledyne Optech Inc. ALTM Titan (Toronto, CA). In August 2016, three overlapping (50%) flight lines were acquired at a site approximately 80 kilometers southwest of Fort McMurray (56°22'N, 112°30'W) Alberta, Canada. Survey parameters include a flying altitude of approximately 1000 m above ground level and an average point density of 6.8 points per square meter. The size of the survey area is 35 km x 1.6 km. Table 1 summarizes the lidar system settings used during the survey.

Table 1. Parameters of multispectral lidar sensor

Parameters	Sensor values		
	1	2	3
Channel			
Wavelength (nm)	1550	1064	532
PRF (kHz)	75	75	75
Divergence (l/e) (mRad)	0.35	0.35	0.7
Half-scan angle (degree)	± 20	± 20	± 20
Pulse energy (μ J)	~50-20	~15	~30
Intensity range (bits)	12	12	12

3.2.3. Data analysis

Raw sensor point clouds were derived for each flight line using proprietary data integration routines (Teledyne Optech, Canada), while subsequent point cloud and raster analyses were carried out using TerraScan (TerraSolid, Finland), LAStools (RapidLasso, Germany), ArcGIS (ESRI, USA) and Surfer (Golden Software, USA). Ground classification was performed using TerraScan on channel 2 (1064 nm) returns due to pulse emissions in the nadir direction providing more reliable ground elevation data beneath canopy (Hopkinson et al. 2016). A digital elevation model (DEM) was created at 0.5 m pixel resolution by applying a triangulation with linear interpolation method in Surfer. The digital surface model was created using a localised maxima filter applied to non-ground returns from all three channels. This was based on a minimum height cutoff of 0.5 m, such that shrubs and short vegetation were included in the digital surface model in areas where tree canopies are open or non-existent. To determine spatial variations in canopy heights with distance from seismic lines, a canopy height model (CHM) was generated by subtracting the DEM from the digital surface model. Canopy cover (Cov) was derived based the division of CHM pixels into heights ≤ 0.5 m and heights > 0.5 m, whereby pixels in the first group were classified to “0” and those in the second group were classified to “1” at 0.5 m pixel resolution. To convert Cov into the fraction of canopy cover (FCov), a broader 5 m grid was used such that FCov was averaged for multiple individuals instead of within single plants.

In this study, the edges of the seismic lines were manually delineated from the CHM and included only north to south (N-S) and east to west (E-W) oriented seismic lines to ensure endmember maximum and minimum periods of incident solar radiation. The north side of seismic lines are characterised as “south-facing”, whereas the south side of seismic lines are characterised as “north-facing” when describing incident radiation (Figure 2a and b). Seismic lines were classified into three width classes: 1 m – 3 m; 3 m – 6 m and > 6 m). A total of 30 seismic lines, 10 from each width class were examined, where approximately 50% of each class was oriented N-S and E-W. Further, we were able to determine the approximate age of 24 seismic lines, eight of each width class, using Google Earth images from 1984 to 2016.

Figure 2. Schematic representation of seismic line classification according to incident radiation based on a) east and west-facing sides, and b) south and north-facing sides; c) is a schematic illustrating the layout of buffer lines used to examine changes with distance from seismic lines.

A buffer analysis was used to quantify the differences in vegetation structure surrounding seismic lines with distance from each seismic line centreline (Figure 2c). This provides a proximity-based comparison with different seismic line attributes, topographical and geological characteristics. To perform the buffer analysis, centerlines were first delineated for each seismic line using ArcGIS. We constructed two types of buffers for each line feature: a) a buffer polygon extending from the centerline to 100 m into the adjacent land cover type, defined as the ‘landscape’ buffer; and b) a multiple ring buffer containing 5 m wide contour lines from the centerline to 100 m into the adjacent land cover type, derived using a low-pass moving average filter in Surfer. Average vegetation height and FCov was

determined within the landscape buffer (a), and within each of the 5 m buffers (b). The difference between vegetation heights and FCov within the 5 m buffers (b) and landscape average (a) (e.g. b-a) was used to determine spatial residuals of each buffer with proximity from the seismic lines. A positive residual indicates that vegetation is taller/denser than the landscape average, while a negative residual indicates that vegetation is shorter/sparser than the landscape average. The Topographic Position Index (TPI) tool was applied to the DEM to determine the spatial positioning of the local geomorphological attributes of the land surface as an indicator of the localised potential for accumulation of surface water. The TPI was applied using the DEM and a circular search window of 50 m, approximating the average size of land cover units found in the region. The duration of direct incoming solar radiation (RAD) in units of watt hours per m² was modelled using the digital surface model from April to October and provides a proxy indicator of either: a) the potential to support biomass growth through elevated or lowered photosynthetically active radiation; or b) the potential for in situ evapotranspiration due to locally warmer/drier or cooler/shaded environmental conditions. Both outputs were created in ArcGIS using TPI (Jenness, 2006) and Area Solar Radiation tools, respectively. The high-resolution (1:1,000,000) surface geology (GEOL) layer was derived by Fenton et al. (2013; <http://www.ags.gov.ab.ca/publications/MAP/PDF>).

