SPATIAL AND TEMPORAL MORPHOLOGICAL CHANGE IN CANADIAN BOREAL FORESTS

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A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

GRADUATE PROGRAM IN GEOGRAPHY
YORK UNIVERSITY
TORONTO, ONTARIO

May 2018

Abstract

Boreal forest cover change occurs as a result of various processes acting on a landscape (e.g., wildfire, harvest, insect damage, regeneration, disease). Quantification and comparison of this change over vast extents and long periods can be challenging but holds the potential to characterize disturbance regimes and how their characteristics differ in space and time. This study compares morphological patterns of boreal forest cover change between 2001 and 2014 across the entire Canada and seeks to answer whether forest disturbance patterns differ among provinces and territories and further whether these patterns have changed through time. The Canadian portion of the boreal part of the Global Forest Cover dataset from the University of Maryland is processed to obtain morphological pattern element classes using the Morphological Spatial Pattern Analysis (MSPA) tool and further encoded by nominal geographic and temporal grouping variables to facilitate comparison among them. The use of join count statistics enabled assessing the composition and configuration of the spatial patterns on binary maps, where fire disturbances were not mapped as objects but by individual and independent. Bootstrap resampling produced empirical distributions that facilitated the comparisons of the join count analysis outcomes among the factor groups: (1) spatially groupings (i.e., Canadian provinces and territories) and (2) temporal groups (i.e., years 2001 through 2014). In order to answer the questions and statistically test the effect of spatial and temporal groupings, ANOVA and Levene's tests were used to compare means and variances of join count outcomes for each of the morphological classes, respectively. This study concludes that the spatial and temporal morphology of forest disturbance pattern within the boreal biome of Canada differ through time and among provinces and/or territories and identifies the main cases where the differences are significant. Several possible explanations as to why the differences in the aforementioned cases for each of the morphological classes, how their shape and size can be explained using the number of joins as well as how they could be interpreted in the context of disturbances are provided. This study sets a promising direction for future studies in which each of the curious irregularities in the pattern that was mentioned holds a potential to be a topic for another study and be explored in more detail with consideration of influential factors.

Dedication

This thesis is dedicated to my mom, whose unconditional love is the purest love that can be found on this Earth.

Acknowledgements

The last two years was a period of learning and development for me in both professional and personal levels and I would like to reflect on the people who helped me throughout this journey. I would first like to thank my thesis supervisor, Dr. Tarmo K. Remmel who supported me greatly and was always accessible and willing to provide me with his valuable guidance through weekly meetings, workshops, and instant messaging. I have learned a lot from him and come to appreciate his vast knowledge, work ethic, and high standards which set a great example for me. I am also grateful that he offered me the necessary hardware and software to carry out my research in the Geoinformatics Research Laboratory. I would also like to express my gratitude to Dr. Taly D. Drezner and Dr. Martin Bunch, the other members of my examining committee, for reviewing my research and their helpful feedback.

My special thanks go out to the Department of Geography at York University as well as the Faculty of Graduate Studies for granting me York Master's International Fellowship and Teaching assistantship opportunities. I also thank York University LA&PS research grant for funding Dr. Remmel's project "Does forest change morphology differ among biomes, vector of change, continent and counties"? that allowed me to work as a research assistant in the summer of 2016, a project that gave me a lead up to my M.Sc. Thesis.

I would like to thank my lab mates and colleagues in the department who supported me during my time at York University and also my roommates, Célia and Jon, it was nice to come back home to such friendly faces. Last but not least, I would like to thank my loving family who always wanted the best for me, even if that meant being apart from each other.

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1. Introduction

1.1 Forest disturbances

A *forest* is defined as an area larger than 0.05 to 1.00 ha where there is 10 to 30% coverage of plants that are taller than 5 m at their maturity stage (UNFCCC, 2001). The Food and Agriculture Organization of the United Nations describes forest as an area larger than 0.5 ha with trees taller than 5 m (FAO, 2010). Almost 30% of the global terrestrial area is covered by forests, which translates to over 40 million km^2 (FAO, 2010).

Forests are the most substantial source of plant biomass and contain over 80% of the global biomass (Kindermann et al., 2008). Tropical forests with 44% are the largest source, temperate forests, and boreal forests are ranked as second and third with 30%, and 9%, respectively, while the share of Mediterranean shrublands is 8%, and tropical savannas and grasslands are 6% (Chapin et al., 2002). Additionally, forests are one of the key elements in the delivery of the ecosystem services, such as timber, habitat, water quality, carbon sequestration, and recreation (Luque and Iverson, 2016). Forests are also crucial in reducing the risks of global climate change, since diminished deforestation and forest degradation buffer carbon emissions, so does increased afforestation and reforestation (FAO, 2010).

Forests are dynamic environments that change over time and across geographic areas (Linke et al., 2007). Biotic processes (e.g., forest succession), forest disturbances, human activities, and environmental factors (e.g., climate) are the primary vectors in changing the composition and distribution of forests (Linke et al., 2007). Understanding this change, disturbances that drive this change as well as the produced spatial patterns from this change not only is relevant for the conservation of forest landscapes but also is essential for the protection of the species diversity (Balmford et al., 2003), and studying ecological patterns and processes (Turner, 2010), as the landscape patterns that we see in the real world are the result of various ecological processes, by looking into the patterns, we can develop hypothesis about the ecological processes and start to make assumptions about how the processes work and eventually infer the processes from the patterns.

A disturbance is defined as an ecosystem force causing a remarkable change in the landscape pattern and function (Forman and Godron, 1986), or an event that disturbs the structure of an ecosystem, community, or population that alters its natural resources (White and Pickett, 1985). A disturbance regime refers to the long-term spatial and temporal dynamics of a disturbance (Turner, 2010) and in order to understand them and their impacts, several parameters are suggested to be quantified: return interval, rotation period, intensity, severity, residual, size, and spatial pattern (Hunter, 1999; Turner et al., 2001; White and Pickett, 1985).

Return interval and *rotation period* refer to the frequency of disturbance occurrence or the average time between the occurrence of the disturbances and their duration (Hunter, 1999; Perera et al., 2007). *Severity* and *intensity* characterize the magnitude of the disturbances (Perera et al., 2007), in other words, the amount of vegetation loss or the rate of the survival in biomass. A parameter that has been shown to be important in this regard is a measure of forest *residual*, also known as, post-fire residual structure (Perera et al., 2007) that refers to the remaining forest after a disturbance (i.e., unburned cover).

These residuals are represented as patches that are defined as contiguous areas that have different appearances, functions, forms, structures, and compositions from their surroundings (Forman and Godron, 1986). The next parameter is the *size* that refers to the extent of the disturbance (Perera et al., 2007). The size parameter relates to the scale or the spatial resolution in which a phenomenon is represented that makes it a crucial determinant of how a phenomena is viewed and interpreted (Schneider, 1994). Therefore, when studying disturbances, size should be taken into account as it impacts our ability to measure the characteristics of the disturbances and examine their observed spatial patterns (Turner et al., 1989), which brings us to the *spatial pattern* or spatial distribution that refers to the extent of the disturbance as well as the spatial arrangement of disturbance patches (Linke et al., 2007).

Wildfire, harvesting, insect outbreaks, ice, wind-throw and human activities are the major ecological disturbances. These disturbances induce the alterations in landscape mosaics and forest cover and produce the patterns that this study seeks to characterize. Wildfire is one of the main disturbances, influencing many of the natural cycles at a global scale (Thonicke et al., 2001) and soil properties (Certini, 2005), caused mainly by lightning and human activities. As a result of the strong relationship between fire occurrences and meteorological elements such as lightning, increased interest in studying climate change caused a growth in interest in wildfire and biomass burning (Levine et al., 1992).

Insect outbreaks kill or damage forests in large extents, such as spruce budworm in Eastern Canada (Bonan and Shugart, 1989) or Siberian silkworm in some of the Siberian forests (Isaev and Krivosheina, 1976). Forest harvesting is a human-caused disturbance that alters forest cover in a controlled manner. Although natural disturbance regimes are shown to the finest guideline for forest management (Seymour and White, 2002), understanding human-caused disturbances such as harvesting and its ecological impacts would provide a better perspective on sustainable forest harvesting strategies (Roberts, 2007).

Wildfire is the primary natural disturbance in the boreal forests, for instance in Canada, wildfires burn 20000 to 30000 km^2 of forests every year in which the majority of them are boreal forests and this number is doubled over the last two decades (Burton et al., 2009). Wildfire has several positive and negative effects. The negative effects include the carbon emissions caused by forest fires that increase the greenhouse gasses in the atmosphere both in a global scale (Mattis et al., 2001) and in the boreal biome (Kasischke et al., 2005). As for the positive impacts, regeneration of many of the plant species, such as species, spruce, and pine depend on the fire (Stocks et al., 2003), but also fire is shown to increase the local mixture of plant diversity (Ruokolainen and Salo, 2006), and its intensity has a clear influence on initial vegetation succession and composition (Ruokolainen and Salo, 2009).

Impacts of the forest disturbance, especially wildfire, on the landscape heterogeneity and spatial patterning of the landscape (Turner et al., 1994) are the main focus of this study. Turner (2010) highlighted the improvements in understanding of heterogeneity in the landscape as one of the general ecological insights that are gained from studying disturbances. As these disturbances have a mutual relationship with landscape heterogeneity and are changing the landscape patterns (Turner, 2010), they are an important topic for landscape studies (Risser, 1984).

1.2 Research questions

Global forest cover change is an undeniable fact that occurs due to various change vectors: forest fires, harvesting, insect damage, regeneration, and human activities to name some of the dominant processes. This research is designed to analyze temporal morphological pattern changes and spatial differences in forest disturbance within the boreal biome of Canada among the years 2001 through 2014. Of specific interest is whether patterns differ among divisions of geographic space (i.e., provinces or territories) and/or through time. This research quantifies the spatial patterns in the Canadian forest cover disturbance using a standardized morphological approach (MSPA) and statistically tests for significant differences across space and through time. The main goals of this study are to (1) characterize patterns of disturbance, and (2) to understand whether differences exist among jurisdictions within the boreal biome of Canada and whether differences appear through time. The main research questions posed are:

1. Does the spatial and temporal morphology of forest disturbance pattern within the boreal biome of Canada differ through time?

2. Do the spatial morphologies of forest disturbance patterns in the boreal biome of Canada differ among provinces and/or territories?

1.3 Research objectives

This research concentrates on the composition and configuration of the morphological classes as the main components of the landscape pattern. The proposed research strives to develop a customized technique for comparing morphological changes in the forest maps. This study has 5 objectives (Figure 1) and the following sub-headings in order to answer the research questions:

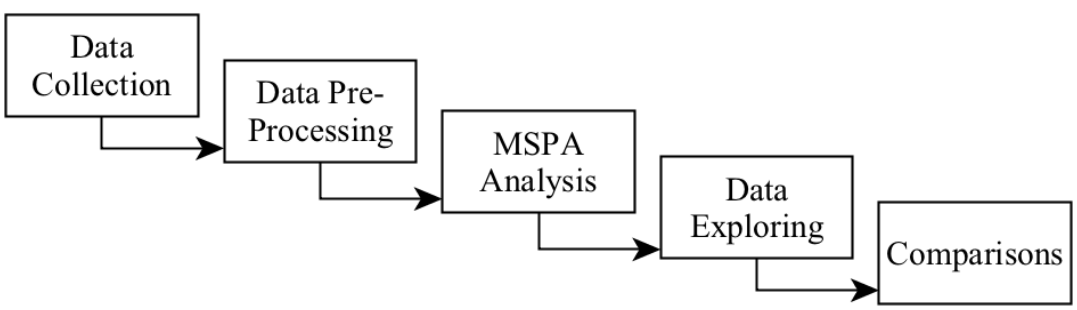


Figure 1. The sequence of subsequent objectives to answer the research questions

1. Obtaining and standardizing of the three main datasets:

    - Download the tiles covering Canadian boreal forests from Global Forest Cover (GFC) website: (https://earthenginepartners.appspot.com)
    - Download boundaries of provinces and territories of Canada from Global Administrative Areas (GADM) website: (http://www.gadm.org)
    - Download boundaries of boreal biomes of Canada from The Nature Conservancy (TNC) website: (http://maps.tnc.org)

2. Data pre-processing of the three main datasets:

    - Extract the boundaries of provinces and territories from GADM dataset
    - Extract the boundaries of boreal biomes of Canada from TNC dataset
    - Clip the GFC dataset based on provinces/territories and boreal biomes of Canada
    - Produce 14 binary maps for each province/territory by reclassifying the GFC layers
    - Create folders for each province/territory in which all the GFC layers are stored

3. Run MSPA analysis on GFC layers:

    - Perform MSPA analysis for 14 layers of each province/territory
    - Create an organized dataset for the map outputs of MSPA analysis (i.e., stored in separate folders per province/territory) with pre-defined naming convention that specifies the name of the province/territory, the year of the disturbance, and MSPA settings
    - Create a collection of Comma-Separated Value (CSV) files for the associated attribute tables and produce a master table for them in R

4. Spatial and temporal comparisons by developing a customized framework for comparing morphological change in the boreal forests

    - Bootstrapping and performing join count statistics and collecting the results
    - Collecting the result files that include the output of the join count statistics

5. Compare the morphological change in the forest cover over time and across geographic areas and understand the spatial and temporal trends in morphological change

    - Producing boxplots from the outcomes of the join count analysis and looking into the patterns that stand out
    - Running ANOVA and Levene's Test on the data that was involved in those patterns that stood out
    - Discussing what different number of joins for each morphological class means and how they can be explained in the context of forest disturbances and their patterns

1.4 Study areas

The study areas of this research are the entire boreal biome of Canada (Figure 2), this massive biogeoclimatic zone which is referred to *boreal forests* in North America (Hoffmann, 1958), occupies a large extent of lands in the northwestern hemisphere with coverage of coniferous forests and woodlands, wetlands, and lakes and a wide range of cold-tolerant tree species.

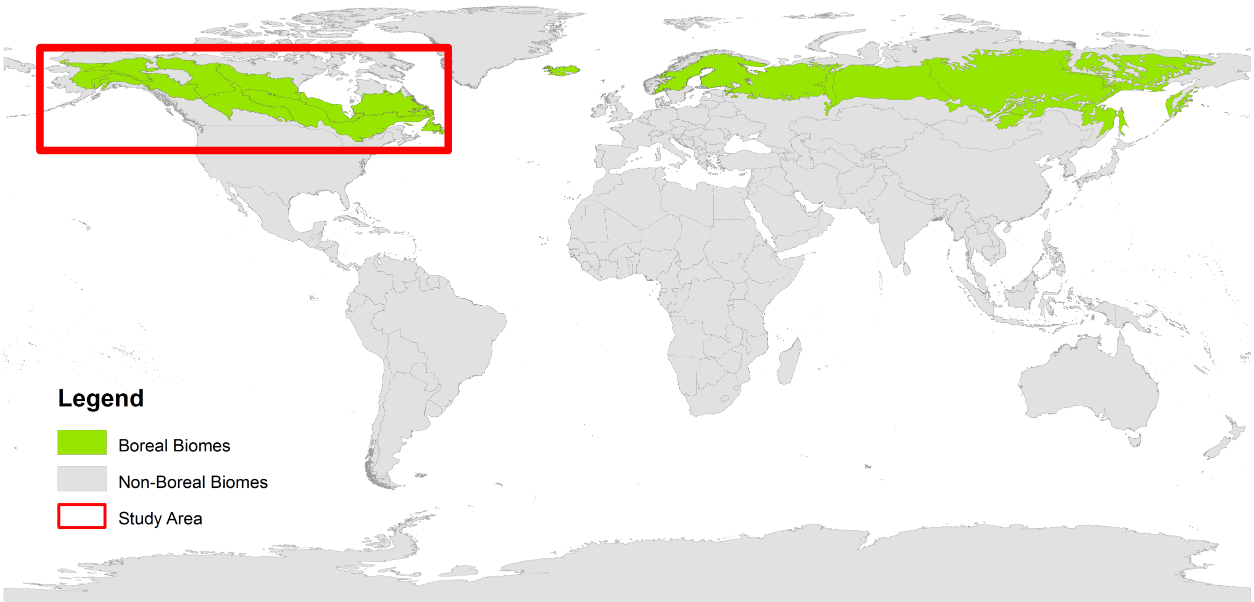


Figure 2. Map of the boreal biomes of Canada as the study area, produced from GADM and TNC datasets.

The North American boreal forests are mainly covered with *Picea mariana* (black spruce) and *Picea glauca* (white spruce) and in the central Canada, drier condition provide a suitable environment for growing *Pinus banksiana* (jack pine), and moister climate is suitable for *Abies balsamea* (balsam fir) and *Larix laricina* (tamarack), however, eastern Canada has wider diversity that includes white spruce, balsam fir, *Pinus resinosa* (red pine), *Pinus strobus* (white pine), and *Thuja occidentalis* (white cedar) (Strahler and Archibold, 2011).

Not only does this zone provide a wide variety of ecosystem services for human and wildlife consumption, such as food, renewable materials, and habitat (Brandt, 2009), but also has cultural value to indigenous and other peoples (Brandt et al., 2013). The boreal biome is not static and is affected by many vectors of change, environmental factors, and ecological processes (Bonan and Shugart, 1989) at various spatial and temporal scales. The natural drivers of change that, influencing the boreal biome are included but not limited to climate, wildfire, insects, and disease and also the interactions between these vectors (Brandt, 2009).

1.5 Literature Review

1.5.1 Landscape pattern analysis

From an ecological perspective, a landscape can be defined as spatially heterogeneous land, consisting of interacting, yet distinctive ecosystem types and their transitions that are under the influence of the same broad climate where an almost identical set of disturbance regimes can be found (Forman and Godron, 1986). Spatial heterogeneity is the variability of a system property (e.g., landscape mosaics) across space (Li and Reynolds, 1994). Forman and Godron (1986) and Turner (2001) indicated three linked characteristics of the landscape that are useful to be understood: its structure, its function, and how it changes.

Structure refers to the spatial relationship between ecosystems, patches, corridors, and the matrix, which will be referred to as landscape pattern in this study, *function* is the interaction between spatial elements in a landscape, and *change* are the alterations that occur over time in the pattern and function (Forman and Godron, 1986; Turner, 1989), primarily caused by natural or anthropogenic disturbances. These disturbances are one of the fundamental processes that affect the landscape pattern and functioning of a landscape over time and across geographic areas, therefore, they are studied in detail in the field of landscape ecology (Turner, 1987).

Two principal components should be considered to describe the landscape pattern: composition and configuration (Remmel and Csillag, 2003). *Composition* or amount refers to how spatial elements and their relative propotions are by looking at the quantities of different elements in a landscape, regardless of their positioning and *configuration* or arrangement refers to how those landscape elemets are distubuted in space by looking at their spatial characteristics and their placement (McGarigal, 2002; Remmel and Csillag, 2003).

Landscape ecology is the field of studying the reciprocal relationship between ecological processes and the spatial patterns that they produce on a broad spatial scale (Turner, 1989), in other words, the connection between the spatial composition and configuration of landscape mosaics and ecological phenomena (Wiens et al., 1993). Therefore, landscape ecology concentrates explicitly on the spatial pattern as its core topic to understand the changes occurring within the landscape to a larger extent than traditional ecology, spatially and temporally (Risser, 1984; Turner et al., 2001).

The important questions regarding the composition and configuration are a) how do they develop and b) how do they change over time and across geographic areas? This is where landscape ecology and the landscape pattern intersect, as the type, size, shape, boundaries, and arrangements of the spatial elements in a landscape and their alterations over time would influence various ecological processes (i.e., dispersal across heterogeneous landscapes (Tischendorf, 2001)) within the landscape (Turner et al., 2001; McGarigal, 2002; Linke et al., 2007) and interfere with biodiversity conservation, population persistence, and ecosystem health (With et al., 1999).

Alterations to landscape patterns are the result of various actions, such as abiotic processes (e.g., climate, landform, and soil) and biotic interactions (e.g., competition, predation, and succession), human land use, natural disturbances (e.g., wildfire, insect outbreaks) and human disturbances (e.g., road building, urbanization, harvesting), and succession (Turner et al., 1999). The landscape is a mosaic of patches, thus examining the spatial arrangement of these patches, or landscape pattern (Turner, 1989) is an essential step in understanding landscape ecology.

Quantification of landscape pattern is crucial in the field of landscape ecology as it enables us to begin exploring the mutual relationships between landscape patterns and the ecological processes that modify them, identify landscape change over time, and provides a consistent framework to compare different landscapes (Turner, 1989). Spatial data structures exist to represent the spatial phenomena and the spatial pattern, thus a few predominant data structures have been introduced for processing the spatial information (e.g., raster, vector) and the raster-based approach seems to be getting the most attention, especially when the comparison of categorical maps is involved (Kuhnert et al., 2005). In order to understand the landscape patterns and their alterations over time numerous map comparison techniques have been developed and will be described in the following sections.

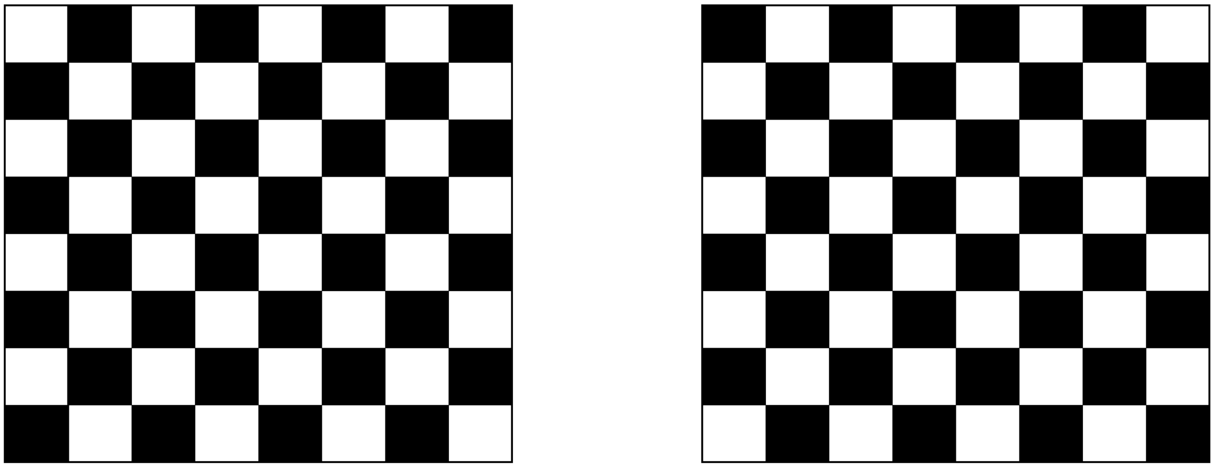
1.5.2 Map comparison

Following advances in the collection methods for spatial data (e.g., remote sensing), the availability of data in various spatial and temporal scales has increased dramatically. One of the applications of the spatial data is to produce categorical maps of the land cover. In order to gain insights from the different land cover types and their alterations through time, numerous map comparison techniques have been developed in a variety of disciplines.

The techniques for performing the comparison vary from the simple visual comparisons to the complex stochastic simulation models. Map comparison techniques have been developed over the years for a variety of reasons (Foody, 2007): a) evaluating the degree of similarity for accuracy assessment purposes (Giri et al., 2005), b) change detection (Comber et al., 2004), c) model validation and uncertainty analysis (Wulder et al., 2004), and d) comparison of landscapes, often based on spatial metrics which are commonly referred to, landscape indices or landscape metrics (O'Neill et al., 1988; Remmel and Csillag, 2003a; Turner, 1990).

It is claimed that in some cases, visual interpretation and human judgments can outperform the automated procedures (i.e., cell-by-cell map comparison) in the map comparison, as human perception is able to take main characteristics of maps into account (Visser and de Nijs, 2006). However, in some other cases, automated procedures can be the reasonable approach, when limited time and human efforts are available, or when the comparison has to be objective and needs to be repeated (Visser and de Nijs, 2006), therefore, a complementary approach, where the benefits of visual interpretation are incorporated into the automated procedures are recommended (Foody, 2006).

Many map comparison techniques do not take any spatial pattern into consideration (Pontius, 2002). A straightforward example for emphasizing the importance of spatial information in map comparison arises when comparing a checkerboard with another that has been inverted – analogous to a 1-pixel spatial shift (Figure 3). If we consider two checkerboards as two maps consisting of black and white cells, with either rotating around one of the checkerboards by 90^0, or shift the checkerboard by one column or row, a comparison technique that is unable to capture the spatial characteristics will explain these two maps (shifted checkerboard and the fixed one) as entirely different map, while a human observer would recognize the similarity in the patterns between two maps (Visser and de Nijs, 2006).



A) B)

Figure 3. The concept of checkerboard shift and how by rotating map A (If we consider two checkerboards as two maps consisting of black and white cells), a map comparison technique that do not consider spatial characteristics, can mistakably determine the map A and map B as entirely “different”, while a human observer would easily recognize the similarity in the patterns between two maps.

In this section, some of the main techniques and approaches that have been used for map comparison will be reviewed. This review starts with a brief review of Kappa statistics and touches upon landscape metrics, morphological analysis, and finishes by reviewing a simulation technique.

1.5.3 Accuracy assessment and Kappa statistics

Accuracy assessment techniques are defined as frameworks that quantifies data quality to ensure the end users of thematic maps which starts with defining the area covered in the land-cover map (Stehman and Czaplewski, 1998). Once the area is defined, a sample of units (i.e., either pixel or polygon) from that area is selected which will be compared to the reference classification that is based on the information collected about each sampling units using various sources (e.g., aerial photography), and the degree at which the land cover classification and the reference classification agree, determines the accuracy (Stehman and Czaplewski, 1998) or the degree of correctness of the classification which is an indicator of the degree that classification agrees with reality (Foody, 2002).

Foody (2004) performs two accuracy assessment techniques in order to compare the accuracy of the classification of different thematic maps. One of the techniques is based on the Kappa coefficient of the level of agreement between maps and the other one is based on evaluating the proportion of the pixels that are allocated accurately (Foody, 2004). The result of the assessments is often provided with the maps as accuracy statement and this statement then could be used to, for instance, examine the quality of classifications in two or more maps and the suitability of the used techniques (Foody, 2004). This study revolves around examining the quality of using Kappa coefficient when conducting a pairwise comparison of those statements and concludes that researchers should not limit themselves to the Kappa-based comparison techniques as there are preferable alternatives and also emphasizes the importance of bearing in mind whether the samples that have been used for producing the statements are related or independent (Foody, 2004).