Statistical analyses were performed in R and RStudio (R Development Core Team, 2017; RStudio, 2015) using raster, rgdal and ggplot2 packages. Due to splitting the data into two types of seismic line orientation and all permutations associated with variations in width, age, and different drivers for varying heights of vegetation, we ensured that the same number of observations were examined for each possible group within the random forest. For graphical analysis, primary drivers of spatial variations indicating taller/shorter vegetation or greater/lesser canopy cover and post-disturbance were used as categorical variables. TPI values were grouped into three classes (Ridge, Transitional and Valley) according to the landform classification method of Weiss (2001). We classified RAD values into three groups (sunny, intermediate and shadow) based on their quantile distribution. Quantile distributions were determined on a per pixel basis, binned into groups representing pixels that were sunlit up to 33% of the time (mostly in shadow ('shadow')), 34% to 66% of the time ('intermediate'), and those pixels that were sunlit more than 66% of the time ('sunny'). Surface geology features included three classes (eolian deposits, glaciolacustrine deposits and fen peat). Finally, the age of the seismic lines was grouped into two categories: those prior to 1999

(Older) and those since 1999 (Younger). To evaluate the interactions between vegetation structure and primary drivers for growth (TPI, RAD and GEOL), a One Sample Wilcoxon Test was used to determine whether the median of each sample was equal to zero (non-difference reference value). Due to non-normality of the data, unless otherwise noted, variations in height and fractional cover according to TPI, RAD, surface geology, and age of the seismic lines are expressed as averages and interquartile ranges (IQRs). In other words, average canopy height and fractional cover was determined for each individual seismic line, and across all buffer distances to a distance of 100 m from the centre of the seismic line. Within each 5 m buffer, average canopy height/cover was also determined along with the interquartile range of both individually. These were then subtracted from the site average to determine the residual deviation and range of deviation (across the IQR of all seismic lines within each class) every 5 m. This provides an estimate of the spatial variability in structural metrics with distance from the seismic line and based on the site average. In this paper the Kolmogorov-Smirnov statistical test, expressed as D-statistic with p-value, was used for the analysis of the equality of height and fractional cover distributions between areas classified as containing older vs. younger regeneration.

A random forest model (randomForest package in R (R Development Core Team, 2017); Breiman, 2001) was used to predict response variables that are spatially discrete based on the height/FCov residuals. Predictors and response variables were analysed in numerically continuous format. Further, a subset from the current dataset was used to cross-validate the random forest model. First, the dataset was randomly divided in half, which generated a training set and a testing set. The training set was used to train the random forest model and perform model optimization, while the testing set served as unseen data to assess model performance. During the training process, 2/3 of the training data was randomly sampled to build a single decision tree based on minimizing Shannon entropy at each decision node. Each branch of the decision tree will terminate when Shannon entropy fails to dip below a predefined threshold (i.e. information gain becomes minimal). At each node, x predictors were sampled, the number of which was determined as optimal via initial model tuning. The process of building a decision tree was repeated 500 times, yielding a random forest trained model. The predictors of the remaining 1/3 of the training data used to build single decision trees were evaluated through the decision tree to provide a so-called out-of-bag estimate of model performance. The importance of each predictor variable as evaluated by the random

forest model is subject to change based on the subset of data sampled from the training set, the order of which may change with model retraining (Mahoney et al. 2017). Therefore, to evaluate variable importance and its stability among a sequence of training repetitions, we performed seven random forest iterations and calculated the average using the variable importance (Gini importance) for each iteration (Strobl et al., 2008). The Gini importance is based on the Gini coefficient which is a measure of income inequality used to describe the overall explanatory power of the variables. The Gini importance measures the mean gain in Gini coefficient (or node purity) by splitting over a given variable. That is, for a variable with high explanatory power, mixed data at nodes are split into more pure classes resulting in a larger mean gain in purity. Conversely, a variable with less explanatory power will yield a less pure result after splitting and will hence receive a smaller mean gain in purity. The mean gain is the sum over all splits (across all trees) that include the variable, and as a result can exceed one (unlike the Gini coefficient which ranges from 0 to 1). The use of multiple random forest runs for importance calculations provided a stable order of predictor importance. Next, a testing data validation set was used to estimate the predictive power of the random forest model. Best model performance was assessed using the adjusted coefficient of determination ($\text{Adj } R^2$) and root mean squared error (RMSE). The use of $\text{Adj } R^2$ is favoured as it adjusts for the number of explanatory terms in a model relative to the number of data points. That is, $\text{Adj } R^2$ increases when a new explainer is included only if the new explainer improves the (non-adjusted) R^2 more than would be expected by chance. This circumvents perceived model improvements through the inclusion of additional random variables.

3.3. Results

3.3.1. Influence of seismic line width and orientation on vegetation

Overall, the greatest variations in vegetation height from the average occurred within 5 m of each seismic line centre ($p < 0.0001$). This is to be expected given the first 5 m buffer contains the edge-effect associated with the transition from disturbed (removed) to comparatively undisturbed canopy condition in all seismic lines sampled. The largest impacts from seismic lines extended up to a distance of 55 m ($p = 0.01$), adjacent to widest, west-facing seismic line edges. Variations in mean vegetation heights within this class ranged from -

3.82 m (west-facing) to -1.19 m (south-facing) (Figure 3). Further, vegetation heights were often greater than the average at distances between 20 and 55 m (Figure 3b). Ecosystems adjacent to narrow seismic lines appeared to be less impacted by seismic lines and tended to more closely represent the average, indicated by the small magnitude of variability of the residuals beyond 10 m (Figure 3 and Table 2). Variations in vegetation height residuals adjacent to edges facing north or south were also only minimally affected (Table 2).

Figure 3. Mean height variation as distances from seismic lines vary for different orientation classes: (a) south and north-facing; (b) west and east-facing areas. Color bands represent interquartile range (between the 25th percentile and 75th percentiles), whereas symbols represent the average deviation per 5 m buffer.

Table 2. Mean and 95 % confidence interval for Height and FCov differences from the average up to 5 m into the forest for narrow, medium and wide seismic lines. N = north-facing, S = south-facing, E = east-facing, W = west-facing.

	Narrow		Medium		Wide	
Edge	Height	FCov	Height	FCov	Height	FCov
S	-0.73 ± 0.14	-0.03 ± 0.01	-2.24 ± 0.30	-0.06 ± 0.02	-1.19 ± 0.26	-0.05 ± 0.02
N	-0.32 ± 0.13	-0.02 ± 0.01	-2.06 ± 0.40	-0.03 ± 0.01	-2.04 ± 0.29	-0.06 ± 0.02
W	-0.51 ± 0.18	-0.06 ± 0.01	-3.53 ± 0.27	-0.13 ± 0.02	-3.82 ± 0.29	-0.18 ± 0.02
E	-0.14 ± 0.14	-0.01 ± 0.01	-0.99 ± 0.31	-0.01 ± 0.01	-3.28 ± 0.38	-0.11 ± 0.02

FCov follows similar patterns observed for vegetation height, where the canopy cover of vegetation adjacent to wider seismic lines tends to vary from that adjacent to narrow seismic lines (Table 2, Figure 4). Average FCov of ecosystems proximal to wide seismic lines, especially those facing west, was 18% lower than site averages to a distance of 15 m, but greatly exceeded the site average (~34%) between 20 to 50 m from the seismic line. Ecosystems adjacent to lines running east-west (north and south-facing) appeared to be less affected, but still contained higher than site average canopy cover demonstrated between the 50th and 75th percentiles (Figure 4), possibly due to differences in resource allocation.

Figure 4. Mean fractional cover (FCov) variation as distances from seismic lines vary for different orientation classes: (a) south and north-facing; (b) west and east-facing areas. Color bands represent interquartile range (between the 25th percentile and 75th percentiles), whereas symbols represent the average deviation per 5 m buffer.

3.3.2. Interactions between vegetation structure and primary drivers for growth

3.3.2.1. Incident radiation

The influence of the duration of shadowed to sunlit pixels on spatial variations in vegetation height and FCov varies significantly depending on the seismic line width. The most significant differences in height occur within 5 m of the seismic line centre ($p < 0.0001$). Average height differences vary from -0.74 m to +0.15 m in wide and medium seismic lines, respectively and for pixels that receive the maximum duration of sunlight ('sunny'). Vegetation at distances greater than 10 m from the edge of seismic lines and in areas receiving the maximum duration of sunlight tend towards canopy heights that exceed the landscape average by 0.68 m (wide) to 1.38 m (medium), on average (Figure 5a). Areas that receive less sunlight (intermediate and shadow) have greatly reduced canopy heights adjacent to seismic lines. This illustrates that vegetation adjacent to medium seismic lines

likely receives adequate energy resources to grow, without excess energy and increased soil drying that may occur in areas containing wide seismic lines. Further increased soil drying along wide seismic lines may inhibit post disturbance growth due to changes in water availability and stomatal conductance.

Fractional canopy cover (Fcov) (Figure 5b) varies less than height with variations in solar duration. Reduced Fcov occurs predominantly in areas adjacent to wide seismic lines to a distance of up to 45 m ($p = 0.01$) where areas receive the greatest duration of solar radiation (Figure 5b). Wide seismic lines had much lower influence on areas that receive intermediate and low amounts of radiation. In these areas, fractional cover was slightly greater than site averages.