Congalton (1994) points out four phases in the development of the accuracy assessment techniques. The first phase is the visual assessment of a map, the second phase is comparison of a classification to the reference classification, the third phase is comparison of the class labels and reference data, instead of sample units, and the last phase which is fundamentally an improvement to the third phase and concerns with more informed procedures regarding the class labels as well as the reference data which has contingency table at its core (Congalton, 1994).

A contingency table is used to represent how the distribution of categories in a particular map relates to the distribution of categories in another map, in other words, a contingency table aims at summarizing of the categories with the reference map. Contingency tables are known to best represent the information regarding composition than configuration (Remmel, 2009), however, in order to characterize spatial patterns, both parameters should be taken into consideration (Csillag and Boots, 2004).

Usage of Kappa and contingency tables in remote sensing goes back to over three decades ago and they became an inseparable part of every accuracy assessment and its indices are an output of many image analysis software packages that process the assessments (Congalton et al., 1983), and has an enteral role in some of the map comparison software (Visser and de Nijs, 2006). Kappa indices have received criticism for many years (Foody, 1992, 2004; Stehman, 1997). Some studies attempted to offer solutions for the flaws of standard Kappa, such as Pontius, (2000) who proposed a suite of variations for Kappa (i.e., Kappa for location and quantity, proportion correct for location and quantity, and Kappa with no ability). However, Kappa and its variants were called "useless", "misleading", and "flawed" by the same author who worked with these indices for over two decade as they are often too complicated to compute, hard to comprehend, and impractical and was suggested that researchers use cross-tabulation matrix for different aspects of disagreements instead of proportion correct or Kappa and its variants (Pontius and Millones, 2011).

Pontius and Millones (2011) introduced two measures to evaluate the disagreements in the quantity and allocation of categories in the under-study maps in oppose, where *quantity* and *allocation* are interchangeable with the terms *composition* and *configuration* in the landscape ecology. In the following Figure, there are 27 comparison maps and one reference map which are organized from left to right by the number of black pixels and the number labels at the bottom indicates that amount (0-9).

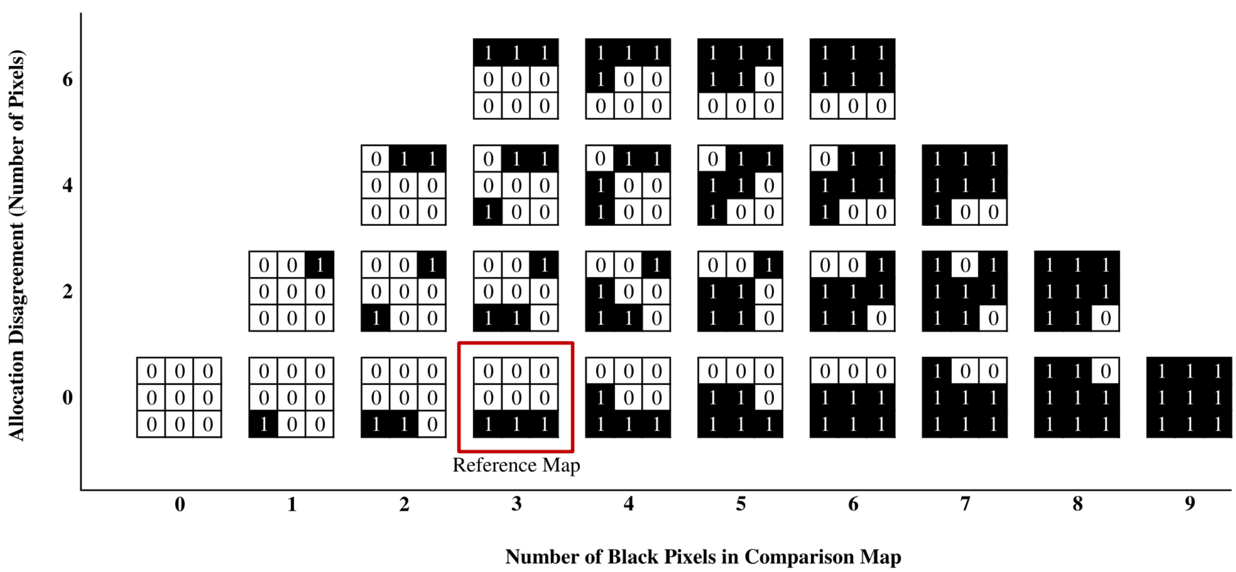


Figure 4. Demonstration of reference map (the one that is circled) and comparison maps and the possible QD and AD, modified from Pontius and Millones (2011).

The maps in each column have the same number of black pixels; however, the allocation of these pixels is different. Therefore, the *quantity disagreement* (QD) is the difference between the number of black pixels with the references map and the comparison map and *allocation disagreement* (AD) is the difference between the location of those black pixels (Pontius and Millones, 2011). Disagreement in allocation is described by *omission* pixels and *commission* pixels, where the omission is the black pixel in the reference map that is not black in the comparison map, and the commission is the black pixel in the comparison map that is not black in the reference map (Pontius and Millones, 2011).

For instance, there are three black pixels in the reference map and six white pixels, so there is zero QD between the reference map and the three maps in column 3, because they all have the same amount of black pixels, thus the same amount of white pixels, or analogically speaking, it takes the same amount of black ink to produce these maps; consequently, the QD between the reference map and each of the maps of other column has a positive value (Pontius and Millones, 2011).

As for the AD, since the three black pixels are located at the bottom of the map, as we move these pixels towards the top of the map, the AD increases, in other words, AD describes the possible ways that the ink can be allocated in the maps (Pontius and Millones, 2011).

The aforementioned demonstration provides an understanding on the concepts of composition and configuration that are the key concepts for map comparison and describing where things change and how things change. Although this demonstration is for binary maps but the same conceptual framework can be used for multi-category cases (Pontius and Millones, 2011) but due to the extreme increase in the number of combinations, it can be much more complex (Boots and Csillag, 2006).

1.5.4 Landscape metrics

Landscape Metrics (LMs) are developed to quantify the landscape patterns into measurable variables to investigate their relationships and correlations with ecological processes (Frohn, 1997). These metrics are measurements that are traditionally concepts such as information theory and fractal geometry (O'Neill et al., 1988) as well as percolation theory (Gustafson and Parker, 1992; Li and Archer, 1997) which attempt to a) understand the shape and patterns of the landscape entities (e.g., patches), b) study the interactions between landscape patches, functions, and changes.

Shannon (1948) introduced information theory and it is the measrement of the amount of information in data that could contain more than one value and one of its key parameters is entropy which concerns with the quantification of uncertaintely in a random variable. Fractal geometry is a matheamtical term that describes naturally occuring objects that is based on self-similiarity and non-integer dimision (Mandelbrot and Pignoni, 1983).

Vogt et al. (2007) pointed out that most of the factors developed are based on either adjacency and connectivity concepts (Musick and Grover, 1991) or patch-corridor-matrix (Forman, 1995). The patch-corridor-matrix model has been used widely after the mid-1990s as a foundation for quantification of the landscape pattern aiming at measuring the patchiness across a landscape (Forman, 1995). Patchiness refers to the level of heterogeneity, and this level can vary due to several natural (e.g., wildfire, insect outbreaks) and humankind (e.g., road building, urbanization, harvesting) forces (Gergel, 2007; Linke et al., 2007). Forman's model was based on an airplane view of the landscape and inspired by how a landscape looks like a mosaic from that view. *Mosaic* is one of the two types of a spatially heterogeneous land; where the land consists of aggregated objects and distinctive boundaries, containing patches and possibly corridors as opposed to *gradient* types in which objects presents gradually over space, and there are no boundaries, no patches, and no corridors (Forman, 1995).

A mosaic is formed by a combination of three basic spatial elements: patches and corridors within a matrix as the dominant land cover, often considered to be the background (Forman, 1995). A *patch* is a homogenous area that is different from its surroundings, and a *corridor* is a connection between two patches; while patches are the main focus in the ecological studies, corridors is the central topic when studying hedgerows and windbreaks (Forman, 1995). Finally, the *matrix* is the most connected and dominant element in a landscape, for instance, in a continuous area that is covered by mature forest and small disturbance patches, the mature forests are considered as the matrix, as they have the largest extent (Forman and Godron, 1986).

O'Neill et al. (1988) introduced three relatively independent metrics: dominance, contagion, and fractal dimension and calculated them on 94 quadrangles that cover the eastern part of United States, with a known percentage of the landscape type coverage in urban, agriculture, and forest in each. *Dominance* refers to the degree of the supremacy of patches in a landscape and determines evenness of the distribution of the patches which is a value between 0.00 to 1.94, where a high value is explained as the dominance of the patch (O'Neill et al., 1988; Turner et al., 2001). In other words, the low dominance value can be explained by relatively even distribution of different land cover types in a landscape, such as coastline where urban, agriculture, and forest tend to be mixed together (O'Neill et al., 1988). The high value of dominance means one or a few land over types have dominated a landscape, such as agricultural or forest landscapes, which could be interpreted as an intensive crop production or undisturbed forests (O'Neill et al., 1988).

C*ontagion* quantifies the aggregation among patches by looking at the adjacency of similar patches to each other or to a chosen spot which results in an index value from 0.0 to 6.8 for the level of contiguously in order to distinguish clumped and dissected patterns (Turner et al., 2001). The low value for contagion can occur where the landscape is dissected into small pieces that could be due to either human development or topography, while the contagion value is high where a landscape is covered by a large cluster, like a landscape with high coverage of forests (O'Neill et al., 1988).

Finally, *fractal dimension* is based on fractal geometry (Mandelbrot and Pignoni, 1983) and a value from 1.0 to 1.5 and used to examine the shape of the patches to reveal their complexity, if a particular landscape consists of simple geometric shapes, such as rectangular or square (i.e., agricultural landscapes), the value of fractal dimension will be close to 1, but a more complex landscape (i.e., forests, coastlines, estuarine boundary lines) will result in a larger value (O'Neill et al., 1988; Turner et al., 2001). Furthermore, this index is correlated with the degree of human manipulation of the landscape, as human activities like urban development or crop production tend to leave the landscape with simpler patch shapes that are reflected in lower fractal dimension values than for naturally occurring and more complex shapes (O'Neill et al., 1988). The values of the three metrics on each of the quadrangles are indices that can be used to differentiate and compare different landscapes types, and as the results of this study had proved, the indices could differentiate between urban coastal landscapes, mountain forests, and agricultural areas (O'Neill et al., 1988).

Turner et al. (1989) measured the same three parameters to examine the effects of spatial resolution and the extent of the study on the spatial pattern. The result of this study showed that with decreasing the spatial resolution, dominance and contagion decrease and with increasing the extent these two parameters increase as well which emphasizes the sensitivity of these parameters to the scale extent (Turner et al., 1989). This study emphasized the importance of spatial scale, extent and, most importantly clarification of the definition of scale when investigating spatial pattern; also it laid the foundation for another software, called spatial analysis program (SPAN); not to be confused with SPANS which is a commercial GIS software (Ebdon, 1992).

SPAN is another attempt for quantification of the landscape patterns and their alterations (Turner, 1990) by introducing new metrics that enabled more through map comparison. It is a grid-cell based program that can be used for categorical data as long as they are in a raster format and have an appropriate spatial resolution (Turner, 1990). SPAN measures dominance, contagion, and fractal dimension too, but five more variables (i.e., proportion, adjacency, edge, patch size, and patch perimeter) are incorporated to better capture the characteristics of the landscape. *Edge* is the sum of adjacent pixels between two different patches that is multiplied by the pixel size (Also known as spatial resolution); *adjacency* is the probability of adjacency between land cover types. For instance, imagine having two land covers, *A* and *B*, then the *adjacency* is calculated by dividing the number of cell of land cover type *A* that are adjacent to land cover type *B* by the number of cell of land cover type *B* and *proportion* is the fraction of each land cover type in a landscape, representing the share of each of the types in the entire landscape (Turner, 1990). Gustafson and Parker (1992) developed habitat island spatial analysis (HISA) by modifying SPAN and adding proximity and linearity indexes. The *proximity* index is for identifying the small and isolated patches from the larger complex ones, and the *linearity* index assesses the linear properties of the patches, more particularly, the overall elongation of the patches (Gustafson and Parker, 1992).

These LMs are shown to be sensitive to scale (e.g., Turner et al., 1989). The importance of the scale and the level of spatial resolution when analyzing the landscape pattern is emphasized by Cullinan and Thomas (1992) in which the determination of the suitable scale for the quantification and measurement of the landscape pattern is the main concern. This concern is tackled through comparing the results of computation of six landscape metrics (testing the randomness, patch size, spectral analysis, fractals dimension, variance ratio and correlation analysis) on three data sets (Cullinan and Thomas, 1992). The paper concludes that none of the metrics can provide us with a suitable scale individually, therefore it has been suggested that determining the scale should be derived from the computation of more than one landscape metric as each of the metrics is meant to answer different statistical questions and has various sensitivity to scale alterations. It also stresses that before making the desired inferences to the spatial processes, one has to carefully determine the scale and the level of resolution (Cullinan and Thomas, 1992).

Following the development of these landscape indices, FRAGSTATS and *r.le* software programs were introduced. McGarigal and Marks (1994) have provided a document for FRAGSTATS which is a program that involves a comprehensive set of metrics for quantifying landscape patterns which provide the users with various arrays of metrics based on the categorical raster layer and can be utilized for both vector and raster data. Even though this document is a manual for the software, but it includes some of the important definitions and classifications for quantifying the landscape pattern. For instance, it provides an approach for summarizing the landscape metrics by defining them at different levels and suggests three levels for these metrics: Patch, class, and landscape (McGarigal and Marks, 1994). While in the patch-level metrics, characterization of the blocks with the same properties (also known as patch) is the main concern, the final value in the class-level metrics is an integrated number based on all of the patches in each specific class in order to manifest the different contribution of the patches, depending on their size. Finally, in the landscape-level metrics, the final value is an integrated number based on the entire landscape, therefore there is a specific value for each LM per landscape (McGarigal and Marks, 1994). The *r.le* is a program that is implemented in GRASS to benefit from the capabilities of geographic information systems (GIS) for analyzing landscape patterns and measures patch, core, shape, and perimeter with the possibility of customizing the sampling area from the map extent to the pixel size as well as applying moving window analysis (Baker and Cai, 1992).

As a number of studies that aimed at summarizing the quantification methods for landscape pattern (Gustafson, 1998; Haines-Young and Chopping, 1996; Neel et al., 2004; O'Neill et al., 1999; Riitters et al., 1995; Turner et al., 2001) indicated, many of the metrics that were developed are closely related. Riitters et al., (1995) has examined fifty-five LMs in order to identify sub-groups for the indices by using multivariate factor analysis, and came to the conclusion that only six of the factors were distinct as those six explained 87% of the variations in this study. The six distinctive metrics were the number of patches or classes, also referred to as dominance, complexity of the shape of the patches or fractal dimension, average size of the patches, level of fineness of the texture, level of compactness of the patches, and linearity of the patches (Riitters et al., 1995; Turner et al., 2001). However, this approach crtitized as not only it could result in landscapes with different characeteristic but similar value for the landscape metrics but also it can be problematic as this approach assume a unrealistic normal distribution across observations (Remmel and Csillag, 2003). Cushman et al. (2008) used FRAGSTATS and performed principal component analysis (PCA) in order to classify the redundancy in the LMs and determined a set of metrics that are able to characterize the main attributes of the landscape patterns.

Haines-Young and Chopping (1996) reviewed the available landscape metrics (LMs) that are developed to understand and describe the landscape patterns, their methodological issues (uniqueness, index sensitivity, index selection and redundancy, edge, non-spatial statistical effects, topographic and boundary effects, and scale) and their applications as an assessment tool to evaluate the large-scale sustainability guidelines. A comprehensive list of these applications includes: a) use and misuse of metrics, b) biodiversity and habitat analysis, c) water quality, d) evaluation of the landscape pattern and its change, e) urban landscape pattern and road network, f) aesthetics of landscape, and g) management, planning and monitor along with interchangeable terms of landscape metrics/indexes/indices were explored in the peer-reviewed papers indexed by ISI web of science, published from 1994 to October 2008 (Uuemaa et al., 2009).

According to (Uuemaa et al., 2009) the term landscape metrics became more relevant recently. These landscape metrics provide a framework for quantifying the landscape composition and landscape configuration. These quantifications enable us to a) make inferences about ecological process based on the differences in the structure of the landscapes and the sensitivity of disturbance regimes to alterations in that structure (i.e., average patch size, length of the borders) and b) assess the conservation value of forest patches and other structural elements, for instance, assessing the impacts of barriers to the quality of life of habitats (Haines-Young and Chopping, 1996).

Li and Wu (2004) believe that even though spatial pattern analysis methods (i.e., LMs) have brought great excitement to the field of landscape ecology, the outcomes from this analysis, which is the understanding of the relationships between spatial pattern and ecological processes, are not satisfactory as there are a few interrelated problems that can be identified with implementing them. One of the general problems is the conceptual flaws in these metrics that includes ignorance of the importance of a) the scale (Li and Reynolds, 1995) and b) ecologically relevance of the metrics (Wiens et al., 1993) as well as shifted focus which is more on the quantification of the patterns rather than exploring the impacts of the patterns on the ecological process (Li and Wu, 2004; Turner et al., 2001). The false assumption that most of the comparison between LMs is based on, which is assuming a normal distribution of the indices, is highlighted by Remmel and Csillag (2003).

Another problem is the limitation of these metrics, such as inconsistency to reacting to the changes to the pattern (Haines-Young and Chopping, 1996; Turner et al., 2001), resulting in major difficulties in the interpretation of the metrics (Turner et al., 2001) and their outputs. Additionally, a remarkable number of these metrics were applied to understand the impacts of fragmentation on landscape pattern (Fahrig, 1998, 2002; Riitters et al., 2000) but the complexity of fragmentation processes and the abundance of available metrics not only makes the selection of a suitable set of metrics for a particular study a difficult task, but will also require that researchers understand the entire theoretical framework behind each metric (Neel et al., 2004), and empirical relationships among these metrics (Cushman et al., 2008).

Studies have shown that LMs tend to capture one specific element of the spatial pattern instead of looking at the pattern as a whole (Remmel and Csillag, 2003). Furthermore, because there is no LM that captures both composition and configuration in the spatial pattern of the landscape, majority of studies have utilized a set of metrics (Remmel and Csillag, 2003; Riitters et al., 1995) instead of one single value which is incapable of describing the complexity of the landscape patterns and functions (Remmel and Csillag, 2003).

However, using a set of metrics can introduce the following issues, which makes the results hard to interpret. Firstly, doing so would result in the same or almost same LM values for different landscapes configuration (Gustafson, 1998), for instance, Figure 5 depicts three different landscapes configurations that resulted in equivalent LM values for the number of patches and the contagion index, landscape shape index, edge density, proportion of two classes and the modified Simpson’s evenness index (Remmel and Csillag, 2003).

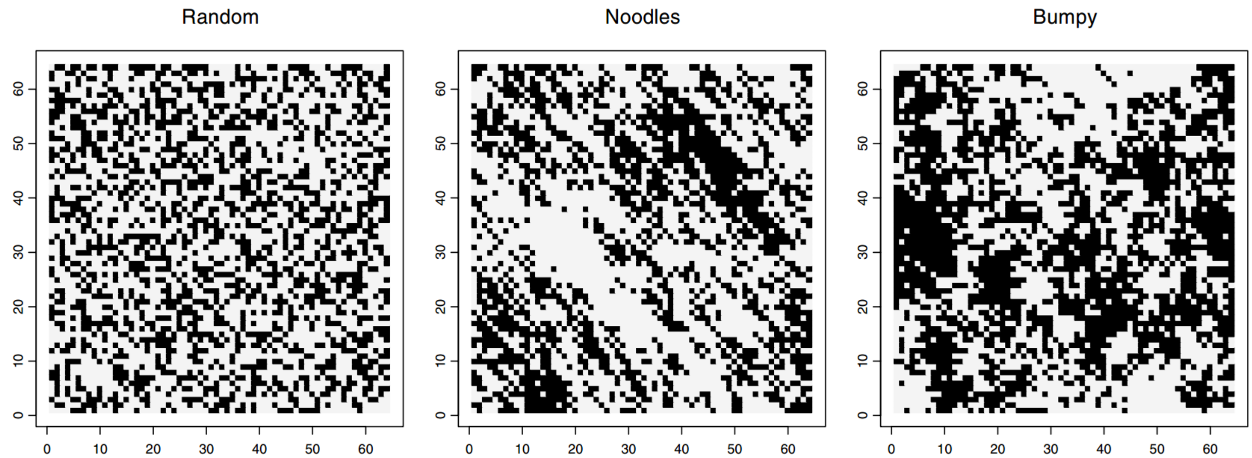


Figure 5. The LM values for three landscapes with different configurations are identical. (Remmel and Csillag, 2003).

Secondly, in the traditional approaches, the composition and configuration are often quantified by different units of measurement. To solve the latter issue, Remmel and Csillag (2006) presented a new approach with hierarchical decomposition algorithm that not only captures both composition and configuration in two or more maps simultaneously but also enables us to perform the comparison between nested thematic classification groups for each of the maps and the comparison outcome can be provided by graphs that are mutual information spectra.

The aforementioned patch-based methods are generally shown to be unsuitable for implementing large areas assessment as a result of abundance in the number of patches and loss of the small patches (Riitters et al., 2004). The alternative to the patch-based methods, are pixel-based methods which perform calculations using a fixed-area window, also known as a kernel. A kernel goes over each pixel and depending on the amount and adjacency of the pixel values of the neighbourhood pixels in the window, a new pixel value will be calculated and stored in the central location of the kernel on an output layer, resulting in the production of a new map (Riitters et al., 2000; Vogt et al., 2007). In pixel-based methods, the number of adjacent pixels considered in a function of the kernel's size that may differ among studies (Riitters et al., 2000).

1.5.5 Morphological analysis

An alternative to using LMs for studying landscape pattern is morphological analysis. Morphology is the study of the form and shape of the objects or in other words, it is a theoretical framework for analyzing the spatial structure of a landscape (Soille, 2013). Morphology is not only a set of mathematical theories (e.g., set theory, internal geometry, and lattice algebra) but also a strong image processing technique for image segmentation (i.e., dividing image into mutually exclusive segments having clearly articulated geometric properties) which is an initial step in characterizing each segment and understanding their adjacency relationships (Soille, 2013).

Soille and Vogt (2009) introduced a pixel-based morphological image processing method, named Morphological Spatial Pattern Analysis (MSPA) for performing measurements in order to examine the shape, size, and connectivity of the spatial patterns of binary maps (Soille and Vogt, 2009). This method is implemented in the Guidos toolbox, a freely available software package (http://forest.jrc.ec.europa.eu/download/software/guidos/mspa/) that can be used for any binary maps at any scale (Soille and Vogt, 2009).

There are many advantages in using MSPA over LMs. The first advantage of MSPA is the intuitive concepts behind their core algorithms. Many of the LMs that were reviewed before are based on relatively complex concepts which not only makes them inconvenient to perceive but also almost impractical when it comes to operating a change in the landscapes based on the calculated metrics. The second advantage is the great visualization that can be provided by the MSPA; when examining the outputs of the analysis, we can actually see what the landscape looks like and how the connectivity and configuration between different parts of the landscape play out. Conversely, the final output of most of the metrics are numeric values (e.g., the number of patches, average patch size, average patch perimeter) which can be difficult to visualize and even harder to interpret.

The difficulty in the interpretation comes from the fact that depending on the metrics, they provide a single value for describing an entire landscape, or a value per class per landscape which may not be the most meaningful approach to characterize the complexity in a landscape and changes in that value is hard to visualize. The third advantage is the clear segmentation at the pixel level, meaning that each pixel in a binary map will be classified to membership within a mutually exclusive class. MSPA is based on performing a series of mathematical morphology operators and transformations to segment binary patterns (Soille and Vogt, 2009). After running the MSPA tool, the Guidos software segments the binary patterns of the foreground pixels into seven morphological classes: Core, Islet, Loop, Bridge, Perforation, Edge, and Branch. Figure 6 is the representation of the input layer for an MSPA analysis, which is a binary map, and the morphological classes in an MSPA analysis output.

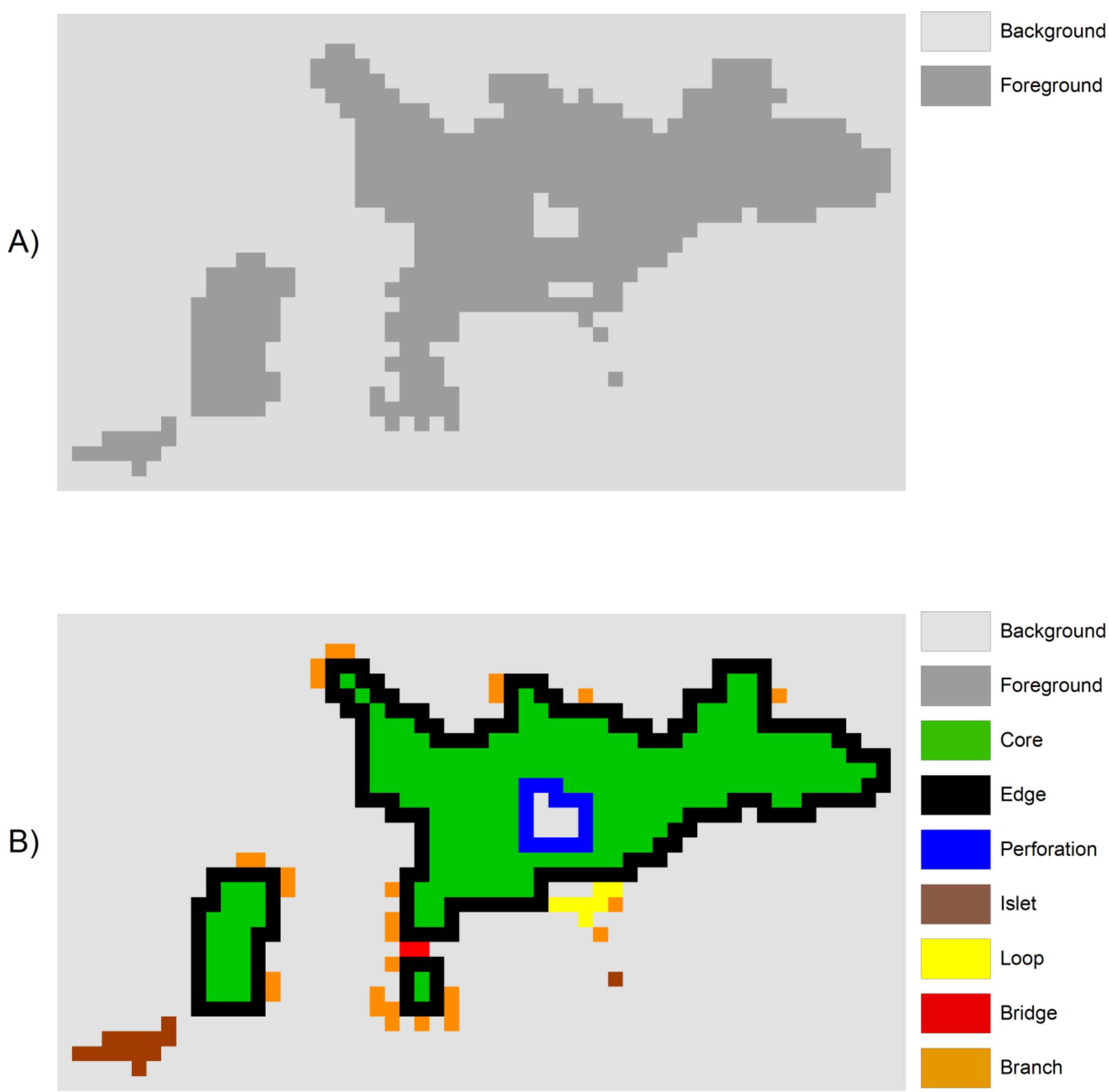


Figure 6. Map A is a binary map that is imported for MSPA analysis and Map B is the output of this analysis, which is the morphological classes.