Figure 5. Variations in mean height (a) and fractional cover (b) in areas of maximum (sunny), intermediate, and low (shadow) sunlit conditions with distance from seismic lines. Color bands represent interquartile range (between the 25th percentile and 75th percentiles), whereas symbols represent the average deviation per 5 m buffer.

3.3.2.2. Influence of Geomorphology/Topographic Position

Local ground surface topographic position or geomorphology may be correlated with land cover type, where wetland/peatland environments are often locally topographically lower than upland forests in this region. While adjacent vegetation structures vary greatly along seismic lines (especially medium ones), we find that correspondence between topographic position, seismic line type, and vegetation structure does not vary greatly compared with other drivers. Despite this, vegetation found adjacent to medium seismic lines had the greatest height variability. Differences from the average at distances greater than 10 m were 0.21 m (on average; stdev. of average with distance = 0.24 m) when found on ridges and 0.06 m (on average; stdev. of average with distance = 0.21 m) areas, when found in valleys (Figure 6a). Vegetation immediately adjacent to medium seismic lines (within 10 m) tended to be taller on ridges ($p_{\text{ridge}} = 0.001$), than in localised depressions ('valley' areas). Vegetation heights found adjacent to narrow seismic lines are not greatly influenced by topographic position, compared with the average ($p_{\text{ridge}} = 0.18$ m; $p_{\text{transitional}} = 0.07$ m; $p_{\text{valley}} = 0.75$ m), while vegetation immediately adjacent to wide seismic lines (10-15 m from the edge) were taller than the average, regardless of topographic position (Figure 6a). Vegetation canopy cover is not greatly different among medium and wide seismic lines with variable topographic position (Figure 6b), however, vegetation adjacent to narrow seismic lines tends to have greater fractional cover deviation in topographically low-lying areas ('valleys') compared with transitional and ridge areas. Transitional topographic positions tend to have vegetation with greater variability of fractional cover, including areas where fractional cover exceeds that found on ridges (Figure 6b; medium and wide seismic lines).

Figure 6. Mean height (a) and fractional cover (FCov) (b) in areas containing different topographic positions and with distance from seismic lines. Color bands represent interquartile range (between the 25th percentile and 75th percentiles), whereas symbols represent the average deviation per 5 m buffer.

3.3.2.3. Surficial geology

Vegetation classified into surficial geology is characterised by taller vegetation height increments within eolian and glaciolacustrine surficial geologies compared with fen peat, as expected due to the often saturated nature of peatlands. Among the three types of surface geologies examined, and irrespective of seismic line width, vegetation found in fen peat showed the smallest height variations from the average, deviating by up to 0.03 m, on average (maximum standard deviation = 0.16 m). Proximal areas underlain by eolian surficial geologies were characterised by the greatest variations in vegetation height, ranging from -2.19 m to 1.43 m, on average, and especially within 5 m – 30 m of medium and wide seismic lines (Figure 7a). Within narrow seismic lines, the greatest height differences from the average occurred within 5 m ($p < 0.0001$) of the seismic lines. Variations in height were also highly variable along medium width seismic lines but is less pronounced adjacent to narrow

and wide seismic lines. Vegetation found on eolian and glaciolacustrine deposits were also taller adjacent to wide seismic lines, and had fewer areas of short vegetation (Figure 7a).

With regards to fractional cover (FCov) within proximal ecosystems, all seismic line widths were similar to the landscape average, varying by $\pm 1\%$ up to 5% except for within areas containing fen peat (Figure 7b). Adjacent land covers underlain by fen peat have less foliage cover (average = 2% medium, 9% wide, greater than average) up to a distance of 10 m from medium seismic lines and from 15 m from wide seismic lines. At distances greater than 15 m from wide seismic lines, vegetation tends to have up to 5% greater canopy cover than the landscape average. This is especially prevalent in peatland areas within close proximity to wide seismic lines. These exhibit greater FCov than in narrow and medium seismic lines, especially between 15 m and 45 m (average = 3% , stdev. of average with distance = 1%).

Figure 7. Mean height (a) and fractional cover (FCov) (b) in areas containing different classes of dominant surficial geology, with distance from seismic lines. Color bands represent interquartile range (between the 25th percentile and 75th percentiles), whereas symbols represent the average deviation per 5 m buffer.

3.3.2.4. Age since disturbance

Wide seismic lines that were developed prior to 1999 (Figure 8a) consistently have reduced vegetation heights averaging 2.22 m (IQR = -4.11 m to -0.61 m) shorter than the landscape average within seismic lines, despite a lengthy period of succession. For proximal ecosystems outside of seismic lines, the height distribution of vegetation was also significantly different between more recently developed ('younger') seismic lines with medium widths ($D = 0.22$, $p\text{-value} < 0.0001$) compared with wide seismic line widths ($D = 0.11$, $p\text{-value} < 0.0001$). As expected, vegetation is taller in areas adjacent to old seismic lines than it is adjacent to more recently developed ones, however, the variability in height is also much greater adjacent to medium seismic lines. For wide seismic lines, the effects extend up to 50 m ($p = 0.12$) for older regeneration, such that average tree heights were between 0.10 m and 0.68 m taller than the landscape average. Variability and height deviations from the average are much smaller adjacent to narrow seismic lines, regardless of age.

Within 5 m of narrow and medium seismic lines, vegetation fractional cover (Fcov) differences of up to 5% (IQR = - 0.13 to 0.11) from the average within distances of 5 m ($p < 0.0001$). While older more recently developed seismic lines have similar fractional cover with increasing distance from seismic lines, variations in fractional cover are much greater in younger, narrow seismic lines ($D = 0.19$, $p < 0.0001$), compared with younger, medium width seismic lines ($D = 0.12$, $p < 0.0001$) (Figure 8b).

Figure 8. Mean height (a) and fractional cover (FCov) (b) in areas classified as containing older vs. younger regeneration depending on interpretation from Google imagery, and with distance from seismic lines. Color bands represent interquartile range (between the 25th percentile and 75th percentiles), whereas symbols represent the average deviation per 5 m buffer.

3.3.3. Interacting influences of seismic lines using random forest methods

Random forest predictions from each model were assessed for optimal performance via analysis of the testing set. Each model parameter and its performance are shown in Table 3. According to the testing data validation, the interaction of six predictors using distance, width, cardinal direction, topographic position (TPI), period of incident solar radiation (RAD), and surface geology (GEOL) provide the best comparative outputs for predicting spatial variations in vegetation height and fractional cover with distance from seismic lines. Indeed, it is possible to see significant differences between results from the best random forest predictions with the other models (Figure 9). The most to least influential variables for predicting height were ranked as: distance from the seismic line, RAD, TPI, GEOL, width, age, and cardinal direction. For fractional cover, the ranking of variable importance is: RAD, distance, TPI, cardinal direction, width, GEOL, and age (Table 3).

Table 3. Summary of RF model performance per number of predictors for testing data

Testing Validation Data					
N _{predictors}	Predictors	R ²		RMSE	
		Height	FCov	Height	FCov
2	Distance, Width	0.22	0.08	1.65	0.16
3	Distance, Width, Cardinal	0.23	0.10	1.64	0.16
4	Distance, Width, Cardinal, Age	0.23	0.10	1.66	0.16
4	Distance, Width, Cardinal, TPI	0.29	0.13	1.60	0.16
4	Distance, Width, Cardinal, GEOL	0.30	0.12	1.60	0.16
4	Distance, Width, Cardinal, RAD	0.32	0.18	1.58	0.15
6	Distance, Width, Cardinal, TPI, RAD, GEOL	0.70	0.50	1.13	0.13
7	Distance, Width, Cardinal, Age, TPI, RAD, GEOL	0.60	0.40	1.22	0.13

Figure 9. Variable importance graph of the most significant variables to predict height (a) and fractional cover (b), in descending order by a mean decrease in Gini coefficient. Variables with high Gini coefficients contribute more to the model and have higher predictive power than variables with low Gini coefficients.

3.4. Discussion

Seismic line linear disturbances can have significant effects on proximal ecosystems, especially when seismic lines are either medium or wide and when they face particular cardinal directions (especially west-facing edges), illustrated here for a small sample area. Further, Finnegan et al. (2018) found that the density of seismic lines within an area can also have significant influences on proximal ecosystems. While the impact of seismic lines on ecosystems is relatively well-known (Bayne et al., 2011; van Rensen et al., 2015; Paulson and

Thomson, 2016; Pigeon et al., 2016 Finnegan et al., 2018), less is understood about the combined interactions between seismic lines and proximal ecosystems. Numerous complex and non-linear interactions influence the condition of ecosystems within and beyond seismic lines, especially as a result of changes to soil moisture and amount of incident solar radiation (Gallardo-Cruz et al., 2009; Méndez-Toribio et al., 2016), related to local topographic variability, surface geology, soil types, and vegetation/seismic line structural variability. Seismic line attributes such as width, time since disturbance and orientation (van Rensen et al. 2015) can complicate soil moisture/radiation relationships and resources required for productivity and maintenance. Here we examined a heterogeneous case study area of upland forest and wetlands crossed by a range of seismic lines of different ages found in the Central Mixedwood ecoregion of the Boreal Plains ecozone of central Alberta. The interactions that occur between the seismic line environment and proximal ecosystems are examined using a combined lidar remote sensing and geospatial analysis approach applied individually to unique drivers and in combination within a random forest machine learning framework (Breiman, 2001).