As this segmentation is based on edge-width, the proportion of each morphological class in the output map relies highly on the size of the distance threshold (*S*). The user determines this parameter and depending on the phenomena being studied, it can be different among studies. The size of 1 in the distance threshold equals to the spatial resolution (or one pixel) of a pixel and can vary from 1 to 8 (Soille and Vogt, 2009).

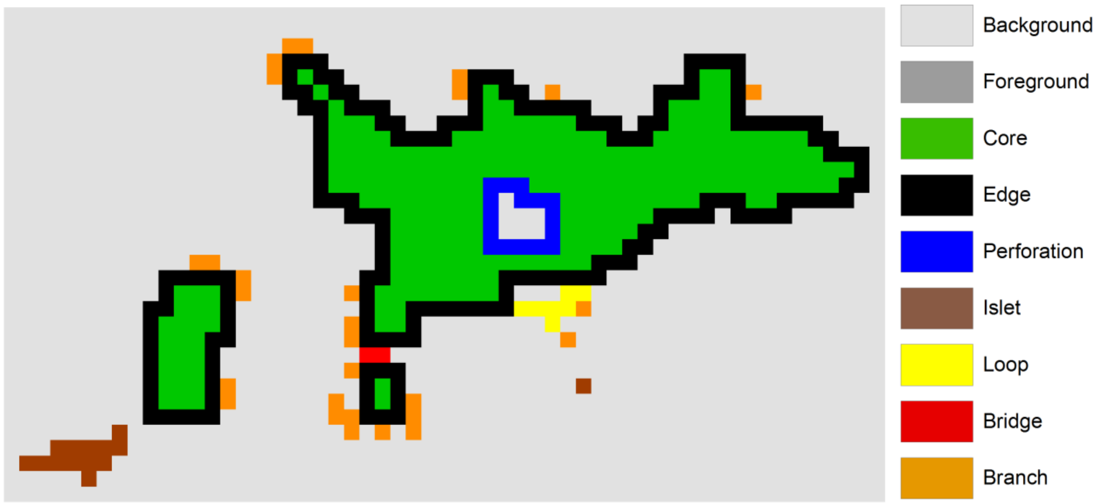
When choosing the size of the distance threshold, it is important to note that MSPA analysis is sensitive to scale as the scale can influence the quantifications of forest patterns (Ostapowicz et al., 2008) and proportion of the morphological classes significantly. Ostapowicz et al. (2008) studied this influence by altering the *S* and *P* (Pixel Size or Spatial Resolution) parameters and comparing the MSPA analysis outputs. The results supported this sensitivity, for instance, increasing *P* will cause generalization in the final segmentation and/or classification of the small patches as non-Core. Also increasing *S* will decrease the proportion of the Core pixels and/or increase the chances of classifying the small Core patches as Islet (Ostapowicz et al., 2008).

The MSPA approach initially processes the binary map imported by the user, called the *input pattern map* by running a binary classification of the entire foreground pixels that are within *S* to the background pixels and the background pixels (Soille and Vogt, 2009). Subsequently, five morphological segmentation algorithms that are embedded in the MSPA processing, will be performed on that input pattern map that will be described in the next section. The first algorithm classifies the *Core* pixels. The foreground pixels in the input pattern map that have a greater distance than *S* to the background pixels are classified as *Core*, in order words Core pixels are the pixels that are entirely surrounded by other foreground pixels, depending on the neighborhood connectivity in the MSPA parameter settings, the surrounding pixels can be either four-pixel (rook's case) or eight-pixel (queen's cases) (Sawada, 1999). *Islet* pixels are the foreground pixels are too small to be recognized as Core (Clerici and Vogt, 2013). The third algorithm is for classifying connector pixels that include *Loop* and *Bridge*. Bridge pixels connect two areas of different Core patches, whereas Loop pixels connect one area of one Core patch to itself (Clerici and Vogt, 2013; Soille and Vogt, 2009).

Following connector pixels, boundary pixels will be classified. Boundary pixels are the foreground pixels with a shorter distance to the Core pixels than *S* and they subdivided into *Edge* and *Perforation*. Edge refers to the outer boundary pixels of the Core patches, a boundary that separates Core patches from non-Core patches (Ostapowicz et al., 2008). Perforation pixels are the inner boundary, meaning that they are the boundary of the Core patches that are located inside of another Core patch, also known as a *hole* (Clerici and Vogt, 2013; Ostapowicz et al., 2008). The last algorithm is to classify *Branch* pixels, these are the pixels that do not belong to any of the other morphological classes (Soille and Vogt, 2009).

Before running the MSPA analysis, parameterization of the analysis can be set by the user. These parameters include neighborhood connectivity, edge width, transition, and intext and altering each of them would likely produce a different output. The user can determine the number of surrounding pixels involved in the MSPA analysis. This number can be either four-pixel (orthogonal neighbours) or eight-pixel (all first-order neighbours). Figure 7 is a representation of how changing this parameter would impact the output of MSPA analysis, however, in this particular sample area, the impacts are not quite substantial.

A)



B)

Figure 7. Map A is the outcome of MSPA analysis with Neighbourhood connectivity of 8 and Map B is the outcome of neighborhood connectivity of 4.

Edge width is the number of necessary pixels that should be classified as an edge in order to separate the Core area from the foreground pixels, in other words, it is the size of transitional zone (symbolized as black) between the Core area and foreground pixels and could be set at integer values between 1-8 pixels. Increasing this size directly decreases the proportion of the Core area and vice versa. To clarify the effects of this parameter, Figure 8 is produced in which edge size of 1 and 2 are compared visually.

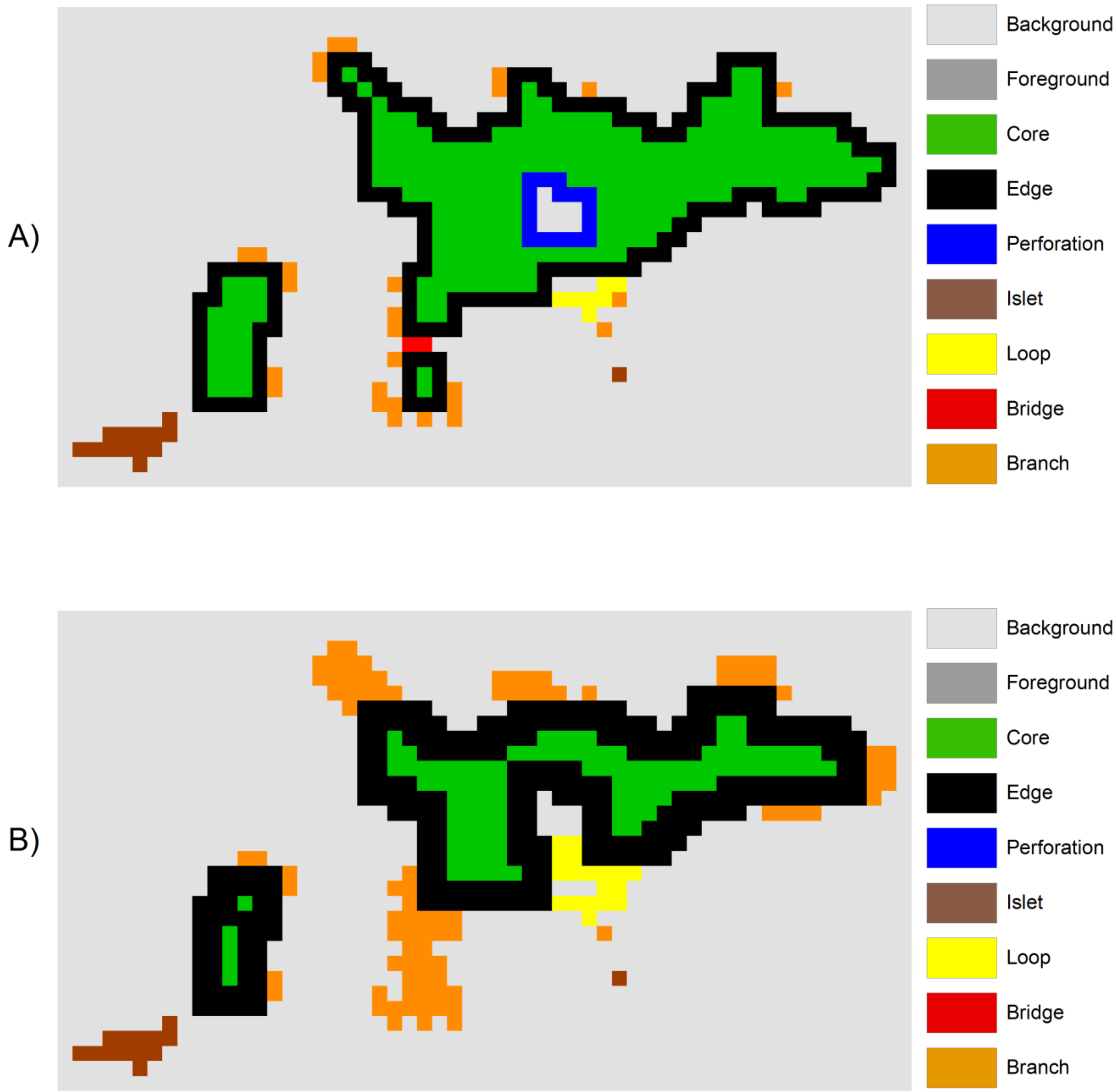
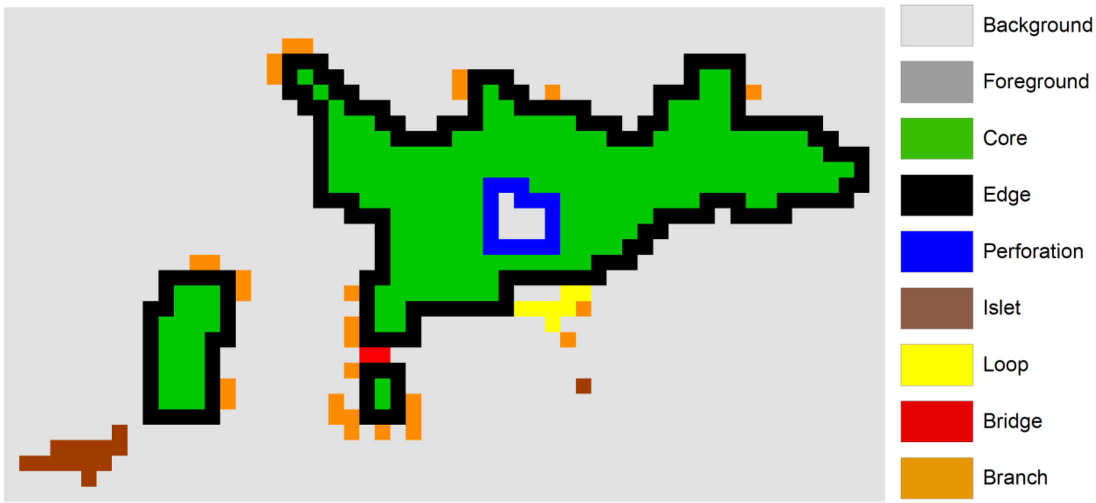


Figure 8. Map A is the outcome of MSPA analysis with edge width of 1 and Map B is for edge width of 2.

Transition refers to how the connector pixels and Branch interact with the boundary pixels. With tuning off the transition parameter, when the connector and Branch pixels link to the boundary pixels, the connecting pixel will be classified as a boundary pixel, while when it is on, the connecting pixel will be classified as either a connector pixel or a Branch. Whether this parameter is off or on impacts the proportion of several morphological classes. Figure 9 is the output of MSPA analysis, when the transition parameter off (A) and when it is off (B).

A)



B)

Figure 9. Map A is the outcome of MSPA analysis with transition off and Map B is for transition on.

Finally, intext is the last parameter in the MSPA settings. It has been mentioned earlier that the Perforation pixels are the inner boundary of the Core patches that are located inside of another Core patch, also known as a *hole*. Whether the user would like to have a separate class for foreground pixels within these holes can be determined by the intext parameter. When the intext parameter is on, MSPA produces the separate class, and when it is off, the separate class will not be produced. The difference between outputs of MSPA analysis with changing this parameter is only visible in the attribute table and not the map outputs.

1.5.6 Simulation

The distributions of LMs are unknown which prompt uncertainty in statistical comparisons between different observations of LMs due to the lack of the consistent and strict confidence interval and unknown expected the range of variations (Remmel and Csillag, 2003). Remmel and Csillag, (2003) introduce an empirical statistical approach with a well-founded confidence interval that is suited for the testing hypothesis of LMs comparisons. Awareness of this confidence interval enables us to a) create inferences on how the stochastic process is generated and b) distinguish different spatial processes (Remmel and Csillag, 2003). A Conditional AutoRegressive (CAR) model is utilized to simulate binary landscapes and examine the sensitivity of six of the most popular metrics (number of patches, patch density, edge density, landscape shape index, area-weighted mean shape index, and contagion) as the two main components of spatial pattern, composition and configuration, are systematically varied. The approach permits testing the likelihood that any binary pattern's metrics are within expectation by first estimating these two components and then simulating 1000 stationary binary landscapes with those parameters and comparing the measured values to the distribution of values calculated for the simulated landscapes (Remmel and Csillag, 2003).

This simulation produces an empirical distribution as a function of composition (proportion) and configuration (spatial autocorrelation) by computing LMs for each of the realizations; the simulation is stochastic and all simulated landscapes are isotropic and stationary (Remmel and Csillag, 2003). This study emphasizes the importance of considering the impacts of composition and configuration on LMs results as well as deliberation of the confidence interval and the expected range of variations in comparison of the LMs results (Remmel and Csillag, 2003). Remmel and Fortin (2013) extend this work from landscape-level metrics to class-level metrics.

This approach relies on estimating the composition and configuration of a landscape and performing stationary stochastic simulations with the equivalent level of composition and configuration in order to produce statistically identical binary landscapes, or the realizations (Remmel and Fortin, 2013). Subsequently, the class-level pattern metrics are calculated on those realizations as a means to generate the global empirical distributions. This paper aims to a) test the significant differences between a landscape pattern and a pattern from Complete Spatial

Randomness (CSR) and b) determining whether two binary landscape patterns could be produced by the same spatial process (Remmel and Fortin, 2013).

2. Methodology

The methodology section of this study revolves around two components. The first component is the computation of the morphological elements of each province of Canada from 2001 to 2014, using MSPA analysis in Guidos software package. The output of the MSPA analysis is a map, classifying each pixel into 8 morphological classes (i.e., Background, Core, Islet, Loop, Bridge, Perforation, Edge, and Branch). Each output map includes an associated attribute table, summarizing the pixel counts of each morphological class. These attribute tables will be converted into Comma Separated Value files (CSV) in order to be imported into the R statistical package (R Core Team, 2016) and stored in the below format (Table 1).

Table 1. Headings of the master table that stores the essential attributes for the first component of the methodology.

Heading	**Description**
Subregion	Provinces or Territories
Year	From 2001 to 2014
MSPA Settings:	
Neighbours	8 or 4
Edge width	From 1 to 8
Intext	0 when intext is off or 1 when it is on
Transition	0 when transition is off or 1 when it is on
MSPA Classes:	
Edge	Pixel counts for Edge class
Perforation	Pixel counts for Perforation class
Islet	Pixel counts for Islet class
Core	Pixel counts for Core class
Bridge	Pixel counts for Bridge class
Loop	Pixel counts for Loop class
Branch	Pixel counts for Branch class
Background	Pixel counts for Background class

The aforementioned CSV files become the inputs for the second component which is performing joint count analysis. The following diagram is to clarify the sequence and relations of each step in the first component (Figure 10) and the following sections will provide the details on each of the steps.

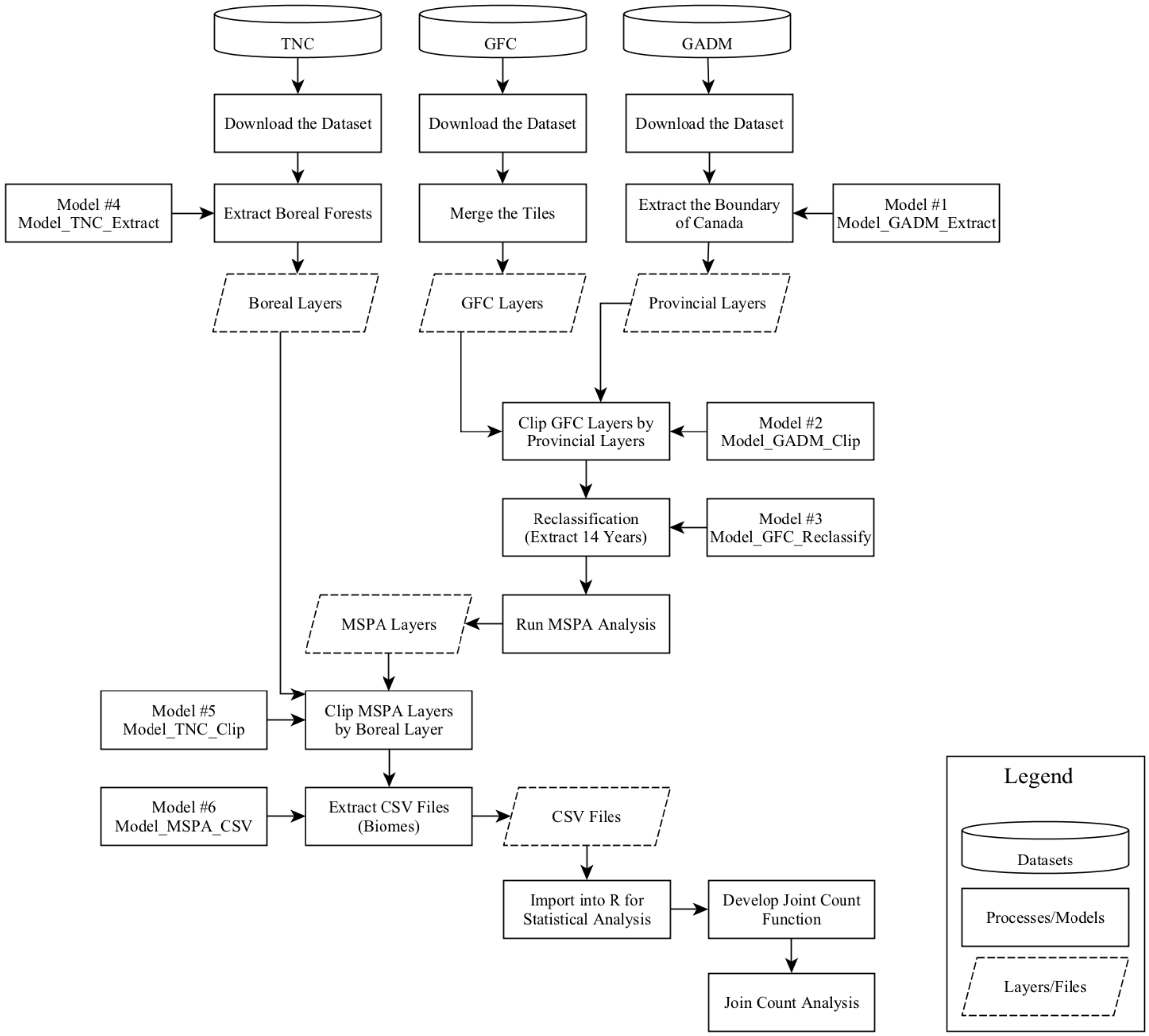


Figure 10. Overall flow diagram for the methodology steps.

2.1 Data pre-processing

2.1.1 Global Administrative Areas (GADM) dataset

The GADM website (http://www.gadm.org) offers a freely available global administrative boundaries dataset for 256 countries and their divisions, such as cities, provinces, territories, states, and so on. The amount of detail, consistency, and the high quality of this dataset is the reason that it is chosen for this study. The dataset can be downloaded in various formats, such as OGC geopackage, *R* file format (R Core Team, 2016), ESRI file and personal geodatabases, Google Earth .kmz, and shapefile.

A model was created by the author in ArcGIS Model Builder to produce a separate shapefile for each province and/or territories outline as well as assign a proper name for each one of them. This model imports the global shapefile into an Iterate Feature Selection tool. This tool is used to select and group classes based on an individual field in the attribute table. The field that contains the province names was chosen for the selection and grouping. The tool selects each province and/or territories, stores it in a "Value" attribute, and then exports the province/territory into new feature class using the Copy Features tool. By running the model, this process takes place 13 times, as there are 13 unique records for Canadian provinces and/or territories. Finally, it assigns a unique name to each province based on the records in the attribute table. Only the provinces and/or territories with boreal forests will be considered for the further processing and the rest will be disregarded.

2.1.2 The Nature Conservancy (TNC) dataset

The TNC Maps website (http://maps.tnc.org) is devoted to sharing the conservation GIS datasets as well as the interactive maps that are produced by The Nature Conservancy, a charitable organization that stands for preserving ecologically valuable lands and waters. It provides three core conservation datasets at a global scale in shapefile and ESRI geodatabase formats. The datasets include: Ecoregional assessment portfolio, TNC lands and waters, and ecoregions (terrestrial ecoregions, freshwater ecoregions, and marine ecoregions). The terrestrial ecoregions dataset is originally produced by Wiken (1986), developed further by Olson et al. (2001), and modified by TNC staff in 2009. It is based on the ecoregions that are determined by World

Wildlife Fund for Nature (WWF) and is the dataset that will be used in this study as it contains the boundaries of the global ecoregions (i.e., boreal forests, Mediterranean forests, temperate conifer forests, tropical and subtropical coniferous forests, and tundra).

After importing the terrestrial ecoregions shapefile into ArcGIS, the boreal layer was produced by selecting and extracting the boundary of the boreal forests of Canada. This layer will be used in order to clip the MSPA outputs that were based on the boundaries of provinces and/or territories (Section 2.1.1) into boreal boundaries. By doing so, the parts of the provinces and/or territories that do not contain boreal forests will be discarded and the final MSPA outputs (maps and their associated attribute tables) will only reflect the morphological classes in the boreal forests of Canada.

2.1.3 Global Forest Change (GFC) dataset

The GFC website (https://earthenginepartners.appspot.com) is a spatially and temporally detailed resource of forest cover change information in a global scale. It is produced from the results of time-series analysis of over 600,000 Landsat 7 ETM+ images at a spatial resolution of 30 m to map global forest loss and gain (Hansen et al., 2013) and is hosted by the University of Maryland's Department of Geographical Sciences. The version 1.0 of this global dataset was published in 2013, containing changes from 2001 to 2012, and the version 1.2 was released in 2015, which covered changes through 2014.

Forest loss and gain data are the main data products. The forest loss is defined as a stand-replacement disturbance causing the changes in forest cover or when the canopy layer of the tree is demolished (Hansen et al., 2013). The layer of forest loss named *lossyear* that contains disaggregation of total forest loss annually from the year 2001 through 2014; different year events are identified with different pixel values, ranging from 1 to 14. The forest gain is the opposite of the forest loss that refers to the conversion of a non-forest cover to the forest (Hansen et al., 2013). The global dataset for each data product is divided into 504 tiles (14 rows and 36 columns), each tile covering 1,440,000 km^2. However, as the study areas in the research are only boreal forests of Canada, only 40 of these tiles were downloaded (Figure 11). The oceans are covered as well, but they do not have any meaningful information about forest cover change, hence, will be disregarded in this study.

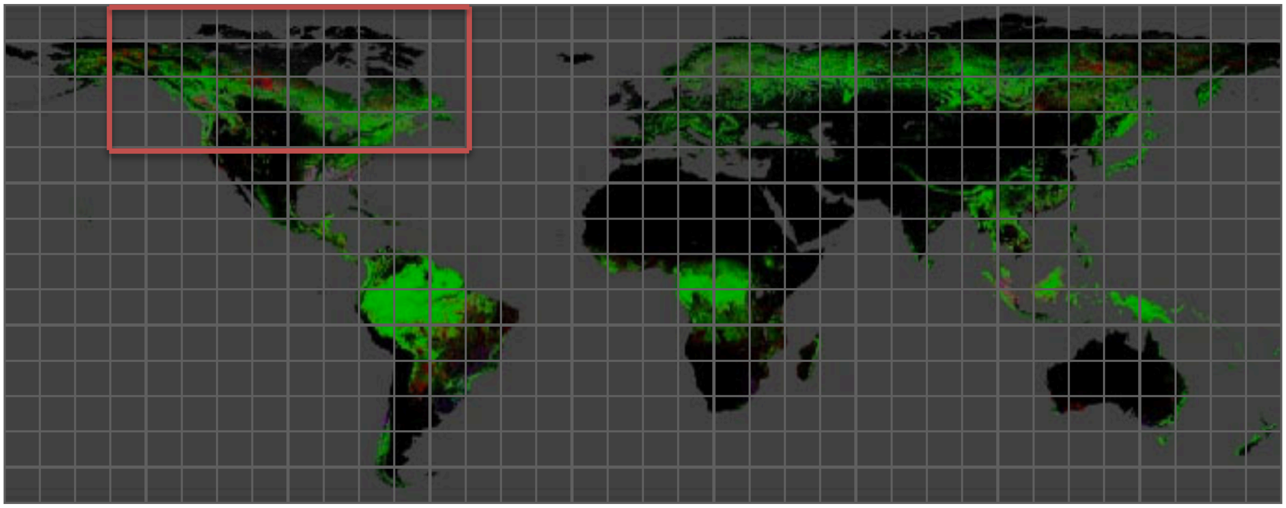


Figure 11. Global Forest Change (GFC) map tiling and outlines of the tiles that were downloaded.