3.4.1.1. Effects of seismic line width and cardinal orientation on vegetation structure

From the random forest model analysis, we find that the proximity of ecosystems to seismic lines has the greatest influence on variations in vegetation height and canopy fractional cover. Vegetation within close proximity to seismic lines leads to pronounced reductions in vegetation height and fractional cover, especially within 5 m to 15 m of seismic line centrelines. Further, our findings demonstrate that wider seismic lines have greater impacts on height and fractional cover up to distances of 60 m from the seismic line, when compared with the 100 m landscape average for similarly oriented and structured seismic lines. Vegetation in close proximity to medium and wide linear disturbances are often characterised by shorter trees and more open canopy coverage than vegetation in close proximity to narrow seismic lines (Figures 3 and 4), but also tend towards taller than average trees and greater canopy cover at distances of 10-35 m from seismic lines. In addition, cardinal orientation of seismic lines and the aspect of seismic line edges relative to solar geometry also have significant effects on the variation of vegetation height and fractional

cover, especially in areas that receive differential amounts of radiation over time. Northern latitude ecosystems receive low amounts of radiation compared to global averages (Holland and Steyn, 1975; Daws et al., 2002) and are therefore frequently radiation and temperature limited, provided adequate soil moisture is available. We found that proximal westerly aspect ecosystems up to 10 m from wide seismic lines contained vegetation that was shorter with reduced canopy cover (i.e. overall lower biomass) compared with vegetation characteristics on north and south-facing sides (Figures 3a and 4a), while vegetation heights beyond these distances were taller. The impacts aspect was less pronounced in narrow and medium seismic lines.

3.4.1.2. Interactions between vegetation structure and primary drivers for growth

Given southerly aspects receive more radiation than northerly aspects in the northern hemisphere, the observation of reduced growth in zones of increased periods of incident radiation indicates some other systematic resource limitation. RAD is also a much stronger driver of proximal vegetation response than GEOL (Figure 9), therefore warming and drying of the land surface through evaporative processes, especially on the southerly aspect side of wide seismic lines is a favoured hypothesis.

Incident radiation and energy balance impact ambient temperatures and water fluxes, which represent two major factors controlling the growth behaviour and distribution of vegetation structure (Holland and Steyn, 1975). Due to relatively slow regeneration rates within some seismic lines and reduced shadowing along seismic line edges, proximal vegetation receives greater duration of incident radiation. Sunny/illuminated areas in narrow seismic lines had taller trees and denser foliage than those areas that were prone to greater shadow cover and reduced duration of the sunlit period, irrespective of the distance from the seismic line. For medium width seismic lines, we hypothesize that greater canopy openness associated with seismic line width has created an environment with reduced water or light limitations. In these environments, the ground surface remains in shadow and therefore is prone to reduced evapotranspiration (Kettridge et al., 2013), while trees are able to receive enough sunlight to sustain growth and productivity levels. These combined mechanisms result in greater height differences from the average because the environment is a non-

limiting factor, though this requires further testing as variations in height and cover are used as proxy indicators for environmental processes. On the other hand, within wide seismic lines, variations in vegetation height appear to be limited by moisture availability.

These results may be indicative of differentials in resource allocation depending on spatial proximity, location and environmental attributes, and assuming that plants require a similar balance of energy, water and mineral nutrients to maintain optimal growth (Chapin et al., 1987). Therefore, increased incident radiation may also increase moisture stress along seismic line boundaries, whereby larger openings result in greater light penetration to the lower canopy and ground surface, ultimately increasing evapotranspiration (Groot et al., 1997). Few studies have demonstrated the implications of seismic line orientation on proximal vegetated ecosystems (Gehlhausen et al., 2000; MacFarlane, 2003; Dabros et al., 2017). In a similar study in discontinuous permafrost, south and westerly facing slopes corresponded with 67% of the areas that had undergone permafrost change over 30 years (Chasmer and Hopkinson, 2017). This indicates the large amount of energy received by forested edges and transition zones to open areas such as wetlands (in the case of Chasmer and Hopkinson, 2017) and especially seismic lines, which are not as directly impacted by local latent heat exchanges.

Boreal mixedwood sites are typically dominated by shade-intolerant species such as trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh.), white spruce (*Picea glauca*) and lodgepole and jack pine (*Pinus contorta* Dougl. ex. Loud. and *Pinus banksiana* Lamb.) (Huang et al., 2013). Spruce shows a strong response in radial and height growth to increases in light (Lieffers and Stadt, 1994; Wright et al., 1998). Furthermore, reduced conifer height growth under dense hardwood canopies is attributed to incident radiation below 20% of full sunlight. These are well below levels needed for optimum growth (Huang et al., 2013; Lieffers and Stadt, 1994). Further, Groot et al. (1997) demonstrate that the height of planted spruce seedlings was directly correlated to the amount of sunlight reaching the strip-cut opening and adjacent south-facing edges. In the boreal mixedwood, increased incident radiation through canopy openings is often compensated by development of a shrub layer (Constabel and Lieffers, 1996), however, in our study, vegetation located in sunny areas displayed more open foliage cover than those in shadow or intermediately irradiated stands, possibly due to moisture limitation.

Local topographic variability is also often indicative of the moisture availability to vegetation, such that lower parts of slopes are usually cooler due to the accumulation of surface water/latent heat exchanges and may have saturated soil moisture conditions (Daws et al., 2002; Holland and Steyn, 1975). Topographically upraised areas often have shallow soils with reduced capacity for moisture retention (Ebel, 2013; Galicia et al., 1999; Wang et al., 2011). In topographically upraised or 'ridge' areas located on medium and wide seismic lines, we observed taller vegetation relative to the landscape average, while topographic depressions or 'valleys' sometimes contained shorter vegetation in areas that were not saturated (Figure 6a). This was sometimes found in areas adjacent to seismic lines up to a distance of ~35 m from the centre of seismic lines. Although our work did not discriminate between different plant species, we hypothesize that most of the vascular vegetation in the study area is likely water-intolerant in saturated conditions. Despite this, valleys had reduced foliage cover than ridges, due to the prevalence of dense peat layers and saturated conditions (Figure 6b).

Topographic variations are also inextricably linked to surficial geology. We found that wider seismic lines underlain by eolian and glaciolacustrine deposits displayed vegetation that was taller and had greater canopy coverage compared with vegetation underlain organic peat soils (fen peat, Figure 7b). Fens are characterised by slow, lateral water movement and have deep organic deposits (> 40 cm). High-water tables often connect wetland systems over vast distances (Downing and Pettapiece, 2006). Minimal height and fractional cover differences from the average within peatland environments adjacent to seismic lines supported by greater occurrence of flooding, which limits soil aeration, chemical and biological reactions (Bonan and Shugart, 1989; Levine et al., 1993). When comparing the impacts of eolian and glaciolacustrine surficial geologies in close proximity to seismic lines, we find that areas underlain by glaciolacustrine deposits tended to have significantly shorter trees than those areas underlain by eolian deposits. Glaciolacustrine deposits comprise sand and clay layers and therefore have less moisture and nutrients available for plant development (Chipman and Johnson, 2002) compared with eolian deposits, which are comprised of silt (Trenhaile, 2010). Within fen peatlands, vascular vegetation foliage cover was lower than the landscape average up to a distance of 10 m into the forest, likely due to changes in hydrology and increased saturation. However, at distances greater than 10 m, we found that proximal areas underlain

by fen peat displayed greater foliage cover, possibly as a result of land cover edge effects, leading to greater shrub development; an indicator of drier soil moisture conditions.

The pronounced variability in average height found in areas underlain by eolian and glaciolacustrine deposits also indicate other factors affecting plant structure, including spatial variability in elevation, water and sunlight. In addition, once seismic lines are established, exposure of the soil surface to rain splash, wind, frost, and desiccation could invariably lead to increased amounts and rates of solid and dissolved sediment runoff, impacting the capacity for soil infiltration and moisture retention (Guthrie, 2002). Further analysis focused on soil infiltration rates and moisture retention could improve understanding of the relationship between seismic lines, surface geology, topography and variations in proximal vegetation height and cover.

Finally, we find that age since disturbance is also important for proximal vegetation structural variability. Greater canopy fractional cover is found in areas near narrow seismic lines, whereas greater vegetation height is found in areas proximal to wide seismic lines. This indicates that older regeneration may be more sensitive to incident radiation than younger vegetation, according to our criteria. Also, younger regeneration had greater variability of fractional cover compared with that of older, likely due to intense productivity and leaf production in the early development of plants (Blackman, 1919; Bar and Ori, 2015).

3.5. Limitations

The comparison of seismic line influences on proximal ecosystems examined in this study is limited by the size of the study area examined. Further, hypotheses described in the discussion should be tested using hydro-meteorological assessment to better understand and validate local environmental drivers. Lidar is already a well-proven technology for detecting structural characteristics (height and cover) of vegetation within boreal ecosystems (Lim et al. 2003; Hopkinson et al. 2005; Morsdorf et al. 2006; Hopkinson et al. 2009) and therefore may require only minimal validation. While these results are informative of the potential for seismic lines to impact local ecosystems in this particular area using vegetation height and cover as cumulative proxy indicators of spatial variations in resource allocation/stress, we encourage the application of the methods described here to other parts of the Boreal Oil Sands Region to further test hypotheses. Future activities confirming and/or suggesting

alternative results should also examine and compare sites that are only disturbed by seismic lines vs. those disturbed by seismic lines and other forms of disturbance such as wildfire, insect/pathogen outbreaks in the recent history of ecosystem monitoring, as well as roads and other forms of anthropogenic disturbance. The combination of airborne lidar data, geospatial data, and derivative products applied to variable age seismic lines also provides a remote sensing-based 'space for time' or chronosequence assessment that does not necessarily require multi-temporal lidar data acquisitions. In other words, a less expensive approach for spatial monitoring of seismic lines and other forms of disturbance through time based on the spatial variability of ecosystem recovery.