The GFC tiles of Canada are mosaicked and clipped to boundaries of provinces and/or territories in order to produce one GFC layer for each province. Next step is reclassifying these clipped layers and creating binary maps by segmentation of the GFC layer into 14 layers based on the year of the forest cover change, indicating that if each given pixel belongs to a specific year (i.e., forest cover change in a certain year versus no forest cover change in that certain year) and assign a proper name to each layer. A model was created to automate this reclassification process. This model runs through the folders that store GFC layers for each province then selects the first layer and import it into 14 Reclassify tools to create the aforementioned binary maps.

2.2 MSPA analysis

The binary maps that were created in section 2.1.1 are imported to Guidos' engine for MSPA analysis. For the maps that are smaller than the maximum size supported by Guidos, which is 101 MB, the regular MSPA analysis was used, but for the larger ones, the tiling tool in the software was used. Tiling tool slices the input layer inside of the software into smaller parts, performs the analysis on each part, and then merges the parts to create one single output map. As it has been mentioned in section 1.5.5, before running the analysis, the software asks the user to determine the parameters of the analysis. For this study, the parameters were set as follows:

Neighbourhood connectivity: 8 | **Edge width**: 1 | **Transition**: off | **Intext**: off

The statistics option in the MSPA analysis setting is disabled that means the text file containing the statistics of the MSPA analysis output cannot be created, however, this statistic will be computed using ArcGIS for further processing. The attribute table of the output layer is indexed with specific codes for each particular morphological class. A model is created to export the statistics of the MSPA analysis outputs in CSV format and assign the proper names to the CSV files. The input for this model is the workspace in which the output layers are stored. It iterates the layers inside of the workspace, builds the attribute table for each one, and then extracts a CSV file from the attribute table of each layer, which can be processed in R for further analysis.

2.3 Data analysis

In order to compare the results of morphological classes, a few options were available, such as running *t*-test and Chi-square tests (Kuhnert et al., 2005) for (a) performing the tests that concern with frequency distribution by using Chi-square tests of the *goodness of fit*, and/or (b) test the *independence of variables* with contingency tables, and/or (c) test the *homogeneity of proportion* using Chi-square distribution (Bluman, 2008). For instance, with testing of the *goodness of fit,* we can answer if frequency/proportion of each of the morphological classes shows a preference for a specific time or geographic space? With testing the *independence of variables,* we can answer if the frequency of each of the morphological classes independent of time and geographic areas? That is, how this frequency change through time and among geographic areas? Finally, with testing the homogeneity of proportion, we can answer if the proportion of each of the morphological classes differs through time and among geographic areas?

The first challenge in analyzing and comparing the results of the morphological classes is that after the pixels that fall into each morphological class are counted, or areas belong to each of the classes are calculated, *t*-test cannot be used to compare the data because the distribution often is not normal, therefore it would be difficult or even meaningless to compare the distributions with each other. The second and the most important challenge with the aforementioned tests is that the spatial characteristics of the data and the neighborhood connectivity (in other words, the configuration) are entirely ignored, and the results of comparison only reflect the composition.

Join counts are used to characterize the spatial grouping within each of the subsamples that will be extracted from each province and/or territories for all the years of study. Join count statistics reflects the Tobler's first law of geography: "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). This law is the fundamental concept of spatial autocorrelation (SA), which speaks to the relationships between different observations in a study area, and if the existence of one locality depends on its neighbouring localities (Sokal and Oden, 1978).

In other words, positive SA means that similar value clustered together and its range of value is from 0 to 1, where 1 is the highest similarity and a negative SA means that dissimilar values are next to each other and its range of value is from -1 to 0, where -1 is the lowest similarity. Figure 12 is the representation of neighbourhood connectivity in the spatial autocorrelation that can be defined as either rook's case, bishop's case, or queen's case (Sawada, 2004).

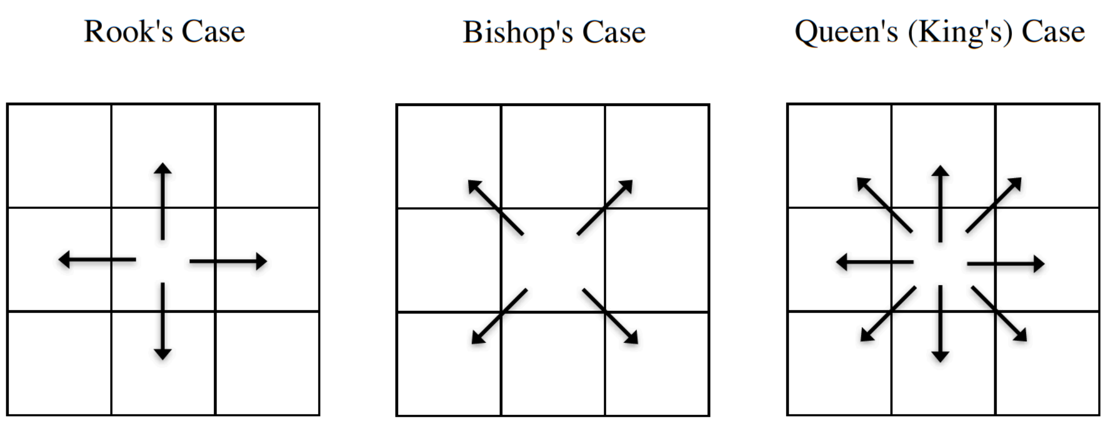


Figure 12. Possibilities of neighbourhood connectivity: rooks case, bishops case, or queen's case.

Although each of these three cases is reasonable options for SA, join count statistics works on the rook's case, where adjacency of each cell with four of the neighbourhood cells (i.e., top, bottom, right, left) matter (Sawada, 2004). Join count statistics are about classifying the joins (also known as links) between black (B) and white (W) pixels (Figure 13), where there are three possible classes: BB, WW, and BW, in which, BB represents a join between two adjacent black cells, BW represents a join between two adjacent black and white cells, and WW represents a join between two adjacent white cells.

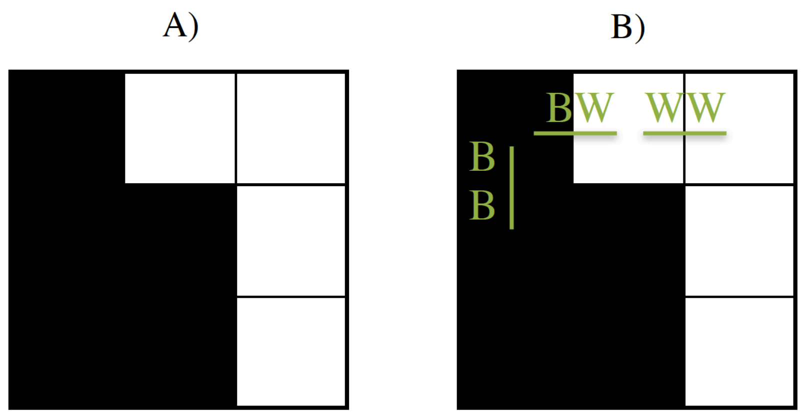


Figure 13. Representation of a 3x3 sample pixels (A) and how three different joins (BB, BW, WW) are determined (B).

The number of joins is influenced by whether we use torus or non-torus when running the join counts. With torus, the link between cells on the edge are considered according to their corresponding cell on the other side of the kernel, while in Non-Torus, the aforementioned link is not considered. For instance, in Figure 14, as there is no cell on the right side of C, a join is assigned to cell C and A (red line). The same applies to the north and south of this sample kernel, where is a join between A and G.

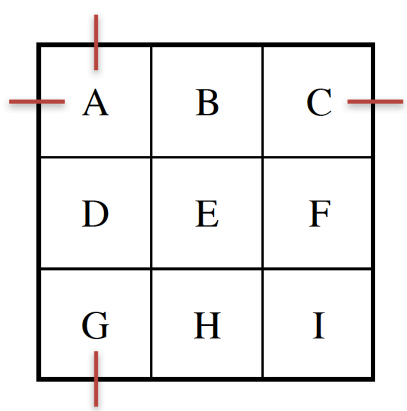


Figure 14. The concept of torus in join count statistics.

Join count statistics are available through an R package (R Core Team, 2016) called *spdep* (Spatial Dependence: Weighting Schemes, Statistics and Models) (Bivand and Piras, 2015). The outcome of this join count processing provides the total number of joins of each type, their respective expected values, variances, and z-values. A statistical function in R was developed to facilitate this analysis. Figure 15 is to clarify that function and depict the relations between its parts.

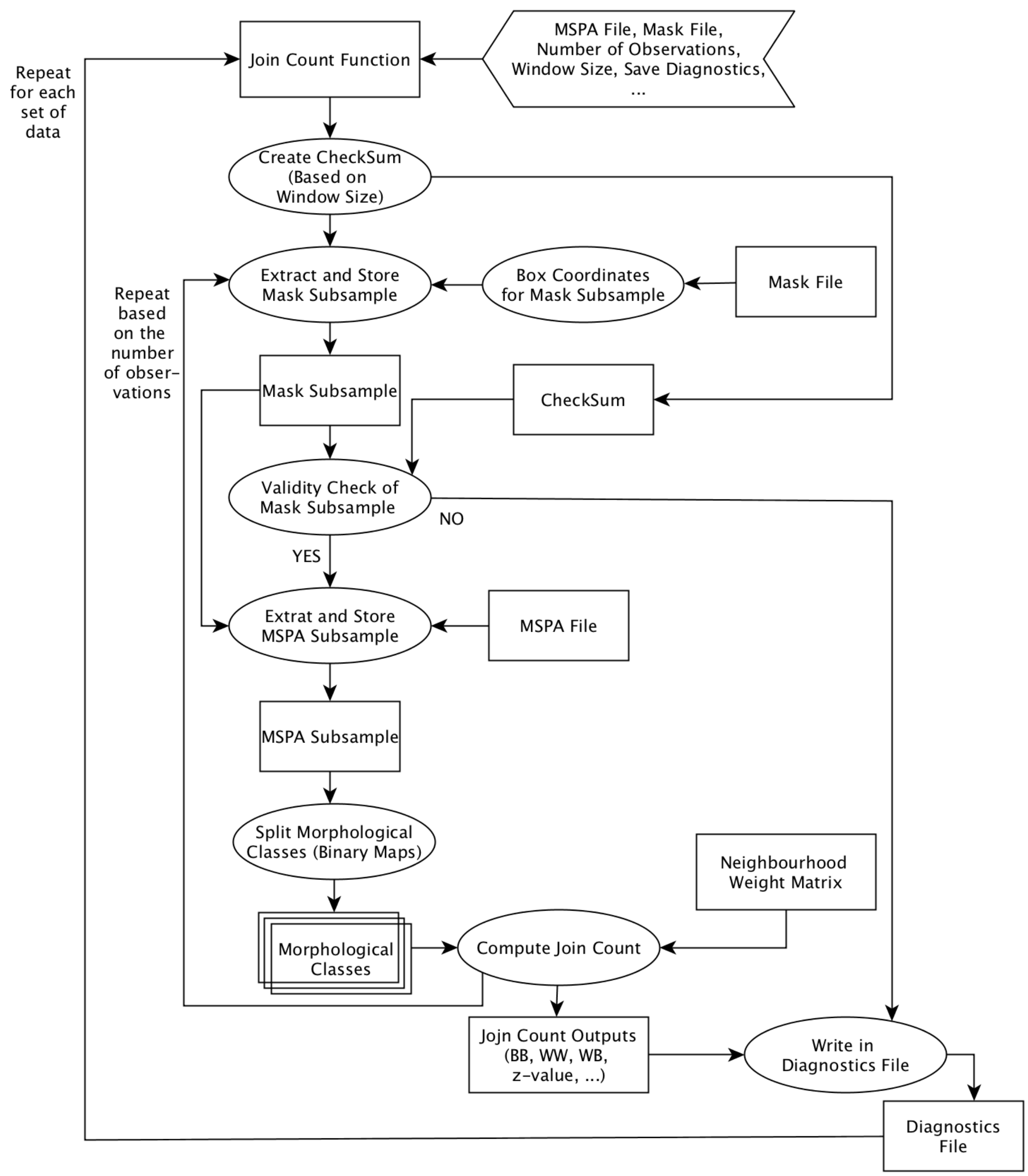


Figure 15. Flow diagram clarifying the main components of a function in R that was developed to facilitate running join count analysis and their relations.

In order to produce a reference/empirical distribution (using spatial randomization) to compare to the observed distribution to determine whether the observed distribution is extreme or not, a resampling technique called bootstrapping is used, in which a large number of subsamples with a fixed size (referred to as the window size), using randomized origin locations from the main dataset are extracted, for a certain number of times (referred to as the number of observations). After performing the analysis with different window sizes and number of observations on Ontario as a sample data, a window size of 200 and a number of observation of 500 were chosen and set in the join count function.

To ensure that each of the subsamples fall within the certain layer (i.e., within the boundaries of the Canadian provinces or territories), two steps were taken. Firstly, a mask file for each province and territories were produced. The *mask* file is a binary raster layer that was created from rasterizing of GADM shape files to identify the boundary of each province/territories by indexing the pixels that are within the province/territories as 1, and the ones that are outside of the province/territories as 0.

The second step was creating an object named *CheckSum* that stores the value of the window size which in this study is 40,000 (i.e., 200 x 200) in order to examine if the extracted subsample is within the study area. The function checks the value of the subsample with CheckSum and if their values are matched, or in other words, they both have the value of 40,000, it means that all of the subsample pixels are falling within the areas that are indexed as 1 (and identified as GOOD), otherwise the values are not matched and the subsample is neglected (and identified as BAD) and only a record of its exact position is stored in a text file, called the diagnostics file. The extraction procedure proceeds to the second subsample, and then the third subsample until the number of GOOD subsamples reaches to the number of observations.

Once the 500 mask subsamples are obtained, MSPA subsamples from the corresponding MSPA file are extracted based on the mask subsamples. For instance, the first MSPA sample is extracted based on the extent of the first mask. After a MSPA subsample is chosen, each one of 8 morphological classes, excluding the background pixels (i.e., Core, Islet, Loop, Bridge, Perforation, Edge, and Branch) for each set of data, is converted into a binary map (e.g., Core vs. non-Core, Islet vs. non-Islet). Therefore, there are 7 binary maps for each subsample of each province/territories of each year of study which resulted in over 400,000 binary maps. A neighborhood weight matrix was produced in order to determine if the binary pixels are contiguous (i.e., the exclusion of the corner-touching), then the join count analysis is run on each one of the binary maps and the outcome of each analysis is written in a separate diagnostic file.

The outcome that are the numbers of joins (i.e., BB, WW, BW) for subsamples of each province/territory per year are saved, however, only BB joins are used for this study. Following the join count analysis, the diagnostic files are imported into *R*. A computer program was written in R in order to automate the production of boxplots that visualize the results of the join counts from different angles. First set of boxplots were produced to represent the results of the join count analysis for each of the morphological classes (e.g., Core versus Core) in each province/territory across all the years of study (e.g., frequency of Core versus Core joins in Ontario). The second set of boxplots were produced to represent the results of the join count analysis for each of the morphological classes in each year of study across all the province/territories (e.g., frequency of Islet versus Islet joins in Canada in 2002). The two functions produced approximately 160 boxplots that are explored in the next section.

Besides from the boxplots, ANOVA and Levene's tests were used to examine whether the aforementioned frequencies are statistically significant and if they indicate any meaningful/interesting patterns.

3. Results

The objective of this research was to assess whether the spatial and temporal morphology of forest disturbance pattern within the boreal biome of Canada differs through time and over provinces and/or territories. In order to achieve this objective, morphological analysis was performed on the forest disturbance patterns which resulted into segmentation of the patterns into seven morphological classes: Core, Islet, Loop, Bridge, Perforation, Edge, and Branch. Following the segmentation, each of the classes converted into a binary map and the said binary maps are imported into *R* to. In order to produce a reference/empirical distribution to compare to the observed distribution to determine whether the observed distribution is extreme or not, bootstrapping is used, in which 500 subsamples with a kernel of 200 pixels (i.e., window size) using randomized origin locations from the main dataset are extracted, for 500 times (i.e., number of observations) and perform join count analysis on each of the samples.

The outcomes of the join count analysis resulted in distributions of the number of joins for each morphological class from each province and/or territories /year the study. In this approach, the extracted distributions are compared to each other, rather than comparing two single data points and the distributions are studied comprehensively through boxplots and the results of two sets of ANOVA tests.

The first set of ANOVA tests were conducted to test whether the average numbers of each of the morphological joins (e.g., Core–Core joins) differ among the years of study in Canada. The result of this test reveals whether the effect of the temporal grouping by year was significant which was followed up with the results of post hoc analyses using Tukey's HSD for significance that indicated in which years, the average numbers of each of the morphological joins are significantly different.

The second set of ANOVA tests were conducted to test whether the average numbers of each of the morphological joins (e.g., Core–Core joins) differ among the Canadian provinces and territories in each of the years of study. The result of this test reveals whether the effect of the spatial grouping by province and/or territories was significant which was followed up with the results of post hoc analyses using Tukey's HSD for significance that indicated in which province and/or territories, the average numbers of each of the morphological joins are significantly different.

Notwithstanding the results of ANOVA tests that are concerned with testing significant differences in the average numbers of each of the morphological joins, two sets of Levene's test were conducted as well in order to discover insights regarding the variability of the number of each of the morphological classes, in terms of the spread of data (i.e., number of joins) from the mean or in order words, how spread out the distributions are from the mean.

The first set of Levene's tests were conducted to test whether the variability of the each of the morphological joins (e.g., Core–Core joins) differ among the years of study in Canada. The result of this test showed whether the effect of the temporal grouping by year was significant which was followed up with the results of post hoc analyses using Tukey's HSD for significance that indicated in which years, the variability of each of the morphological joins are significantly different.

The second set of Levene's tests were conducted to test whether the variability of each of the morphological joins (e.g., Core–Core joins) differ among the Canadian provinces and territories in each of the years of study. The result of this test showed whether the effect of the spatial grouping by province and/or territories was significant which was followed up with the results of post hoc analyses using Tukey's HSD for significance that indicated in which province and/or territories, the variability of each of the morphological joins are significantly different.

Study of the boxplots and the results of the ANOVA and Levene's tests revealed some plausible irregularities for each of the morphological classes. The results section of this study is organized based on those irregularities and divided into five sub-sections to cover the main irregularities for each of the morphological classes, combining Core and Edge into one sub section and Bridge and Loop into one section as well.

3.1 Joins in the boreal portion of Canada

This section is a general overview of the joins in three of the morphological classes that revealed interesting results (i.e., Core, Edge, and Perforation) in the entire boreal portion of Canada during the years 2001 through 2014. The below boxplot represents the frequency of the Core–Core joins in the Canada (Figure 16) and as can be seen in this boxplot, the year 2004, 2005, 2013, and 2014 seem to demonstrate a higher variability in the number of joins. In order to test whether the average number and the variability of the number of joins are significantly different among the years, an ANOVA and Levene’s test are performed.

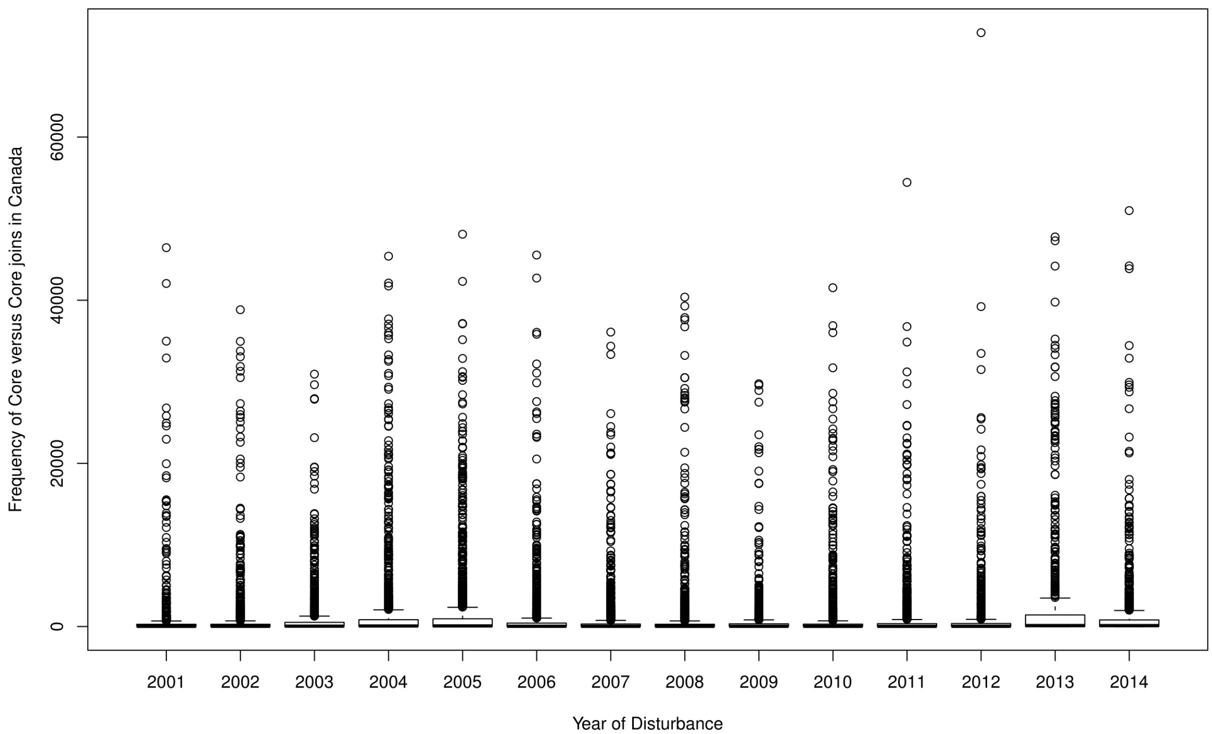


Figure 16. The frequency of the Core–Core joins in Canada from the years 2001 through 2014.

A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Core–Core joins differ among the years 2001 through 2014in Canada. The result of this analysis showed that the effect of the temporal grouping by year was significant $F(13, 15091) = 13.38$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Core–Core occurrences for 2004 are significantly higher than all other years except in 2005 and 2014 where the differences are not significant and 2013 where occurrences are significantly lower in, and the Core–Core occurrences for 2005 are significantly higher than all other years except in 2004 and 2013 where the differences are not significant and 2013 where occurrences are significantly lower in (Table 2). Table 2 also indicates that the Core–Core occurrences for 2013 are significantly higher than all other years.

Table 2. Tukey HSD results of the ANOVA test for Core–Core joins from the years 2001 through 2014 in the Canada, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.9975													
2003	1.0000	0.9996												
2004	**0.0000**	**0.0022**	**0.0000**											
2005	**0.0001**	**0.0134**	**0.0000**	1.0000										
2006	0.9997	1.0000	1.0000	**0.0001**	**0.0008**									
2007	1.0000	0.9953	1.0000	**0.0000**	**0.0000**	0.9992								
2008	0.9931	1.0000	0.9984	**0.0016**	**0.0106**	1.0000	0.9867							
2009	0.9999	0.6971	0.9949	**0.0000**	**0.0000**	0.7770	0.9995	0.5708						
2010	0.9745	1.0000	0.9905	**0.0064**	**0.0349**	1.0000	0.9549	1.0000	0.4313					
2011	0.9995	1.0000	1.0000	**0.0004**	**0.0031**	1.0000	0.9990	1.0000	0.7877	1.0000				
2012	1.0000	1.0000	1.0000	**0.0001**	**0.0007**	1.0000	1.0000	1.0000	0.9248	0.9999	1.0000			
2013	**0.0000**	**0.0000**	**0.0000**	**0.0159**	**0.0014**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**		
2014	0.6424	0.9988	0.7101	0.0902	0.2998	0.9767	0.5151	0.9993	0.0707	1.0000	0.9905	0.9434	**0.0000**	

Subsequently, a Levene's test was conducted to test whether the variability of the numbers of Core–Core joins differ among the years 2001 to 2014 in Canada. The result of this test also showed that the effect of the temporal grouping by year was significant $F(13, 15091) = 33.64$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Core–Core occurrences for 2004 are significantly higher than all other years except in 2005 where the differences are not significant and 2013 where occurrences are significantly lower in, and the variability of the Core–Core occurrences for 2005 are significantly higher than all other years except in 2004 where the differences are not significant and 2013 where occurrences are significantly lower in (Table 3). Table 3 also indicates that the variability of the Core–Core occurrences for 2013 are significantly higher than all other years.

Table 3. Tukey HSD results of the Levene's test for Core–Core joins from the years 2001 through 2014 in Canada, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.7768													
2003	1.0000	0.4936												
2004	**0.0000**	**0.0000**	**0.0000**											
2005	**0.0000**	**0.0000**	**0.0000**	0.9721										
2006	0.9894	0.9999	0.9155	**0.0000**	**0.0000**									
2007	1.0000	0.5235	1.0000	**0.0000**	**0.0000**	0.9308								
2008	0.5207	1.0000	0.2278	**0.0000**	**0.0000**	0.9954	0.2483							
2009	0.8181	**0.0035**	0.8632	**0.0000**	**0.0000**	**0.0252**	0.8308	**0.0005**						
2010	0.3670	1.0000	0.1341	**0.0000**	**0.0002**	0.9734	0.1476	1.0000	**0.0002**					
2011	0.9602	1.0000	0.8166	**0.0000**	**0.0000**	1.0000	0.8401	0.9999	**0.0161**	0.9980				
2012	0.9993	0.9985	0.9876	**0.0000**	**0.0000**	1.0000	0.9910	0.9771	0.0960	0.9214	1.0000			
2013	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**		
2014	0.3898	1.0000	0.1465	**0.0000**	**0.0002**	0.9790	0.1610	1.0000	**0.0002**	1.0000	0.9986	0.9335	**0.0000**	

The boxplot in Figure 17 represents the frequency of the Edge–Edge joins in the Canada and similar to Core–Core joins, the year 2004, 2005, 2013, and 2014 seem to demonstrate a higher variability in the number of joins. The results of ANOVA and Levene's test for Edge–Edge joins follow the same pattern as Core–Core joins.