3.6. Conclusions

Our study demonstrates that seismic lines impact proximal boreal forest plant communities and ecosystems by changing the adjacent landcover edge vegetation structures associated with changes in vegetation height and fractional cover compared with the landscape average (to 100 m). However, the extension of these effects beyond seismic lines varies depending on seismic line width and the distance from the seismic lines, as well as orientation. Wider seismic lines are prone to greater magnitudes of influence on proximal vegetation with greater distances from the seismic lines. Thus, we propose that construction of narrow and east to west oriented seismic lines would reduce significant alterations to the local environment compared with wider, north to south oriented seismic lines. Also, management plans for seismic lines should focus on reclaiming wider seismic lines first to reduce impacts over time. Based on the results presented, several new directions for future research may also be explored. This could include, for example, a) the influence of seismic line characteristics on the spatial variations in vegetation structural characteristics within seismic lines; and b) identifying moisture and radiation limitations proximal to seismic lines would elucidate hypotheses using vegetation structure observations as proxy indicators for environmental conditions. Finally, a random forest model was used to better understand the combined influences of seismic line attributes (width, cardinal orientation and age) and local environment stressors (topographic position and hydrology, radiation, surface geology) on spatial variations in proximal vegetation characteristics. Given the model explains at least 70% of the variance in vegetation height surrounding the seismic lines, the opportunity exists

to apply random forest in a predictive mode to create a spatially variable seismic line impact assessment tool. With this in mind, management strategies for geophysical exploration of oil and gas deposits could virtually establish seismic lines and predict impact on surrounding ecosystems, thus, potentially minimizing ecosystem damage.

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4. CONCLUDING REMARKS

In the first study, we verified that edge effects on height and understory density in native fragments and *Eucalyptus* stands were more intense when they were found nearby pastures. Specifically, in this case, native and riparian native fragments had edge trees shorter than the core and an increased understory density. Meanwhile, *Eucalyptus* trees were also shorter but showed understory less dense than the core habitat.

In both cases, it seems that the relaxing of competition for light associated with thigmomorphogenic responses possibly led by wind in edges within pasture fields, given the opening created by this patch type, might reduce tree height. The increased understory density in the native fragment edge indirectly indicates that pioneer species such as lianas, shrubs and herbaceous plants adapted to the edge conditions have proliferated over this habitat, possibly gradually replacing old-growth forest species, thus, impacting the local biodiversity.

However, the decreased understory density found in edge *Eucalyptus* might be mostly associated with silvicultural treatments such as weed control. An interesting finding was that nearby riparian pasture, edge *Eucalyptus* were taller with understory less dense, suggesting that the available water contributes to avoiding moisture stress.

Additionally, nearby pastures, regardless of proximity to water, the depth of edge influence could be extended to further distances than 40 m. Meanwhile, native fragments adjacent to stands and vice-versa displayed the lowest impacts on vegetation structure, showing a depth of edge influence of 10 m.

Thus, the magnitude of the variation in both variables under study varied primarily because of the edge proximity and type of the adjacent fragment. Greater edge proximity and contrast between fragments resulted in a greater magnitude of influence with distance from the edge. Our findings revealed that protecting native forests in silviculture areas given their capacity to minimise edge effects could assist in maintaining the stand homogeneity, besides helping to preserve the local biodiversity.

In the second study, the results showed significant variations in adjacent forest structure proximal to seismic lines, including reduced height and fractional cover nearest to the centre of the seismic line. In this context, the magnitude of edge effects beyond seismic lines varied according to seismic line width and the distance from the seismic lines, as well as

orientation. Wider seismic lines, especially along west-facing edges, displayed greater magnitudes of influence on proximal vegetation with greater distances from the seismic lines, suggesting that restoration management plans for oil and gas exploration areas should first aim this seismic line type.

In addition, by using a random forest model we observed that combined variables including distance from the seismic line, width of the seismic line, cardinal direction and incident radiation, topographic position and underlying surface geology could be used to predict spatial variability of vegetation height to an accuracy of 70 % (R^2). Therefore, we proposed the use of a spatially variable seismic line impact assessment tool by applying random forest in a predictive mode, allowing management strategies for oil and gas exploration to virtually establish seismic lines and predict their impact on surrounding ecosystems, possibly minimising damage.

In this dissertation, we focused on large-scale edge effects on different types of vegetation, using lidar as a robust tool to assess forest structure variations. The knowledge generated in this study is, therefore, a key point for the development of future studies combining lidar and field data in fragmented landscapes, which could provide a better understanding of edge effects both quantitatively and qualitatively.