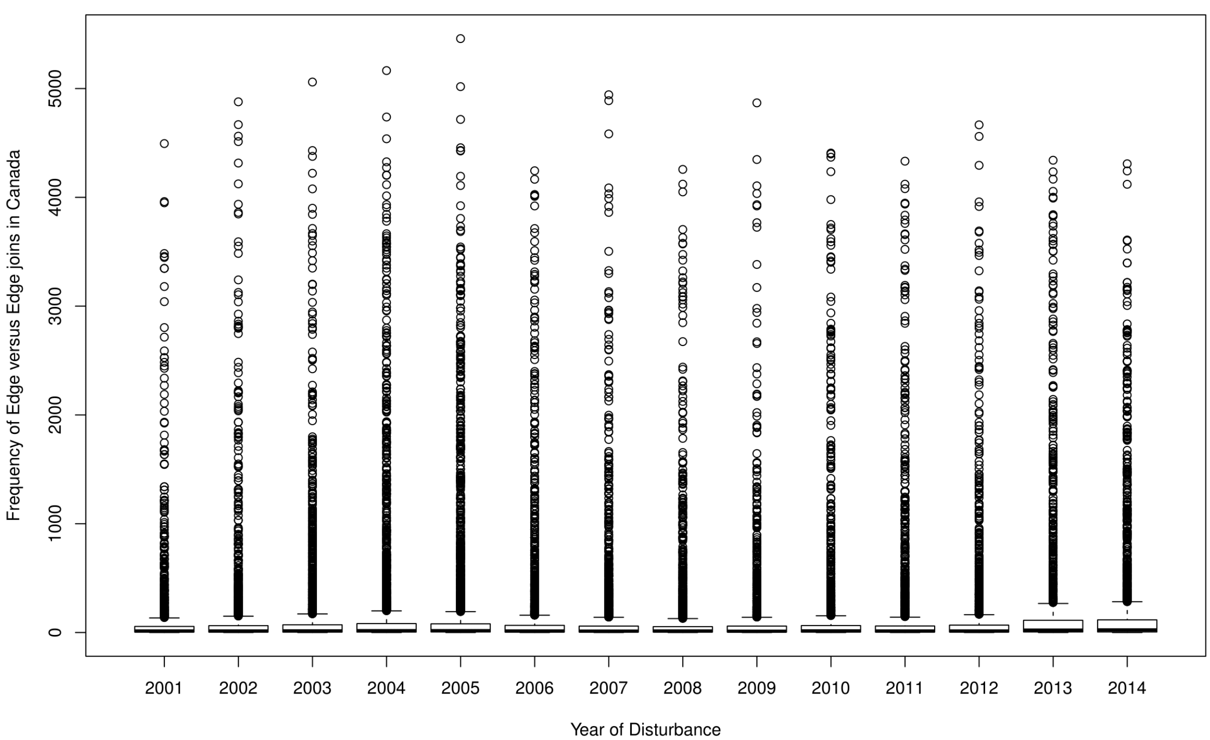


Figure 17. The frequency of the Edge–Edge joins in Canada from the years 2001 through 2014.

The result of a one-way analysis of variance (ANOVA) that was conducted to test whether the average numbers of Edge–Edge joins differ among the years 2001 through 2014in Canada, showed that the effect of the temporal grouping by year was significant $F(13, 30546) = 9.474$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Edge–Edge occurrences for 2004 are significantly higher than all other years except in 2005, 2010, 2013, and 2014, and the Edge–Edge occurrences for 2005 are significantly higher than all other years except in 2010, 2013, and 2014 (Table 4). Table 4 also indicates that the Edge–Edge occurrences for 2013 are significantly higher than all other years, except in 2004, 2005, and 2014.

Table 4. Tukey HSD results of the ANOVA test for Edge–Edge joins from the years 2001 through 2014 in Canada, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	0.9910													
2003	0.7628	1.0000												
2004	**0.0000**	**0.0017**	**0.0119**											
2005	**0.0000**	**0.0019**	**0.0138**	1.0000										
2006	0.8914	1.0000	1.0000	**0.0022**	**0.0024**									
2007	0.9996	1.0000	0.9971	**0.0001**	**0.0001**	0.9999								
2008	0.9999	1.0000	0.9964	**0.0001**	**0.0001**	0.9998	1.0000							
2009	1.0000	0.9289	0.4488	**0.0000**	**0.0000**	0.6319	0.9902	0.9950						
2010	0.6011	0.9995	1.0000	0.0728	0.0857	1.0000	0.9779	0.9753	0.3016					
2011	0.7614	1.0000	1.0000	**0.0226**	**0.0266**	1.0000	0.9965	0.9957	0.4585	1.0000				
2012	0.9929	1.0000	1.0000	**0.0007**	**0.0008**	1.0000	1.0000	1.0000	0.9358	0.9987	0.9999			
2013	**0.0000**	**0.0001**	**0.0005**	0.9954	0.9858	**0.0001**	**0.0000**	**0.0000**	**0.0000**	**0.0046**	**0.0011**	**0.0000**		
2014	0.0081	0.3303	0.7434	0.9107	0.9414	0.4737	0.0829	0.0907	**0.0008**	0.9481	0.8173	0.2440	0.2758	

The result of a Levene's test that was conducted to test whether the variability of the numbers of Edge–Edge joins differ among the years 2001 through 2014in Canada, showed that the effect of the temporal grouping by year was significant $F(13, 30546) = 26.08$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Edge–Edge occurrences for 2004 are significantly higher than all other years except in 2005 and 2013 and the variability of the Edge–Edge occurrences for 2005 are significantly higher than all other years except in 2004 and 2013 (Table 5). Table 5 also indicates that the variability of the Edge–Edge occurrences for 2013 are significantly higher than all other years, except in 2004 and 2005.

Table 5. Tukey HSD results of the Levene's test for Edge–Edge joins from the years 2001 through 2014 in Canada, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.5940													
2003	**0.0484**	0.9988												
2004	**0.0000**	**0.0000**	**0.0000**											
2005	**0.0000**	**0.0000**	**0.0000**	1.0000										
2006	0.1158	1.0000	1.0000	**0.0000**	**0.0000**									
2007	0.9137	1.0000	0.8781	**0.0000**	**0.0000**	0.9775								
2008	0.9187	1.0000	0.9093	**0.0000**	**0.0000**	0.9854	1.0000							
2009	1.0000	0.1843	**0.0031**	**0.0000**	**0.0000**	**0.0101**	0.5223	0.5479						
2010	**0.0051**	0.8745	0.9999	**0.0000**	**0.0000**	0.9941	0.3803	0.4435	**0.0002**					
2011	**0.0174**	0.9783	1.0000	**0.0000**	**0.0000**	0.9999	0.6548	0.7134	**0.0009**	1.0000				
2012	0.7073	1.0000	0.9897	**0.0000**	**0.0000**	0.9996	1.0000	1.0000	0.2566	0.7212	0.9185			
2013	**0.0000**	**0.0000**	**0.0000**	0.9908	0.9638	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**		
2014	**0.0000**	0.1251	0.7135	**0.0004**	**0.0005**	0.3748	0.0079	0.0132	0.0000	0.9975	0.9492	0.0492	**0.0000**	

The third morphological class that revealed an interesting result is Perforation. The following boxplot represents the frequency of the Perforation–Perforation joins in the Canada (Figure 18) and as might be seen in this boxplot, the year 2013 seems to demonstrate a higher variability in the number of joins and not only is the overall range the highest in year 2013, but the inter-quartile range is also larger than for other years. In order to test whether the average number and the variability of the number of joins are significantly different throughout the years, an ANOVA and Levene's test are performed.

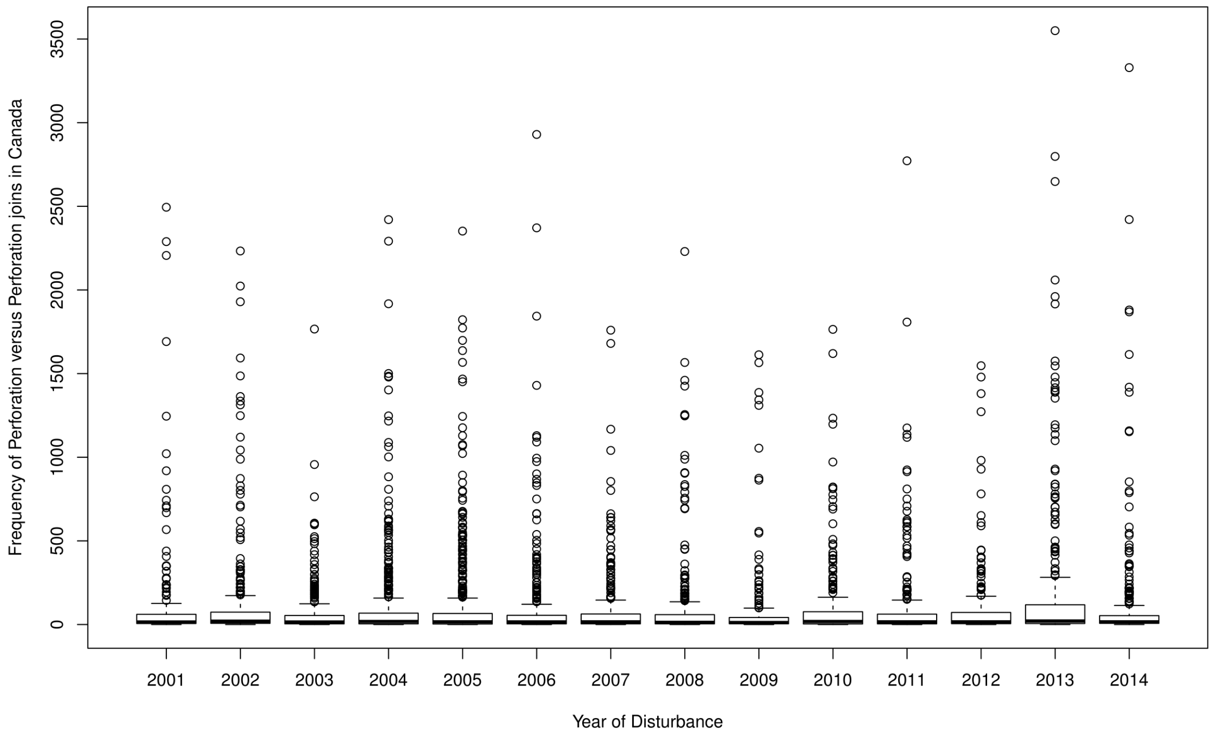


Figure 18. The frequency of the Perforation–Perforation joins in Canada from the years 2001 through 2014.

A one-way analysis of variance (ANOVA) was conducted to test whether the average number of Perforation–Perforation joins differs from the years 2001 through 2014 in Canada. While the result of this analysis showed that the effect of the temporal grouping by year was significant $F(13, 4688) = 2.596$, $p < 0.05$, post hoc analyses using Tukey's HSD for significance only indicated that the occurrences for Perforation–Perforation for 2013 are significantly higher than 2003, 2009, 2011, 2012, 2014 (Table 6).

Table 6. Tukey HSD results of the ANOVA test for Perforation–Perforation joins from the years 2001 through 2014 in Canada, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	1.0000													
2003	0.5136	0.1335												
2004	1.0000	0.9986	0.5717											
2005	1.0000	0.9973	0.5385	1.0000										
2006	0.9998	0.9838	0.8835	1.0000	1.0000									
2007	0.9994	0.9744	0.9784	1.0000	1.0000	1.0000								
2008	1.0000	0.9999	0.7056	1.0000	1.0000	1.0000	1.0000							
2009	0.9703	0.7797	1.0000	0.9963	0.9963	0.9999	1.0000	0.9972						
2010	0.9998	0.9886	0.9501	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000					
2011	0.9985	0.9531	0.9797	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000				
2012	0.9944	0.9103	0.9977	0.9998	0.9999	1.0000	1.0000	0.9999	1.0000	1.0000	1.0000			
2013	0.8637	0.9323	**0.0001**	0.1186	0.0734	0.0613	0.0841	0.3640	**0.0171**	0.1188	**0.0463**	**0.0387**		
2014	0.9990	0.9551	0.9471	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	**0.0325**	

When a Levene's test was conducted to test whether the variability of the numbers of Perforation–Perforation joins differ among the years 2001 through 2014in Canada, the result of this test also showed that the effect of the temporal grouping by year was significant $F(13, 4688) = 6.858$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the occurrences for Perforation–Perforation for 2013 are significantly higher than in all other years, except in 2001 and 2003, and the variability of the occurrences for Perforation–Perforation for 2003 are significantly higher than in 2001-2005, 2008 and lower in 2013 (Table 7).

Table 7. Tukey HSD results of the Levene's test for Perforation–Perforation joins from the years 2001 through 2014 in Canada, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	1.0000													
2003	**0.0011**	**0.0000**												
2004	0.9897	0.8687	**0.0066**											
2005	0.9863	0.8336	**0.0038**	1.0000										
2006	0.9192	0.6229	0.0717	1.0000	1.0000									
2007	0.7892	0.4396	0.4033	0.9996	0.9995	1.0000								
2008	0.9999	0.9946	**0.0088**	1.0000	1.0000	0.9998	0.9944							
2009	0.3646	0.1089	0.9223	0.9143	0.8983	0.9960	1.0000	0.8254						
2010	0.7968	0.4466	0.3721	0.9997	0.9996	1.0000	1.0000	0.9951	1.0000					
2011	0.7250	0.3465	0.3713	0.9988	0.9985	1.0000	1.0000	0.9890	1.0000	1.0000				
2012	0.3820	0.1127	0.8763	0.9282	0.9135	0.9975	1.0000	0.8450	1.0000	1.0000	1.0000			
2013	0.4751	0.4935	**0.0000**	**0.0002**	**0.0001**	**0.0001**	**0.0001**	**0.0164**	**0.0000**	**0.0001**	**0.0000**	**0.0000**		
2014	0.8420	0.4719	0.1277	1.0000	1.0000	1.0000	1.0000	0.9985	0.9993	1.0000	1.0000	0.9996	**0.0000**	

3.1.1 Review of the results of joins in the boreal portions of Canada

Reviewing the results of the join count analysis on the morphological patterns of the disturbances in the entire boreal portion of Canada, revealed that the number of Core–Core joins and following that, Edge–Edge joins are significantly higher in the years 2004, 2005, and 2013 in terms of mean and variability. Furthermore, those results showed that the number of Perforation–Perforation joins seem to be significantly higher in terms of mean and variability in the year 2013 and in terms of variability in the year 2013.

3.2 Islet–Islet joins

This section aims at highlighting some of the cases in which Islet–Islet joins revealed curious results in various provinces and/or territories and years. The first boxplot represents the frequency of the Islet–Islet joins in the Canadian provinces and territories in the year 2002 (Figure 19). The province of Ontario seems to have a higher number of outliers and looks different in terms of variability around the mean in in comparison to the other provinces and territories. This variability is tested using ANOVA and Levene's tests.

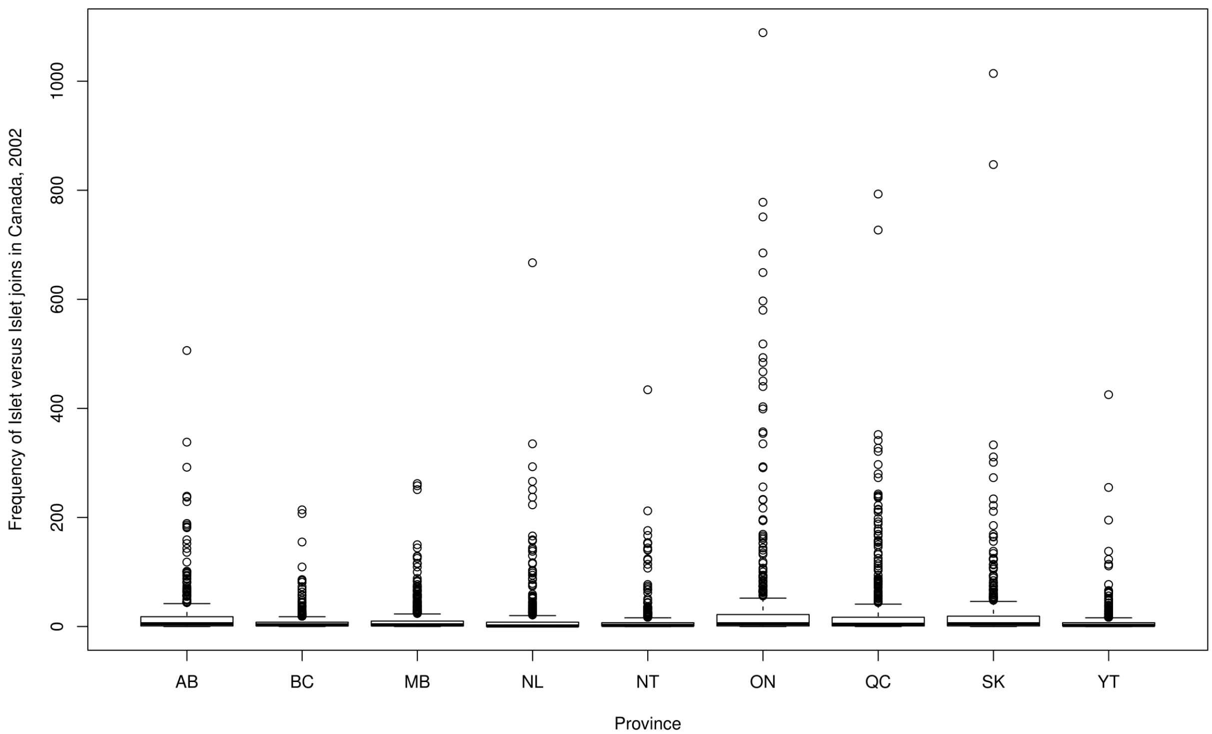


Figure 19. The frequency of the Islet–Islet joins in the Canadian provinces and territories in the year 2002.

A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Islet–Islet joins differ among the Canadian provinces and territories in the year 2002. The result of this analysis showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 4426) = 15.64$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Islet–Islet occurrences for Ontario are significantly higher than in all other provinces/territories and Islet–Islet occurrences for Québec are significantly higher than in all other provinces/territories, except in Alberta where the occurrences are not significantly different and Ontario where the occurrences are significantly lower (Table 8).

Table 8. Tukey HSD results of the ANOVA test for Islet–Islet joins in Canadian provinces and territories in the year 2002, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	BC	MB	NL	NT	ON	QC	SK	YT
AB									
BC	0.1705								
MB	0.7250	0.9925							
NL	0.9817	0.8033	0.9989						
NT	0.3604	1.0000	0.9998	0.9497					
ON	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**				
QC	0.2559	**0.0000**	**0.0009**	**0.0139**	**0.0001**	**0.0322**			
SK	0.9396	0.0030	0.0656	0.3317	0.0118	**0.0003**	0.9603		
YT	0.2039	1.0000	0.9959	0.8444	1.0000	**0.0000**	**0.0000**	0.0041	

Subsequently, a Levene's test was conducted to test whether the variability of the numbers of Islet–Islet joins differ among the Canadian provinces and territories in the year 2002. The result of this test showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 4426) = 39.19$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance also indicated that the variability of the Islet–Islet occurrences for Ontario are significantly higher than in all other provinces/territories and the variability of the Islet–Islet occurrences for Québec are significantly higher than in all other provinces/territories, except in Saskatchewan (Table 9). The results also indicated that the variability of the Islet–Islet occurrences for Saskatchewan are significantly higher than in British Columbia, Manitoba, Northwest Territories, and Yukon (Table 9).

Table 9. Tukey HSD results of the Levene's test for Islet–Islet joins in Canadian provinces and territories in the year 2002, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	BC	MB	NL	NT	ON	QC	SK	YT
AB									
BC	0.0148								
MB	0.5128	0.8801							
NL	1.0000	0.0352	0.6982						
NT	0.2403	0.9854	1.0000	0.3948					
ON	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**				
QC	**0.0001**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**			
SK	0.4629	**0.0000**	**0.0011**	0.2891	**0.0001**	**0.0000**	0.1515		
YT	0.0486	1.0000	0.9776	0.1020	0.9994	**0.0000**	**0.0000**	**0.0000**	

When looking into the boxplots for Islet–Islet in Ontario from the years 2001 through 2014 (Figure 20), it can be seen that the year 2002 seems to have the highest variability which makes it more interesting to scrutinize what happened in terms of disturbances in the year 2002 in Ontario that led to an increase in the variability of the number of Islet–Islet joins.

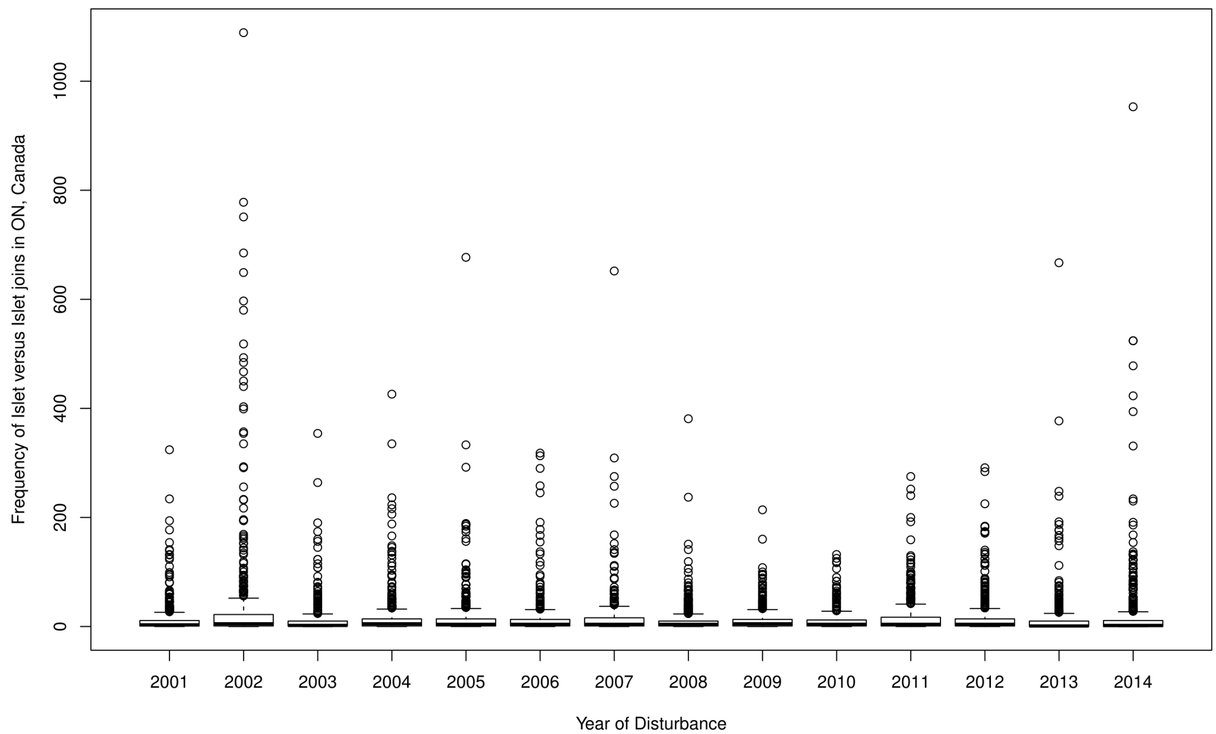


Figure 20. The frequency of the Islet–Islet joins in the Ontario from the years 2001 through 2014.

In order to confirm the aforementioned difference, a one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Islet–Islet joins differ among the years 2001 through 2014 in Ontario. The result of this analysis confirmed that the effect of the spatial grouping by province and/or territories was significant $F(8, 6842) = 11.22$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Islet–Islet occurrences for 2002 are significantly higher than in all other years (Table 10).

Table 10. Tukey HSD results of the ANOVA test for Islet–Islet joins from the years 2001 through 2014 in Ontario, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	**0.0000**													
2003	1.0000	**0.0000**												
2004	0.9946	**0.0000**	0.9720											
2005	0.9971	**0.0000**	0.9819	1.0000										
2006	1.0000	**0.0000**	0.9998	1.0000	1.0000									
2007	0.9994	**0.0000**	0.9942	1.0000	1.0000	1.0000								
2008	1.0000	**0.0000**	1.0000	0.9048	0.9302	0.9972	0.9694							
2009	1.0000	**0.0000**	1.0000	0.9586	0.9722	0.9995	0.9903	1.0000						
2010	1.0000	**0.0000**	1.0000	0.7777	0.8212	0.9823	0.9006	1.0000	1.0000					
2011	0.9945	**0.0000**	0.9715	1.0000	1.0000	1.0000	1.0000	0.9036	0.9579	0.7757				
2012	0.9988	**0.0000**	0.9903	1.0000	1.0000	1.0000	1.0000	0.9553	0.9843	0.8695	1.0000			
2013	1.0000	**0.0000**	1.0000	0.9993	0.9997	1.0000	1.0000	1.0000	1.0000	0.9994	0.9993	0.9999		
2014	0.2764	**0.0000**	0.1604	0.9721	0.9588	0.7431	0.9153	0.0792	0.1303	0.0359	0.9726	0.9344	0.4179	

Subsequently, a Levene’s test was conducted to test whether the variability of the numbers of Islet–Islet joins differ among the years 2001 through 2014 in Ontario, the result of this test showed that the effect of the temporal grouping by year was significant $F(13, 6842) = 32.24$, $p < 0.05$. Post hoc analyses using Tukey’s HSD for significance indicated that the variability of the Islet–Islet occurrences for 2002 are significantly higher than in all other years and the variability of the Islet–Islet occurrences for 2014 are significantly higher than in all other years, except in 2002 where the occurrences are significantly lower in (Table 11).

Table 11. Tukey HSD results of the Levene’s test for Islet–Islet joins from the years 2001 through 2014 in Ontario, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	**0.0000**													
2003	1.0000	**0.0000**												
2004	0.9824	**0.0000**	0.9678											
2005	0.9794	**0.0000**	0.9631	1.0000										
2006	1.0000	**0.0000**	1.0000	1.0000	0.9999									
2007	0.9996	**0.0000**	0.9989	1.0000	1.0000	1.0000								
2008	0.9989	**0.0000**	0.9997	0.4517	0.4333	0.9375	0.7779							
2009	0.9977	**0.0000**	0.9993	0.3937	0.3763	0.9120	0.7261	1.0000						
2010	0.9502	**0.0000**	0.9741	0.1454	0.1363	0.6519	0.3922	1.0000	1.0000					
2011	0.9825	**0.0000**	0.9680	1.0000	1.0000	1.0000	1.0000	0.4524	0.3944	0.1457				
2012	0.9785	**0.0000**	0.9617	1.0000	1.0000	0.9999	1.0000	0.4281	0.3713	0.1336	1.0000			
2013	0.9981	**0.0000**	0.9954	1.0000	1.0000	1.0000	1.0000	0.6669	0.6075	0.2840	1.0000	1.0000		
2014	**0.0000**	**0.0000**	**0.0000**	**0.0028**	**0.0031**	**0.0001**	**0.0004**	**0.0000**	**0.0000**	**0.0000**	**0.0028**	**0.0032**	**0.0007**	

Following examining the province of Ontario, boxplots for Islet–Islet in Québec from the years 2001 through 2014 (Figure 21) was looked into. Although it can be seen for Québec, 2014 is different than the rest of the years in terms of variability and outliers.

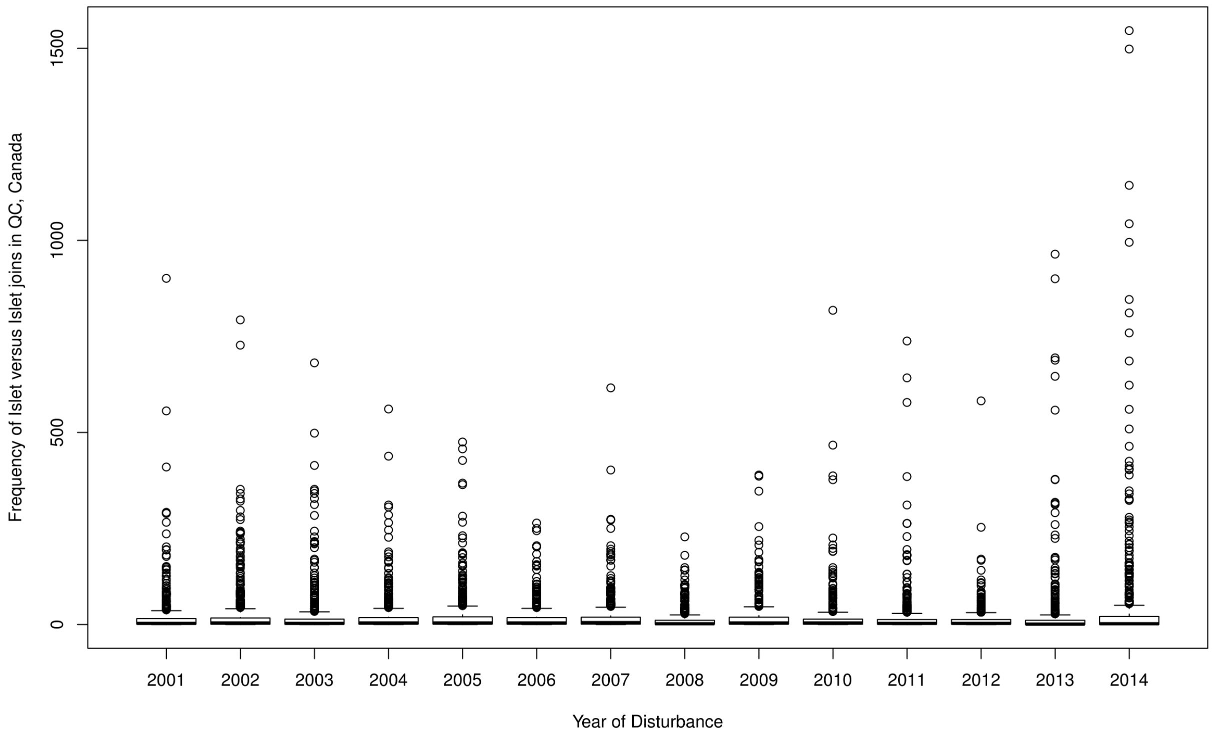


Figure 21. The frequency of the Islet–Islet joins in Québec from the years 2001 through 2014.

To confirm the aforementioned difference, a one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Islet–Islet joins differ among the years 2001 through 2014 in Québec. The result of this analysis confirmed that the effect of the spatial grouping by province and/or territories was significant $F(13, 6878) = 9.016$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Islet–Islet occurrences for 2014 are significantly higher than in all other years (Table 12).

Table 12. Tukey HSD results of the ANOVA test for Islet–Islet joins from the years 2001 through 2014 in Québec, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	0.9794													
2003	1.0000	0.9994												
2004	1.0000	0.9940	1.0000											
2005	0.9999	1.0000	1.0000	1.0000										
2006	0.9984	0.4037	0.9664	0.9932	0.7973									
2007	1.0000	0.9467	1.0000	1.0000	0.9989	0.9998								
2008	0.8068	0.0505	0.5163	0.6973	0.2260	0.9999	0.8976							
2009	1.0000	0.9521	1.0000	1.0000	0.9991	0.9997	1.0000	0.8865						
2010	1.0000	0.7631	0.9992	1.0000	0.9752	1.0000	1.0000	0.9872	1.0000					
2011	1.0000	0.8179	0.9997	1.0000	0.9859	1.0000	1.0000	0.9766	1.0000	1.0000				
2012	0.8385	0.0591	0.5579	0.7360	0.2542	1.0000	0.9191	1.0000	0.9096	0.9916	0.9838			
2013	0.9924	1.0000	0.9999	0.9983	1.0000	0.5110	0.9757	0.0786	0.9787	0.8480	0.8904	0.0912		
2014	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	

Subsequently, a Levene's test was conducted to test whether the variability of the numbers of Islet–Islet joins differ among the years 2001 through 2014 in Ontario, the result of this test showed that the effect of the temporal grouping by year was significant $F(13, 6878) = 29.18$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance also indicated that the variability of the Islet–Islet occurrences for 2014 are significantly higher than in all other years and the variability of the Islet–Islet occurrences for 2013 are significantly higher than in 2006-2012 (Table 13).

Table 13. Tukey HSD results of the Levene's test for Islet–Islet joins from the years 2001 through 2014 in Québec, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	0.5463													
2003	0.9999	0.9694												
2004	1.0000	0.5244	0.9999											
2005	0.9997	0.9852	1.0000	0.9995										
2006	0.6044	**0.0005**	0.1303	0.6362	0.0893									
2007	0.9999	0.0917	0.9342	0.9999	0.8864	0.9841								
2008	0.0881	**0.0000**	**0.0062**	0.1002	**0.0035**	0.9997	0.5462							
2009	1.0000	0.1314	0.9659	1.0000	0.9345	0.9643	1.0000	0.4427						
2010	0.9954	**0.0296**	0.7647	0.9967	0.6737	0.9991	1.0000	0.7948	1.0000					
2011	1.0000	0.1535	0.9760	1.0000	0.9511	0.9497	1.0000	0.3941	1.0000	1.0000				
2012	0.0854	**0.0000**	**0.0058**	0.0973	**0.0033**	0.9997	0.5409	1.0000	0.4370	0.7915	0.3884			
2013	0.1214	1.0000	0.6120	0.1129	0.6982	**0.0000**	**0.0077**	**0.0000**	**0.0127**	**0.0017**	**0.0157**	**0.0000**		
2014	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	

Identifying the other cases in which Islets have more variability can be helpful when looking into the reasons causing this variability. Another example of the case in which Islet–Islet joins differ significantly in terms of mean and variability is Alberta in which the variability of the joins in the years 2004 and 2012 looks different (Figure 22).

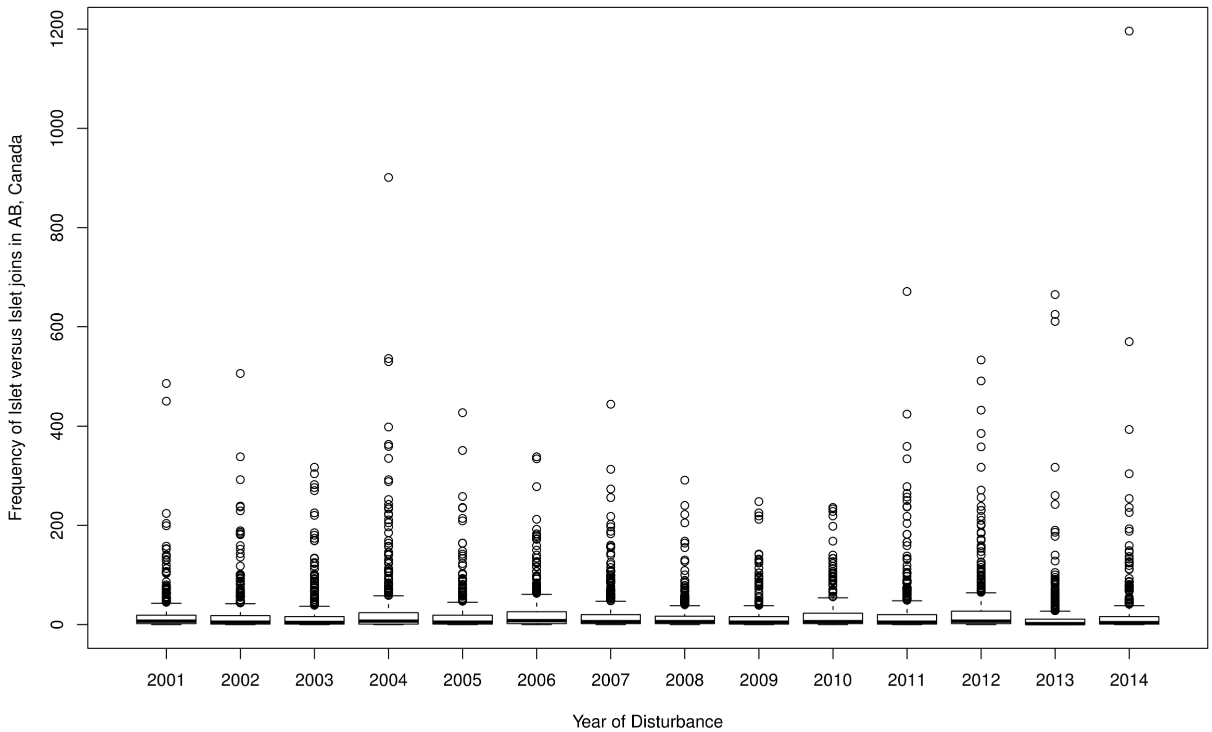


Figure 22. The frequency of the Islet–Islet joins in the Alberta from the years 2001 through 2014.

When a one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Islet–Islet joins differ among the years 2001 through 2014 in Alberta. The result of this analysis showed that the effect of the spatial grouping by province and/or territories was significant $F(13, 6795) = 4.003$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Islet–Islet occurrences for 2004 are significantly higher than in 2001-2005, 2008-2010 and 2013 and the Islet–Islet occurrences for 2012 are significantly higher than in 2008, 2009, and 2013 (Table 14).

Table 14. Tukey HSD results of the ANOVA test for Islet–Islet joins from the years 2001 through 2014 in Alberta, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	1.0000													
2003	1.0000	1.0000												
2004	**0.0225**	**0.0105**	**0.0207**											
2005	1.0000	1.0000	1.0000	**0.0257**										
2006	0.9932	0.9733	0.9912	0.5373	0.9939									
2007	1.0000	0.9999	1.0000	0.1568	1.0000	1.0000								
2008	0.9968	0.9996	0.9979	**0.0002**	0.9970	0.4675	0.8788							
2009	0.9956	0.9993	0.9970	**0.0002**	0.9959	0.4416	0.8615	1.0000						
2010	1.0000	1.0000	1.0000	**0.0101**	1.0000	0.9714	0.9999	0.9996	0.9994					
2011	0.9942	0.9764	0.9924	0.5158	0.9949	1.0000	1.0000	0.4814	0.4552	0.9746				
2012	0.1514	0.0853	0.1410	1.0000	0.1642	0.9200	0.5411	**0.0029**	**0.0026**	0.0828	0.9103			
2013	0.9999	1.0000	1.0000	**0.0008**	0.9999	0.7100	0.9740	1.0000	1.0000	1.0000	0.7234	**0.0106**		
2014	1.0000	1.0000	1.0000	0.0723	1.0000	0.9998	1.0000	0.9606	0.9522	1.0000	0.9999	0.3407	0.9956	

Subsequently, a Levene's test was conducted to test whether the variability of the numbers of Islet–Islet joins differ among the years 2001 through 2014 in Alberta, the result of this test showed that the effect of the temporal grouping by year was significant $F(13, 6795) = 9.167$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Islet–Islet occurrences for 2004 are significantly higher than in all other years, except in 2011 and 2012 and the variability of the Islet–Islet occurrences for 2012 are significantly higher than in all other years, except in 2004, 2006, 2011, and 2014 (Table 15).

Table 15. Tukey HSD results of the Levene's test for Islet–Islet joins from the years 2001 through 2014 in Alberta, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	1.0000													
2003	1.0000	1.0000												
2004	**0.0000**	**0.0000**	**0.0000**											
2005	1.0000	1.0000	1.0000	**0.0000**										
2006	0.9542	0.9792	0.9994	**0.0014**	0.9991									
2007	0.9981	0.9996	1.0000	**0.0002**	1.0000	1.0000								
2008	0.8970	0.8263	0.5421	**0.0000**	0.5835	0.0572	0.1996							
2009	0.9749	0.9452	0.7542	**0.0000**	0.7877	0.1338	0.3711	1.0000						
2010	1.0000	1.0000	0.9998	**0.0000**	0.9999	0.8237	0.9767	0.9804	0.9978					
2011	0.3290	0.4256	0.7471	0.0642	0.7259	0.9990	0.9669	**0.0011**	**0.0039**	0.1545				
2012	**0.0001**	**0.0002**	**0.0018**	0.9986	**0.0016**	0.0678	**0.0143**	**0.0000**	**0.0000**	**0.0000**	0.6200			
2013	1.0000	1.0000	1.0000	**0.0000**	1.0000	0.9975	1.0000	0.6348	0.8293	1.0000	0.6370	**0.0008**		
2014	0.9671	0.9861	0.9997	**0.0009**	0.9996	1.0000	1.0000	0.0669	0.1535	0.8555	0.9978	0.0505	0.9986	

The third instance is Figure 23 in which the frequency of the Islet–Islet joins in the Canadian provinces and territories in the year 2005 was represented. Yukon has a higher variability in the number of joins and Northwest Territories seem to have the highest outliers.

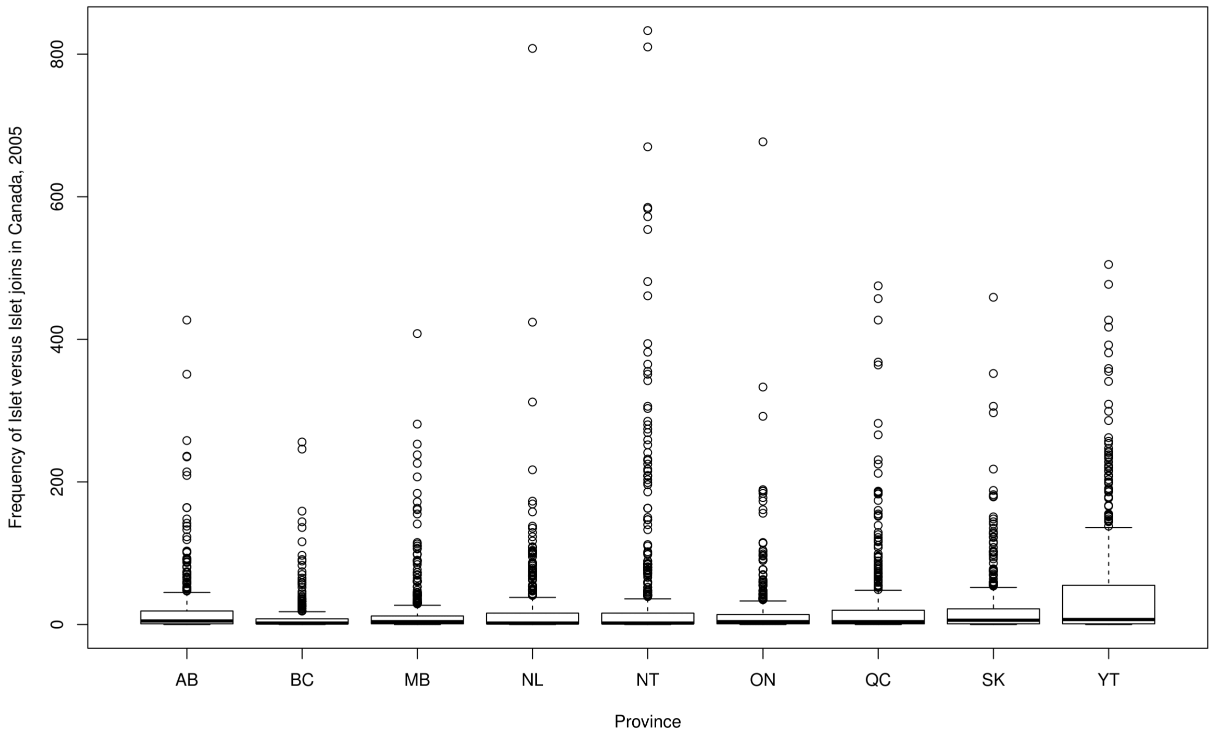


Figure 23. The frequency of the Islet–Islet joins in the Canadian provinces and territories in the year 2005.

Table 16 is the result of a one-way analysis of variance (ANOVA) that was conducted to test whether the average numbers of Islet–Islet joins differ among the Canadian provinces and territories in the year 2005. The result of this analysis showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 4360) = 18.96$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated Islet–Islet occurrences for Northwest Territories and Yukon are significantly higher than in all other provinces/territories except in one another where the occurrences are not statistically significant (Table 16).

Table 16. Tukey HSD results of the ANOVA test for Islet–Islet joins in Canadian provinces and territories in the year 2005, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	BC	MB	NL	NT	ON	QC	SK	YT
AB									
BC	0.2115								
MB	0.9952	0.7388							
NL	0.9999	0.5051	1.0000						
NT	**0.0000**	**0.0000**	**0.0000**	**0.0000**					
ON	0.9977	0.6819	1.0000	1.0000	**0.0000**				
QC	0.8263	0.0012	0.2639	0.4721	**0.0245**	0.3093			
SK	0.9998	0.0456	0.8871	0.9756	**0.0005**	0.9177	0.9851		
YT	**0.0000**	**0.0000**	**0.0000**	**0.0000**	0.3667	**0.0000**	**0.0000**	**0.0000**	

When a Levene's test was conducted to test whether the variability of the numbers of Islet–Islet joins differ among the Canadian provinces and territories in the year 2005, the result of this test showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 4360) = 50.33$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance also indicated that the variability of the Islet–Islet occurrences for Northwest Territories and Yukon are significantly higher than in all other provinces/territories except in one another where the variability of the occurrences are not statistically significant (Table 17).

Table 17. Tukey HSD results of the Levene's test for Islet–Islet joins in Canadian provinces and territories in the year 2005, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	BC	MB	NL	NT	ON	QC	SK	YT
AB									
BC	0.0103								
MB	0.9927	0.1449							
NL	1.0000	0.0096	0.9932						
NT	**0.0000**	**0.0000**	**0.0000**	**0.0000**					
ON	0.9833	0.1897	1.0000	0.9842	**0.0000**				
QC	0.0863	0.0000	0.0037	0.0740	**0.0000**	0.0023			
SK	0.9996	0.0008	0.8468	0.9995	**0.0000**	0.7813	0.3191		
YT	**0.0000**	**0.0000**	**0.0000**	**0.0000**	1.0000	**0.0000**	**0.0000**	**0.0000**	

Furthermore, the results of a Levene's test that was conducted to test whether the variability of the numbers of Islet–Islet joins differ among the years 2001 through 2014in Northwest Territories, the result of this test showed that the effect of the temporal grouping by year was significant $F(13, 6902) = 296.9$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Islet–Islet occurrences for 2014 are significantly higher than in all other years and the Islet–Islet occurrences for 2005 are significantly higher than in all other years, except in 2012 (Table 18).

Table 18. Tukey HSD results of the Levene's test for Islet–Islet joins from the years 2001 through 2014 in Northwest Territories, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	**0.0259**													
2003	0.8126	0.9379												
2004	1.0000	**0.0435**	0.8918											
2005	**0.0054**	**0.0000**	**0.0000**	**0.0027**										
2006	1.0000	**0.0048**	0.4949	1.0000	**0.0293**									
2007	0.7704	0.9565	1.0000	0.8600	**0.0000**	0.4435								
2008	0.9820	0.6591	1.0000	0.9942	**0.0000**	0.8500	1.0000							
2009	0.9983	0.4306	0.9999	0.9997	**0.0000**	0.9590	0.9998	1.0000						
2010	0.8794	0.8905	1.0000	0.9378	**0.0000**	0.5934	1.0000	1.0000	1.0000					
2011	1.0000	0.2327	0.9971	1.0000	**0.0002**	0.9948	0.9947	1.0000	1.0000	0.9992				
2012	0.9502	**0.0000**	**0.0299**	0.8959	0.4815	0.9977	**0.0236**	0.1422	0.2915	**0.0458**	0.5134			
2013	1.0000	0.0603	0.9297	1.0000	**0.0017**	1.0000	0.9052	0.9976	0.9999	0.9629	1.0000	0.8472		
2014	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	

Subsequently, when a Levene's test that was conducted to test whether the variability of the numbers of Islet–Islet joins differ among the years 2001 through 2014 Yukon, the result of this test showed that the effect of the temporal grouping by year was significant $F(13, 6857) = 53.93$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Islet–Islet occurrences for a number of years (i.e., 2004-2006, 2010, 2014) are significantly higher than in all other years (Table 19).

Table 19. Tukey HSD results of the Levene's test for Islet–Islet joins from the years 2001 through 2014 in Yukon, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	1.0000													
2003	1.0000	1.0000												
2004	**0.0000**	**0.0000**	**0.0000**											
2005	**0.0000**	**0.0000**	**0.0000**	0.5883										
2006	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**									
2007	**0.0207**	**0.0263**	0.0500	**0.0000**	**0.0000**	**0.0064**								
2008	0.8984	0.9220	0.9707	**0.0000**	**0.0000**	**0.0000**	0.8439							
2009	0.0714	0.0869	0.1480	**0.0000**	**0.0000**	**0.0014**	1.0000	0.9697						
2010	**0.0001**	**0.0001**	**0.0002**	**0.0000**	**0.0000**	0.3279	0.9891	0.0802	0.9167					
2011	1.0000	1.0000	1.0000	**0.0000**	**0.0000**	**0.0000**	0.1872	0.9993	0.4092	**0.0021**				
2012	0.1502	0.1775	0.2776	**0.0000**	**0.0000**	**0.0004**	1.0000	0.9952	1.0000	0.7760	0.6106			
2013	0.9997	0.9994	0.9956	**0.0000**	**0.0000**	**0.0000**	**0.0004**	0.2863	**0.0024**	**0.0000**	0.9258	**0.0071**		
2014	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	0.9994	**0.0001**	**0.0000**	**0.0000**	**0.0210**	**0.0000**	**0.0000**	**0.0000**	

3.2.1 Review of the results of Islet–Islet joins

Reviewing the results of the join count analysis on the Islet–Islet joins for Canada in the year 2002 revealed that the number of Islet–Islet joins in Ontario and Québec are significantly different in that year in terms of mean and variability and the Islet–Islet occurrences are significantly higher than in all other provinces and/or territories. Furthermore, after looking into Ontario and Québec separately and examining their results of Islet–Islet joins throughout the years of study, the results for Ontario confirmed that 2002 is significantly different than the rest of the years in terms of mean and the Islet–Islet occurrences are significantly higher than in all other provinces and/or territories, but when it comes to variability not only 2002 and 2014 are significantly different and the variability of the Islet–Islet occurrences are significantly higher than in all other provinces and/or territories. In addition, even though the results for Québec showed that 2002 and also 2013 are significantly different than a few of the years in terms of variability, but what stood out in the Québec results was the year 2014, as 2014 is significantly different than the rest of the years and the variability of the Islet–Islet occurrences are significantly higher than in all other years in terms of both mean and variability.

Several other instances were provided in this section where Islet–Islet joins in a certain year/province and/or territory showed irregularities. The first instance is the province of Alberta in the year 2004 in which the number of Islet–Islets joins is significantly higher in terms of mean and variability. The second example was Northwest Territories and Yukon that showed that was different than the rest of the provinces and/or territories in the year 2005 and Islet–Islet occurrences for Northwest Territories and Yukon are significantly higher than in all other provinces/territories except in one another. Further investigations into each province and/or territory not only confirmed the differences in the year 2005 but also pointed out some other years, such as the year 2014 in Northwest Territories and 2004-2006, 2010 and 2014 in Yukon.

3.3 Core–Core joins

This section aims at highlighting some of the cases in which Core–Core joins revealed curious results in various provinces and/or territories and years. The following boxplot represents the frequency of the Core–Core joins differ among the years 2001 through 2014 in Ontario (Figure 24). Some years look different in terms of variability and outliers; however, in order to test whether the average number and the variability of the number of joins are significantly different throughout the years, an ANOVA and Levene's test are performed.

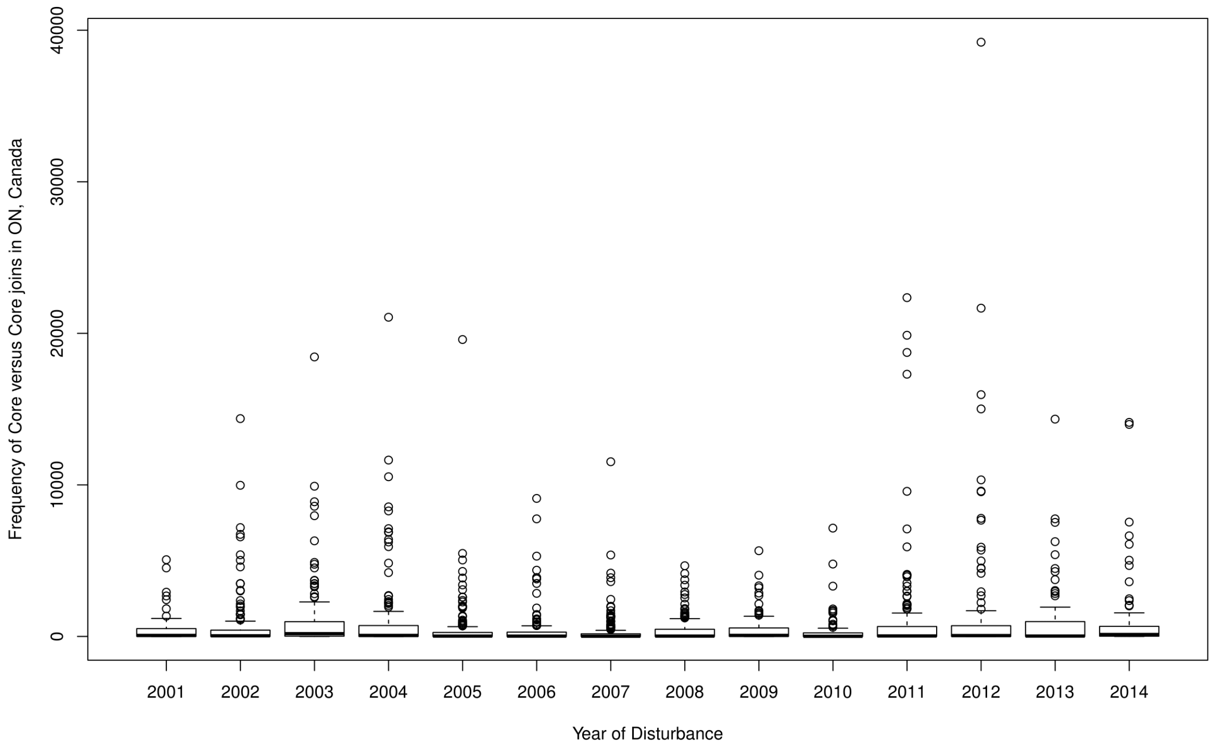


Figure 24. The frequency of the Core–Core joins in Ontario from the years 2001 through 2014.

A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Core–Core joins differ among the years 2001 through 2014 in Ontario. The result of this analysis showed the effect of the spatial grouping by province and/or territories was significant $F(8, 1815) = 3.765$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Core–Core occurrences for 2012 are significantly higher than in 2001, 2002, 2005-2010 (Table 20).

Table 20. Tukey HSD results of the ANOVA test for Core–Core joins from the years 2001 through 2014 in Ontario, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.9996													
2003	0.5535	0.9616												
2004	0.4984	0.9434	1.0000											
2005	1.0000	1.0000	0.6832	0.6236										
2006	1.0000	0.9999	0.5785	0.5171	1.0000									
2007	1.0000	0.9990	0.4097	0.3530	1.0000	1.0000								
2008	1.0000	0.9999	0.6208	0.5637	1.0000	1.0000	1.0000							
2009	1.0000	0.9999	0.6158	0.5583	1.0000	1.0000	1.0000	1.0000						
2010	1.0000	0.9966	0.4238	0.3734	1.0000	1.0000	1.0000	1.0000	1.0000					
2011	0.2215	0.7049	1.0000	1.0000	0.2874	0.2143	0.1220	0.2587	0.2537	0.1496				
2012	**0.0057**	**0.0443**	0.8581	0.8815	**0.0058**	**0.0037**	**0.0015**	**0.0064**	**0.0061**	**0.0033**	0.9896			
2013	0.9038	0.9995	1.0000	1.0000	0.9669	0.9347	0.8528	0.9391	0.9382	0.8206	0.9999	0.7482		
2014	0.8437	0.9978	1.0000	1.0000	0.9321	0.8824	0.7724	0.8913	0.8897	0.7408	1.0000	0.8373	1.0000	

A Levene's test was conducted to test whether the variability of the numbers of Core–Core joins differ among the years 2001 through 2014 in Ontario the result of this test showed that the effect of the temporal grouping by year was significant $F(13, 1815) = 10.58$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Core–Core occurrences for 2012 are significantly higher than in all other years, except in 2011 and the variability of the Core–Core occurrences for 2011 are significantly higher than in all other years, except in 2003, 2004, and 2012-2014 and the variability of the Core–Core occurrences for 2004 are significantly higher than in 2001 and 2006-2010 and lower in 2012 (Table 21).

Table 21. Tukey HSD results of the Levene's test for Core–Core joins from the years 2001 through 2014 in Ontario, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.7608													
2003	**0.0356**	0.9207												
2004	**0.0039**	0.5177	1.0000											
2005	0.9972	0.9996	0.3396	0.0657										
2006	1.0000	0.9847	0.1463	**0.0196**	1.0000									
2007	1.0000	0.9382	0.0755	**0.0081**	1.0000	1.0000								
2008	1.0000	0.9507	0.1056	**0.0142**	1.0000	1.0000	1.0000							
2009	1.0000	0.9016	0.0672	**0.0078**	0.9999	1.0000	1.0000	1.0000						
2010	1.0000	0.8233	0.0550	**0.0071**	0.9987	1.0000	1.0000	1.0000	1.0000					
2011	**0.0000**	**0.0286**	0.8875	0.9969	**0.0008**	**0.0002**	**0.0000**	**0.0001**	**0.0001**	**0.0001**				
2012	**0.0000**	**0.0000**	**0.0025**	**0.0229**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	0.4404			
2013	0.1576	0.9917	1.0000	1.0000	0.6989	0.4438	0.2978	0.3428	0.2588	0.2039	0.8752	**0.0057**		
2014	0.1206	0.9816	1.0000	1.0000	0.6160	0.3653	0.2352	0.2766	0.2035	0.1595	0.9237	**0.0093**	1.0000	

The results of ANOVA and Levene’s test for Edge–Edge joins follow the same pattern as Core–Core joins. The result of a one-way analysis of variance (ANOVA) that was conducted to test whether the average numbers of Edge–Edge joins differ among the years 2001 through 2014 in Ontario, showed that the effect of the temporal grouping by year was significant $F(13, 3654) = 3.986$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Edge–Edge occurrences for 2012 are significantly higher than in 2001, 2002, 2005-2010 (Table 22).

Table 22. Tukey HSD results of the ANOVA test for Edge–Edge joins from the years 2001 through 2014 in Ontario, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	1.0000													
2003	0.6099	0.8823												
2004	0.1552	0.3405	0.9999											
2005	1.0000	1.0000	0.7774	0.2405										
2006	1.0000	0.9994	0.3048	0.0403	1.0000									
2007	1.0000	0.9996	0.3356	0.0488	1.0000	1.0000								
2008	1.0000	1.0000	0.7468	0.2428	1.0000	1.0000	1.0000							
2009	1.0000	0.9998	0.3994	0.0672	1.0000	1.0000	1.0000	1.0000						
2010	1.0000	0.9996	0.4972	0.1250	1.0000	1.0000	1.0000	1.0000	1.0000					
2011	0.1541	0.3376	0.9999	1.0000	0.2390	0.0415	0.0499	0.2396	0.0680	0.1231				
2012	**0.0228**	**0.0581**	0.9493	0.9999	**0.0368**	**0.0038**	**0.0049**	**0.0417**	**0.0075**	**0.0201**	1.0000			
2013	1.0000	1.0000	0.9824	0.7025	1.0000	0.9995	0.9996	1.0000	0.9998	0.9996	0.6898	0.2524		
2014	0.9966	1.0000	0.9998	0.9379	0.9998	0.9687	0.9729	0.9994	0.9821	0.9808	0.9304	0.5475	1.0000	

The result of a Levene’s test that was conducted to test whether the variability of the numbers of Edge–Edge joins differ among the years 2001 through 2014 in Canada, showed that the effect of the temporal grouping by year was significant $F(13, 3654) = 12.44$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Edge–Edge occurrences for 2012 are significantly higher than in all other years, except in 2011 and the variability of the Edge–Edge occurrences for 2011 are significantly higher than in all other years, except in 2003, 2004, 2012, and 2014 and the variability of the Edge–Edge occurrences for 2004 are significantly higher than in 2001, 2002, 2005-2010, and 2013 (Table 23).

Table 23. Tukey HSD results of the Levene's test for Edge–Edge joins from the years 2001 through 2014 in Canada, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	0.9919													
2003	**0.0074**	0.1552												
2004	**0.0000**	**0.0004**	0.9448											
2005	0.9994	1.0000	0.0960	**0.0002**										
2006	1.0000	0.9077	0.0006	**0.0000**	0.9830									
2007	1.0000	0.9717	0.0022	**0.0000**	0.9969	1.0000								
2008	1.0000	0.9999	0.0389	**0.0001**	1.0000	1.0000	1.0000							
2009	1.0000	0.9462	0.0015	**0.0000**	0.9918	1.0000	1.0000	1.0000						
2010	1.0000	0.9740	0.0096	**0.0000**	0.9960	1.0000	1.0000	1.0000	1.0000					
2011	**0.0000**	**0.0001**	0.8348	1.0000	**0.0001**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**				
2012	**0.0000**	**0.0000**	0.0975	0.9498	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	0.9928			
2013	0.9501	1.0000	0.7528	**0.0405**	1.0000	0.7872	0.8949	0.9968	0.8463	0.9034	**0.0191**	**0.0002**		
2014	0.7739	0.9997	0.9278	0.1073	0.9970	0.4776	0.6433	0.9556	0.5667	0.6956	0.0548	**0.0008**	1.0000	

The second example of the same case concerned the province of Manitoba in which join count analyses for Core–Core joins showed a significantly higher average number of joins and variability in 2013 than in any of the other years observed (Figure 25), additionally, 2003 shows a relatively higher variability as well.

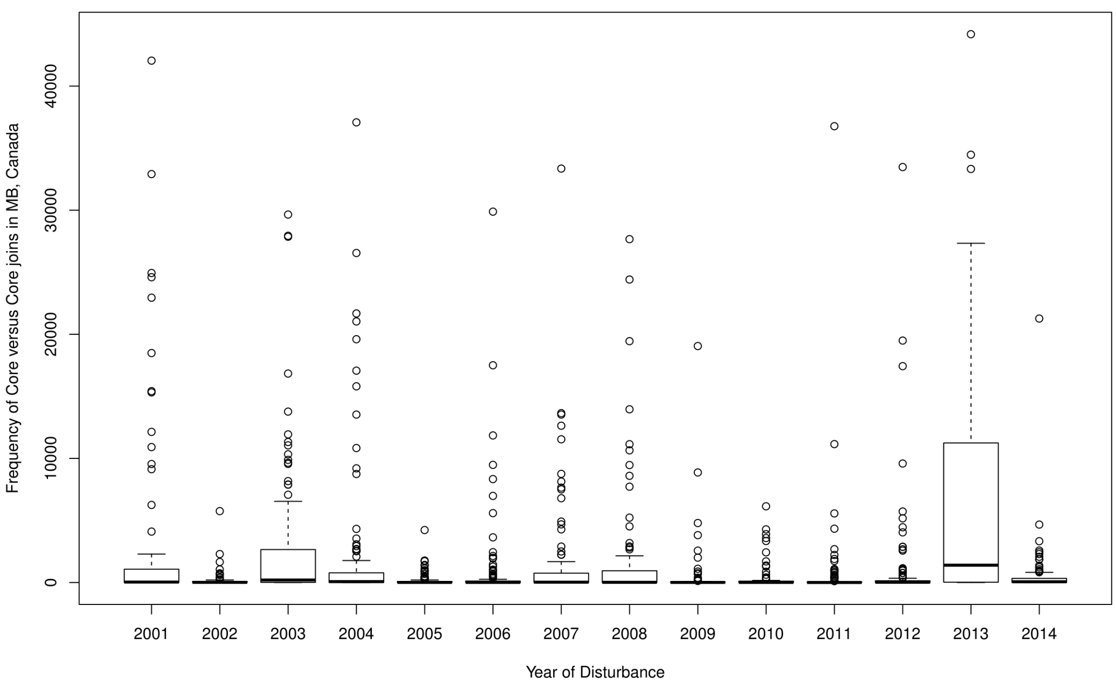


Figure 25.Boxplot representing the frequency of the Core–Core joins in the Manitoba from the years 2001 through 2014.

A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Core–Core joins differ among the years 2001 through 2014 in Manitoba. The result of this analysis showed that the effect of the temporal grouping by year was significant $F(13, 6902) = 117.6$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Core–Core occurrences for 2013 are significantly higher than in all other years and the Core–Core occurrences for 2001 are significantly higher than in all other years, except in 2003, 2004, 2007, and 2008 and lower in 2013 (Table 24).

Table 24. Tukey HSD results of the ANOVA test for Core–Core joins from the years 2001 through 2014 in Manitoba, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	**0.0001**													
2003	0.6957	**0.0297**												
2004	0.3871	0.1674	1.0000											
2005	**0.0000**	1.0000	**0.0041**	0.0507										
2006	**0.0009**	0.9989	0.2044	0.6480	0.9941									
2007	0.0954	0.7053	0.9850	0.9999	0.4870	0.9934								
2008	0.2037	0.5118	0.9990	1.0000	0.2921	0.9561	1.0000							
2009	**0.0001**	1.0000	**0.0418**	0.2414	1.0000	1.0000	0.8413	0.6617						
2010	**0.0002**	1.0000	0.0504	0.2528	1.0000	0.9999	0.8283	0.6524	1.0000					
2011	**0.0005**	1.0000	0.1287	0.4883	0.9999	1.0000	0.9675	0.8802	1.0000	1.0000				
2012	**0.0015**	0.9968	0.2820	0.7457	0.9844	1.0000	0.9978	0.9787	0.9999	0.9997	1.0000			
2013	**0.0141**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**		
2014	**0.0000**	1.0000	**0.0145**	0.1385	1.0000	1.0000	0.7600	0.5443	1.0000	1.0000	1.0000	0.9997	**0.0000**	

For testing whether the variability of the numbers of Core–Core joins differ among the years 2001 through 2014 in Manitoba, a Levene's test was conducted. The result of this test showed that the effect of the temporal grouping by year was significant $F(13, 6902) = 296.9$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Core–Core occurrences for 2013 are significantly higher than in all other years, except in 2001 and the variability of the Core–Core occurrences for 2001 are significantly higher than in all other years, except in 2013 (Table 25).

Table 25. Tukey HSD results of the Levene's test for Core–Core joins from the years 2001 through 2014 in Manitoba, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	**0.0000**													
2003	**0.0000**	**0.0000**												
2004	**0.0001**	**0.0000**	1.0000											
2005	**0.0000**	1.0000	**0.0000**	**0.0000**										
2006	**0.0000**	0.6091	**0.0090**	**0.0061**	0.3150									
2007	**0.0000**	**0.0048**	0.9827	0.9533	**0.0004**	0.6549								
2008	**0.0000**	**0.0006**	0.9999	0.9994	**0.0000**	0.2706	1.0000							
2009	**0.0000**	0.9998	**0.0000**	**0.0000**	0.9982	0.9799	**0.0461**	**0.0077**						
2010	**0.0000**	1.0000	**0.0000**	**0.0000**	1.0000	0.9096	**0.0240**	**0.0039**	1.0000					
2011	**0.0000**	0.9410	**0.0017**	**0.0011**	0.8117	1.0000	0.3180	0.0902	1.0000	0.9980				
2012	**0.0000**	0.4389	**0.0244**	**0.0164**	0.1784	1.0000	0.8185	0.4317	0.9267	0.7951	0.9999			
2013	0.0970	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**		
2014	**0.0000**	1.0000	**0.0000**	**0.0000**	0.9999	0.8084	**0.0050**	**0.0005**	1.0000	1.0000	0.9950	0.6261	**0.0000**	

The third example is Northwest Territories. The following boxplot represents the frequency of the Core–Core joins in Northwest Territories from the years 2001 through 2014 (Figure 26) and as it can be seen We can see that some of the years are different than the others.

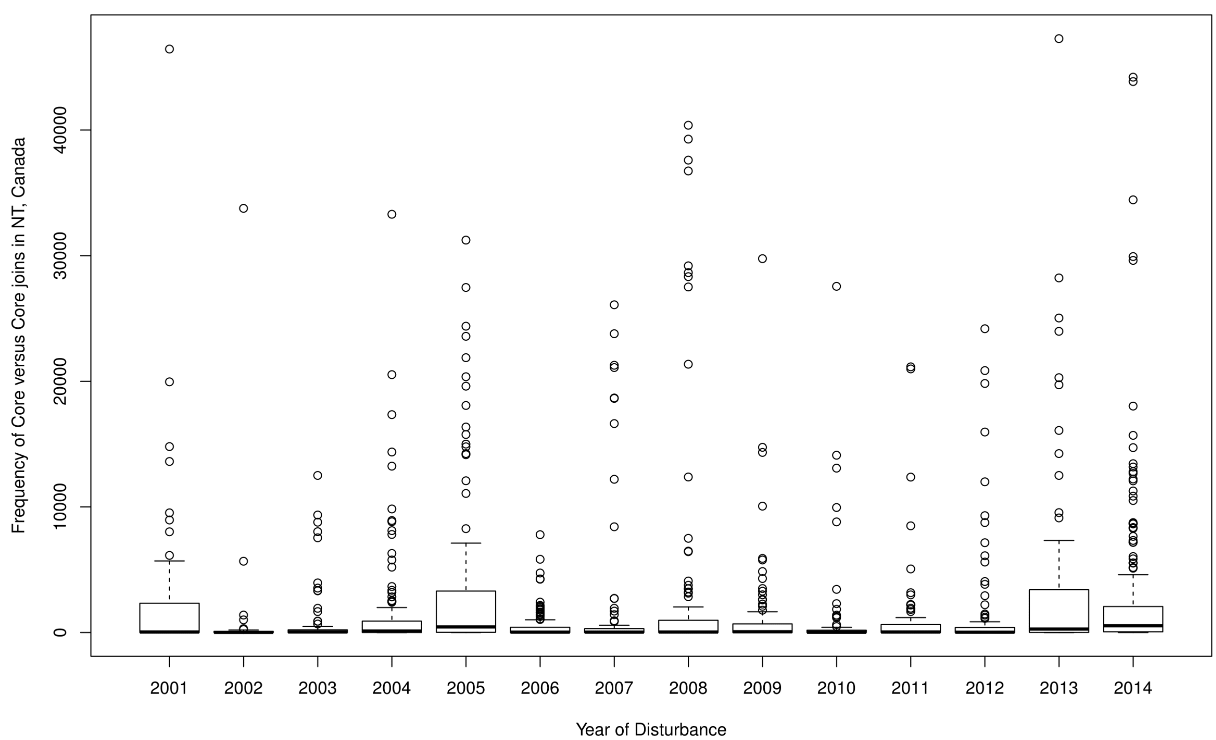


Figure 26. The frequency of the Core–Core joins in Northwest Territories from the years 2001 through 2014.

A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Core–Core joins differ among the years 2001 through 2014 in Northwest Territories. The result of this analysis showed the effect of the spatial grouping by province and/or territories was significant $F(8, 1457) = 3.984$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Core–Core occurrences for 2013 are significantly higher than in 2003, 2006, and 2009-2012 (Table 27).

Table 26. Tukey HSD results of the ANOVA test for Core–Core joins from the years 2001 through 2014 in Northwest Territories, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.9705													
2003	0.9121	1.0000												
2004	1.0000	0.9992	0.9955											
2005	0.9997	0.4549	0.1735	0.8784										
2006	0.5592	1.0000	1.0000	0.8697	**0.0120**									
2007	1.0000	0.9965	0.9847	1.0000	0.9728	0.7869								
2008	0.9780	0.2207	0.0627	0.5722	1.0000	0.0037	0.7893							
2009	0.9744	1.0000	1.0000	0.9998	0.2428	0.9997	0.9984	0.0896						
2010	0.9058	1.0000	1.0000	0.9955	0.1291	1.0000	0.9843	**0.0440**	1.0000					
2011	0.9178	1.0000	1.0000	0.9969	0.1289	1.0000	0.9879	**0.0436**	1.0000	1.0000				
2012	0.9904	1.0000	1.0000	1.0000	0.3285	0.9975	0.9997	0.1279	1.0000	1.0000	1.0000			
2013	0.7761	0.0780	**0.0186**	0.2442	0.9828	**0.0011**	0.4232	1.0000	**0.0271**	**0.0129**	**0.0129**	**0.0397**		
2014	1.0000	0.9051	0.6796	0.9999	0.9895	0.1310	1.0000	0.8198	0.8257	0.6166	0.6281	0.9089	0.4266	

A Levene's test was conducted to test whether the variability of the numbers of Core–Core joins differ among the years 2001 through 2014 in Northwest Territories, the result of this test showed that the effect of the temporal grouping by year was significant $F(13, 1457) = 10.62$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated the variability of the Core–Core occurrences for 2013 are significantly higher than in all other years, except in 2005 and 2008 and the variability of the Core–Core occurrences for 2008 are significantly higher than in all other years, except in 2005 and 2013 (Table 28).

Table 27. Tukey HSD results of the Levene's test for Core–Core joins from the years 2001 through 2014 in Northwest Territories, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	0.8382													
2003	0.4424	1.0000												
2004	1.0000	0.9841	0.8027											
2005	0.9960	0.1048	**0.0043**	0.6439										
2006	**0.0214**	0.9979	0.9995	0.0809	**0.0000**									
2007	1.0000	0.6786	0.2318	0.9994	0.9992	0.0040								
2008	**0.0335**	**0.0001**	**0.0000**	**0.0004**	0.2157	**0.0000**	**0.0369**							
2009	0.6668	1.0000	1.0000	0.9511	0.0078	0.9433	0.4048	**0.0000**						
2010	0.5420	1.0000	1.0000	0.8864	**0.0048**	0.9899	0.2975	**0.0000**	1.0000					
2011	0.3583	1.0000	1.0000	0.7344	**0.0011**	0.9981	0.1579	**0.0000**	1.0000	1.0000				
2012	0.9538	1.0000	0.9976	0.9997	0.0701	0.5301	0.8271	**0.0000**	1.0000	0.9998	0.9965			
2013	**0.0403**	**0.0001**	**0.0000**	**0.0010**	0.2368	**0.0000**	**0.0469**	1.0000	**0.0000**	**0.0000**	**0.0000**	**0.0000**		
2014	1.0000	0.8517	0.3124	1.0000	0.6077	**0.0015**	1.0000	**0.0000**	0.5247	0.3883	0.1828	0.9505	**0.0003**	

The above results shows that there are some reasons causing these differences in 2008 and 2013 in Northwest Territories, however, when A Levene's test was conducted to test whether the variability of the numbers of Edge–Edge joins differ among the years 2001 through 2014 in Northwest Territories, the result of this test showed that the effect of the temporal grouping by year was significant $F(13, 1457) = 10.62$, $p < 0.05$, but post hoc analyses using Tukey's HSD for significance surprisingly indicated that the variability of the Core–Core occurrences for 2005 are significantly higher than in 2002, 2003, 2006, 2009-2012 and the variability of the Core–Core occurrences for 2014 are significantly higher than in 2002, 2006, 2009-2011 (Table 29).

Table 28. Tukey HSD results of the Levene's test for Edge–Edge joins from the years 2001 through 2014 in Northwest Territories, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	**0.0105**													
2003	0.0785	0.9978												
2004	0.7370	0.4894	0.9735											
2005	1.0000	**0.0027**	**0.0185**	0.4856										
2006	**0.0007**	1.0000	0.9996	0.2794	**0.0000**									
2007	0.9499	0.3609	0.9118	1.0000	0.8806	0.1893								
2008	0.9195	0.3370	0.9010	1.0000	0.8029	0.1502	1.0000							
2009	0.0034	1.0000	1.0000	0.5870	**0.0001**	1.0000	0.4339	0.3788						
2010	0.0058	1.0000	1.0000	0.6276	**0.0003**	1.0000	0.4726	0.4254	1.0000					
2011	0.0089	0.9998	1.0000	0.7511	**0.0005**	1.0000	0.5939	0.5461	1.0000	1.0000				
2012	0.1119	0.9539	1.0000	0.9974	**0.0190**	0.9500	0.9790	0.9754	0.9979	0.9975	0.9997			
2013	0.9997	0.1221	0.5578	0.9989	0.9994	**0.0341**	1.0000	1.0000	0.1105	0.1368	0.1941	0.7195		
2014	0.9998	**0.0112**	0.0739	0.8821	0.9986	**0.0000**	0.9970	0.9911	**0.0004**	**0.0015**	**0.0020**	0.0782	1.0000	

3.3.1 Review of the results of Core–Core joins

Join count analyses for Core–Core joins in Ontario showed a significantly higher average number of joins in 2012 than in all other years observed. Interestingly, a significantly higher variability in the number of these joins was measured in 2004 and 2011. Furthermore, the results of Edge–Edge joins also follow the same pattern as Core–Core. Several other instances were provided in this section where Core–Core joins in a certain year/province and/or territory showed some irregularities.

The first instance was the province of Manitoba in the year 2001 and 2013 in which the number of Core–Core joins is significantly higher in terms of mean and variability. The second example was Northwest Territories in which the year 2008 and 2013 are significantly higher in terms of variability; however, the results of Edge–Edge do not follow the same pattern, as only the year 2005 and 2014 are significantly higher than some of the years in terms of the variability.

3.4 Perforation–Perforation joins

This section aims at highlighting some of the cases in which Perforation–Perforation joins revealed curious results in various provinces and/or territories and years. The following boxplot that represents the frequency of the Perforation–Perforation joins in the Canadian provinces and territories in the year 2011 (Figure 27). It showed a difference in terms of variability around the mean in the province of Yukon in comparison to the other provinces and territories which will be explored in this section.

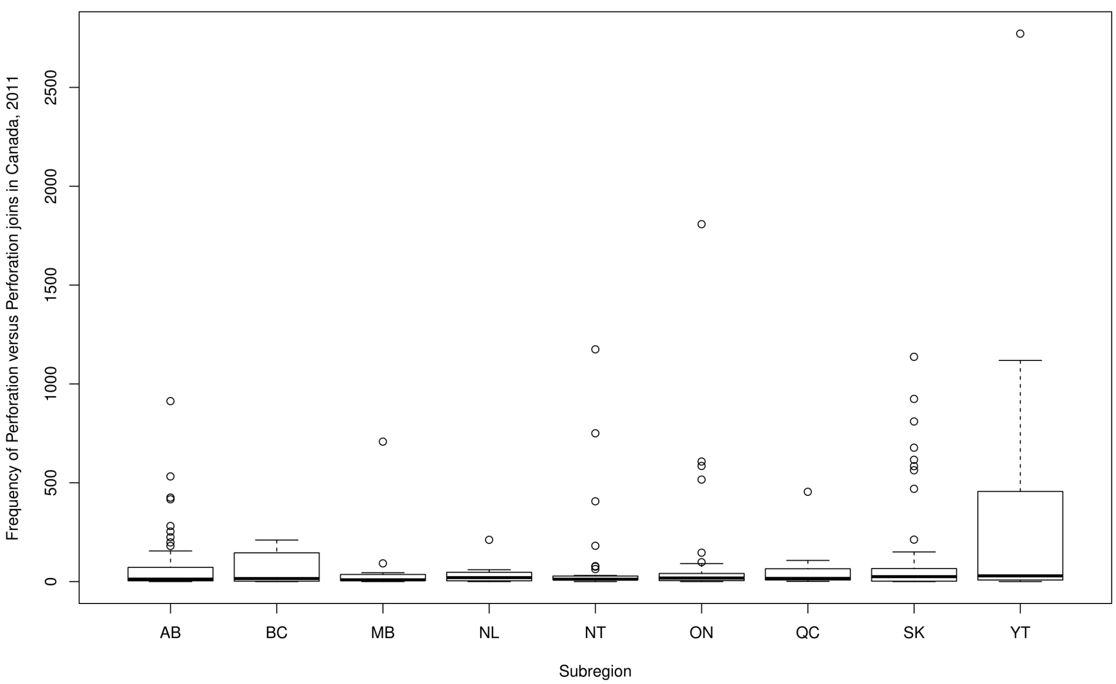


Figure 27. The frequency of the Perforation–Perforation joins in the Canadian provinces and territories in the year 2011.

A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Perforation–Perforation joins differ among the Canadian provinces and territories in the year 2011. The result of this analysis showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 300) = 3.057$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Perforation–Perforation occurrences for Yukon are significantly higher than in all other provinces/territories (Table 30).

Table 29. Tukey HSD results of the ANOVA test for Perforation–Perforation joins in Canadian provinces and territories in the year 2011, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	**BC**	**MB**	**NL**	**NT**	**ON**	**QC**	**SK**	**YT**
AB									
BC	1.0000								
MB	1.0000	1.0000							
NL	0.9999	1.0000	1.0000						
NT	1.0000	1.0000	1.0000	0.9998					
ON	1.0000	1.0000	0.9999	0.9990	1.0000				
QC	1.0000	1.0000	1.0000	1.0000	1.0000	0.9995			
SK	0.9975	0.9995	0.9978	0.9936	0.9999	1.0000	0.9939		
YT	**0.0002**	**0.0035**	**0.0019**	**0.0035**	**0.0009**	**0.0009**	**0.0010**	**0.0011**	

Subsequently, a Levene's test was conducted to test whether the variability of the numbers of Perforation–Perforation joins differ among the Canadian provinces and territories in the year 2011. The result of this test showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 300) = 8.164$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance also indicated that the variability of the Perforation–Perforation occurrences for Yukon are significantly higher than in all other provinces/territories (Table 31).

Table 30. Tukey HSD results of the Levene's test for Perforation–Perforation joins in Canadian provinces and territories in the year 2011, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	**BC**	**MB**	**NL**	**NT**	**ON**	**QC**	**SK**	**YT**
AB									
BC	1.0000								
MB	1.0000	1.0000							
NL	0.9943	0.9999	0.9998						
NT	0.9996	0.9989	0.9990	0.9562					
ON	0.9895	0.9926	0.9927	0.8954	1.0000				
QC	0.9980	1.0000	1.0000	1.0000	0.9664	0.8936			
SK	0.9214	0.9725	0.9708	0.8043	0.9999	1.0000	0.7644		
YT	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	

After examining the boxplots for Perforation–Perforation in Yukon from the years 2001 through 2014 (Figure 28), it can be seen that not only Yukon has the highest variability around the mean in comparison to the other provinces and territories in the year 2011, but also it that year has the highest variability around the mean in comparison to the rest of the years of study which makes it more interesting to scrutinize what happened in terms of disturbances in the year 2011 in Yukon that led to an increase in the variability of the number of Perforation–Perforation joins.

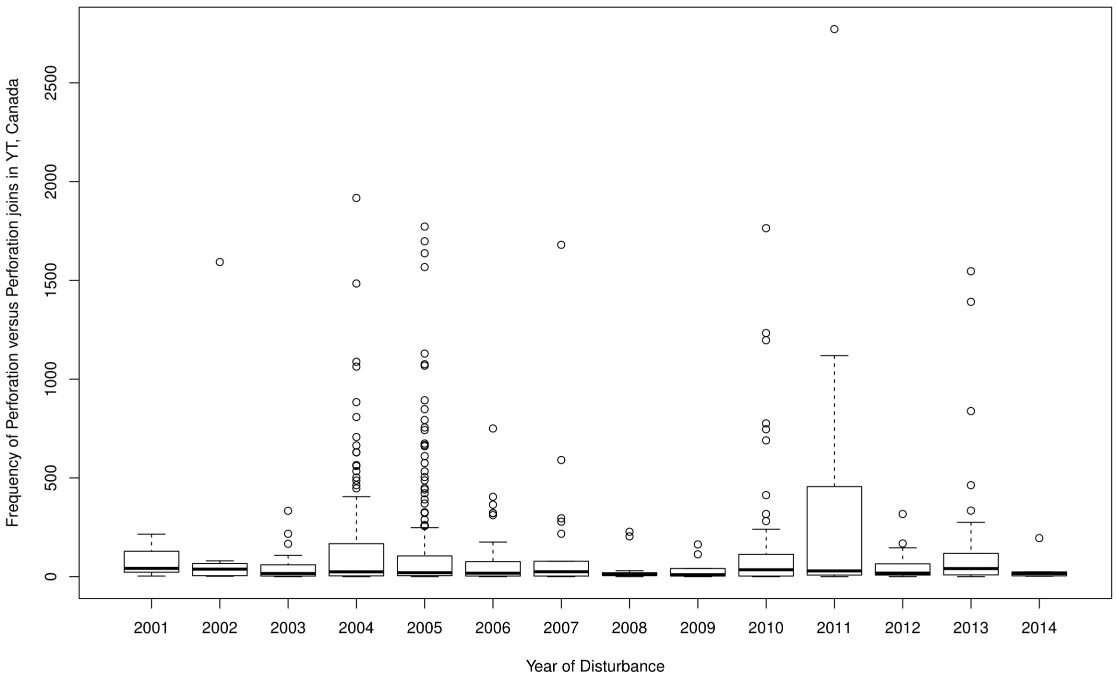


Figure 28. The frequency of the Perforation–Perforation joins in the Yukon from the years 2001 through 2014.

In order to confirm the aforementioned difference, a one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Perforation–Perforation joins differ among the years 2001 through 2014 in Yukon. Even though the result of this analysis confirmed that the effect of the spatial grouping by province and/or territories was significant $F(8, 609) = 1.745$, $p = 0.048$. Post hoc analyses using Tukey's HSD for significance indicated that the Perforation–Perforation occurrences for 2011 are significantly higher than in 2003, 2005, 2006, and 2012 (Table 32).

Table 31. Tukey HSD results of the ANOVA test for Perforation–Perforation joins from the years 2001 through 2014 in Yukon, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.9999													
2003	1.0000	0.9614												
2004	1.0000	0.9996	0.9896											
2005	1.0000	0.9991	0.9950	1.0000										
2006	1.0000	0.9843	1.0000	0.9974	0.9992									
2007	1.0000	1.0000	0.9966	1.0000	1.0000	0.9996								
2008	1.0000	0.9685	1.0000	0.9968	0.9985	1.0000	0.9980							
2009	1.0000	0.9629	1.0000	0.9956	0.9978	1.0000	0.9971	1.0000						
2010	1.0000	0.9999	0.9816	1.0000	1.0000	0.9943	1.0000	0.9931	0.9910					
2011	0.8502	0.9866	**0.0259**	0.0680	**0.0470**	**0.0234**	0.3521	0.0603	0.0608	0.1554				
2012	1.0000	0.9575	1.0000	0.9868	0.9934	1.0000	0.9958	1.0000	1.0000	0.9776	**0.0241**			
2013	1.0000	1.0000	0.9111	0.9997	0.9985	0.9493	1.0000	0.9560	0.9494	1.0000	0.5137	0.9003		
2014	1.0000	0.9968	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.4272	1.0000	0.9990	

However, when Levene’s test was conducted to test whether the variability of the numbers of Perforation–Core joins differ among the years 2001 through 2014 in Yukon, the result of this test showed that the effect of the temporal grouping by year was significant $F(13, 609) = 5.187$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Perforation–Perforation occurrences for 2011 are significantly higher than in all other years, except in 2001 and 2002 (Table 33).

Table 32. Tukey HSD results of the Levene’s test for Perforation–Perforation joins from the years 2001 through 2014 in Yukon, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.8588													
2003	1.0000	0.0912												
2004	1.0000	0.5776	0.6496											
2005	1.0000	0.5329	0.6755	1.0000										
2006	1.0000	0.1470	1.0000	0.7864	0.8079									
2007	0.9998	0.9351	0.6629	1.0000	1.0000	0.8368								
2008	1.0000	0.1421	1.0000	0.8636	0.8814	1.0000	0.7955							
2009	1.0000	0.1072	1.0000	0.7682	0.7907	0.9999	0.6991	1.0000						
2010	0.9999	0.8061	0.4716	1.0000	0.9999	0.6058	1.0000	0.7214	0.6082					
2011	0.0806	0.9158	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0033**	**0.0000**	**0.0000**	**0.0001**				
2012	1.0000	0.0684	1.0000	0.5085	0.5326	1.0000	0.5581	1.0000	1.0000	0.3503	**0.0000**			
2013	0.9966	0.9888	0.1886	0.9513	0.9141	0.2573	1.0000	0.3839	0.2955	0.9996	**0.0081**	0.1289		
2014	1.0000	0.5112	1.0000	0.9980	0.9985	1.0000	0.9877	1.0000	1.0000	0.9899	**0.0039**	1.0000	0.9152	

The second example of the same case concerned the year 2008 in which join count analyses for Perforation–Perforation joins showed a significantly higher variability in these joins in Northwest Territories than in any of the other provinces/territories observed. A Levene's test was conducted to test whether the variability of the numbers of Perforation–Perforation joins differ among the Canadian provinces and territories in the year 2008, the result of this test showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 273) = 14.14$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance also indicated that the variability of the Perforation–Perforation occurrences for Northwest Territories are significantly higher than in all other provinces/territories (Table 34).

Table 33. Tukey HSD results of the Levene's test for Perforation–Perforation joins in Canadian provinces and territories in the year 2008, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	AB	**BC**	**MB**	**NL**	**NT**	**ON**	**QC**	**SK**	**YT**
AB									
BC	1.0000								
MB	0.6875	0.8816							
NL	1.0000	1.0000	0.9455						
NT	**0.0000**	**0.0000**	**0.0000**	**0.0000**					
ON	1.0000	1.0000	0.5334	1.0000	**0.0000**				
QC	1.0000	1.0000	0.5962	1.0000	**0.0000**	1.0000			
SK	0.0121	0.1832	0.5463	0.1974	**0.0000**	0.0010	0.0038		
YT	0.9999	0.9999	0.9890	1.0000	**0.0000**	0.9999	0.9998	0.3279	

The other case is the province of Québec in the year 2014. A Levene's test was conducted to test whether the variability of the numbers of Perforation–Perforation joins differ among the Canadian provinces and territories in the year 2014. The result of this test showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 377) = 4.917$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance also indicated that the variability of the Perforation–Perforation occurrences for Québec are significantly higher than in all other provinces/territories, except in Yukon (Table 35).

Table 34. Tukey HSD results of the Levene's test for Perforation–Perforation joins in Canadian provinces and territories in the year 2014, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	BC	MB	NL	NT	ON	QC	SK	YT
AB									
BC	1.0000								
MB	1.0000	1.0000							
NL	1.0000	1.0000	1.0000						
NT	0.2889	0.8792	0.6771	0.7674					
ON	1.0000	1.0000	1.0000	1.0000	0.6526				
QC	**0.0000**	**0.0091**	**0.0004**	**0.0020**	**0.0011**	**0.0002**			
SK	0.4191	0.9064	0.7693	0.8226	1.0000	0.7598	**0.0039**		
YT	1.0000	1.0000	1.0000	1.0000	0.9983	1.0000	0.2733	0.9987	

3.4.1 Review of the results of Perforation–Perforation joins

Reviewing the results of the join count analysis on the Perforation–Perforation joins for Canada in the year 2011 revealed that the number of Perforation–Perforation joins in Yukon is significantly higher in 2011 than all other years in terms of mean and variability. Furthermore, after looking into Yukon individually and examining their results of Perforation–Perforation joins throughout the years of study, even though the results for Yukon showed that the year 2011 is only significantly higher than a few of the years in terms of mean, but when it comes to variability, 2011 is has higher occurrences of joins than all other years, except in 2001 and 2002.

Several other instances were provided in this section where Perforation–Perforation joins in a certain year/province and/or territory showed some irregularities. The first instance is Northwest Territories in the year 2008 in which the number of Perforation–Perforation joins is significantly higher in terms of mean and variability and it is confirmed when looking into that territory separately throughout the years of study. The second example was Québec in the year 2014 in which the number of Perforation–Perforation joins is significantly higher in terms of mean and variability.

3.5 Morphological connectors' joins (Bridge and Loop)

This section aims at highlighting some of the cases in which the morphological connectors' joins (i.e., Bridge and Loop) revealed curious results in various provinces and/or territories and years. The following boxplots represent the frequency of the morphological connectors' joins that includes Bridge–Bridge joins (Figure 29) and Loop–Loop joins (Figure 30) in the Canadian provinces and territories in the year 2014. They show a difference in terms of variability around the mean in Northwest Territories and Saskatchewan in comparison to the other provinces and territories which will be explored in this section.

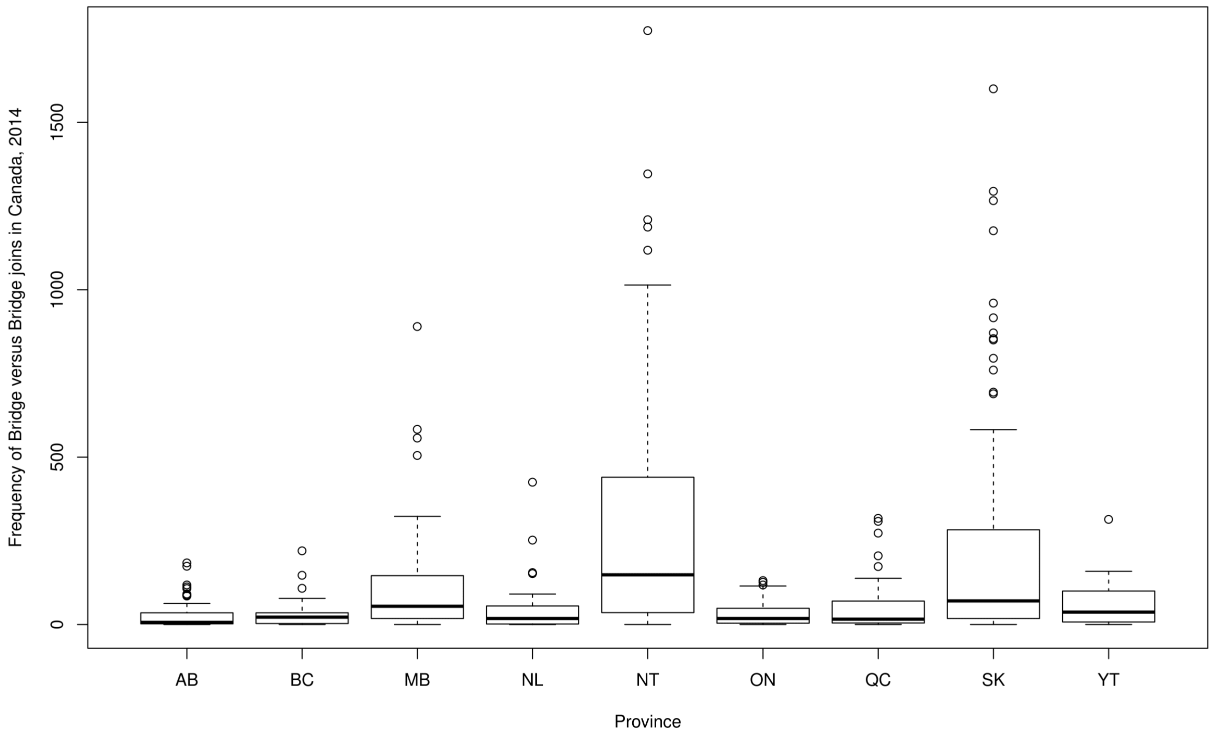


Figure 29. The frequency of the Bridge–Bridge joins in the Canadian provinces and territories in the year 2014.

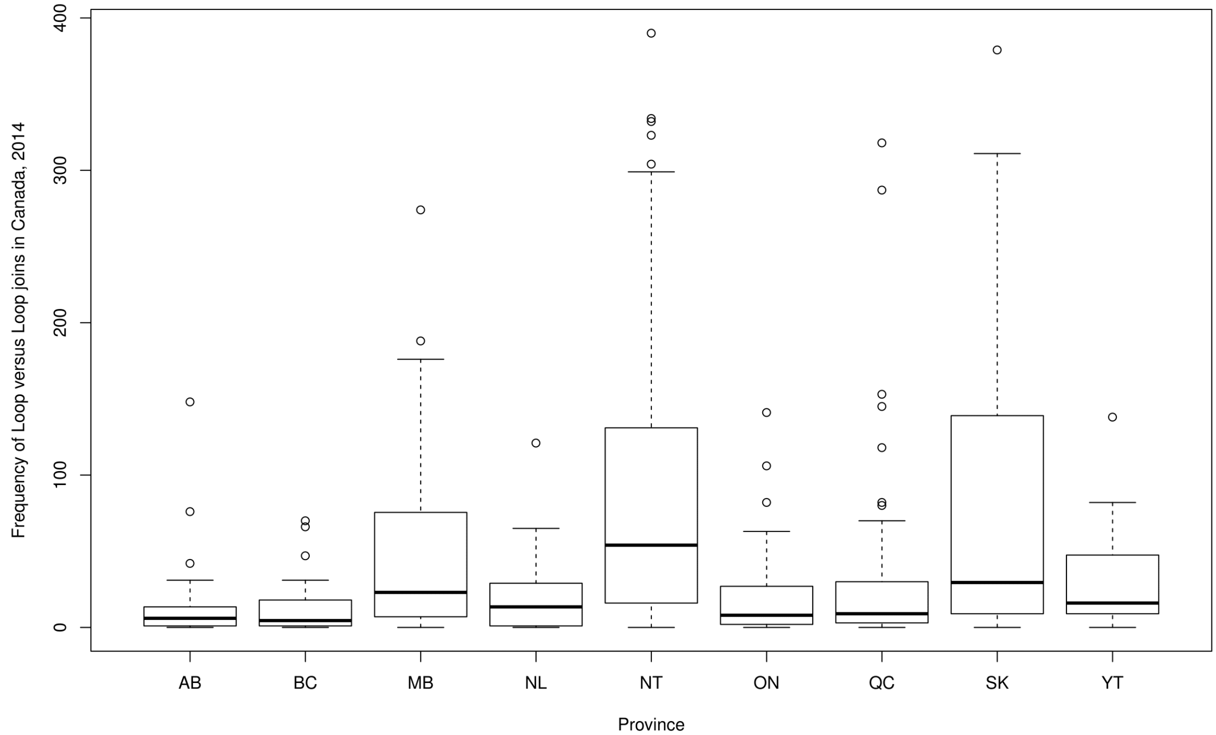


Figure 30. The frequency of the Loop–Loop joins in the Canadian provinces and territories in the year 2014.

A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Bridge–Bridge joins differ among the Canadian provinces and territories in the year 2014. The result of this analysis showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 667) = 17.96$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Bridge–Bridge occurrences for Norwest Territories and Saskatchewan are significantly higher than in all other provinces/territories, except in one another (Table 36).

Table 35. Tukey HSD results of the ANOVA test for Bridge–Bridge joins in Canadian provinces and territories in the year 2014, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	BC	MB	NL	NT	ON	QC	SK	YT
AB									
BC	1.0000								
MB	0.5809	0.9112							
NL	1.0000	1.0000	0.9564						
NT	**0.0000**	**0.0000**	**0.0000**	**0.0000**					
ON	1.0000	1.0000	0.6798	1.0000	**0.0000**				
QC	0.9999	1.0000	0.8902	1.0000	**0.0000**	1.0000			
SK	**0.0000**	**0.0008**	**0.0008**	**0.0006**	0.9945	**0.0000**	**0.0000**		
YT	0.9994	1.0000	0.9987	1.0000	**0.0013**	0.9998	1.0000	**0.0230**	

Subsequently, a Levene’s test was conducted to test whether the variability of the numbers of Bridge–Bridge joins differ among the Canadian provinces and territories in the year 2014. The result of this test showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 667) = 37.99$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance also indicated that the variability of the Bridge–Bridge occurrences for Norwest Territories and Saskatchewan are significantly higher than in all other provinces/territories, except in one another (Table 37).

Table 36. Tukey HSD results of the Levene’s test for Bridge–Bridge joins in Canadian provinces and territories in the year 2014, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	BC	MB	NL	NT	ON	QC	SK	YT
AB									
BC	1.0000								
MB	0.1830	0.5621							
NL	0.9993	0.9999	0.8535						
NT	**0.0000**	**0.0000**	**0.0000**	**0.0000**					
ON	1.0000	1.0000	0.1751	0.9989	**0.0000**				
QC	0.9975	0.9998	0.6808	1.0000	**0.0000**	0.9962			
SK	**0.0000**	**0.0000**	**0.0000**	**0.0000**	0.7709	**0.0000**	**0.0000**		
YT	0.9994	0.9999	0.9601	1.0000	**0.0000**	0.9991	1.0000	**0.0000**	

Another one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Loop–Loop joins differ among the Canadian provinces and territories in the year 2014. The result of this analysis showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 694) = 15.84$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Loop–Loop occurrences for Norwest Territories and Saskatchewan are significantly higher than in all other provinces/territories, except in one another (Table 38).

Table 37. Tukey HSD results of the ANOVA test for Loop–Loop joins in Canadian provinces and territories in the year 2014, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	BC	MB	NL	NT	ON	QC	SK	YT
AB									
BC	1.0000								
MB	0.0332	0.2394							
NL	0.9995	0.9999	0.6708						
NT	**0.0000**	**0.0000**	**0.0003**	**0.0002**					
ON	0.9996	1.0000	0.2127	1.0000	**0.0000**				
QC	0.8501	0.9648	0.7260	0.9998	**0.0000**	0.9942			
SK	**0.0000**	**0.0001**	**0.0258**	**0.0022**	1.0000	**0.0000**	**0.0001**		
YT	0.9356	0.9777	0.9785	0.9997	**0.0064**	0.9966	1.0000	**0.0331**	

The second Levene's test was conducted to test whether the variability of the numbers of Loop–Loop joins differ among the Canadian provinces and territories in the year 2014. The result of this test showed that the effect of the spatial grouping by province and/or territories was significant $F(8, 694) = 25.97$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance also indicated that the variability of the Loop–Loop occurrences for Norwest Territories and Saskatchewan are significantly higher than in all other provinces/territories, except in one another (Table 39).

Table 38. Tukey HSD results of the Levene's test for Loop–Loop joins in Canadian provinces and territories in the year 2014, in which the bold numbers represent the values that are significantly different at α = 0.05.

	AB	BC	MB	NL	NT	ON	QC	SK	YT
AB									
BC	1.0000								
MB	0.0004	0.0370							
NL	0.9943	0.9997	0.2731						
NT	**0.0000**	**0.0000**	**0.0000**	**0.0000**					
ON	0.9907	0.9998	0.0290	1.0000	**0.0000**				
QC	0.1069	0.5045	0.8822	0.9216	**0.0000**	0.6665			
SK	**0.0000**	**0.0000**	**0.0000**	**0.0000**	0.7711	**0.0000**	**0.0000**		
YT	0.8330	0.9636	0.7751	0.9997	**0.0001**	0.9971	0.9996	**0.0000**	

After examining the boxplots for the morphological connectors' joins in Norwest Territories and Saskatchewan, it can be seen that not only the year 2014 has the highest variability around the mean in comparison to the rest of the years of study. A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Bridge–Bridge joins differ among the years 2001 through 2014 in Norwest Territories. The result of this analysis confirmed that the effect of the spatial grouping by province and/or territories was significant

$F(8, 826) = 11.85$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Bridge–Bridge occurrences for 2014 are significantly higher than in all other years, except in 2001 (Table 40).

Table 39. Tukey HSD results of the ANOVA test for Bridge–Bridge joins from the years 2001 through 2014 in Northwest Territories, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.6338													
2003	0.8605	1.0000												
2004	0.4530	1.0000	1.0000											
2005	0.9488	0.9933	1.0000	0.9957										
2006	0.2431	1.0000	1.0000	1.0000	0.9324									
2007	0.8899	1.0000	1.0000	1.0000	1.0000	0.9998								
2008	0.9867	0.9960	1.0000	0.9989	1.0000	0.9748	1.0000							
2009	0.3873	1.0000	1.0000	1.0000	0.9890	1.0000	1.0000	0.9969						
2010	0.7533	1.0000	1.0000	1.0000	0.9999	1.0000	1.0000	1.0000	1.0000					
2011	0.8972	0.9998	1.0000	1.0000	1.0000	0.9988	1.0000	1.0000	1.0000	1.0000				
2012	0.9711	0.9979	1.0000	0.9996	1.0000	0.9854	1.0000	1.0000	0.9987	1.0000	1.0000			
2013	0.9892	0.9958	1.0000	0.9988	1.0000	0.9745	1.0000	1.0000	0.9967	1.0000	1.0000	1.0000		
2014	0.0936	**0.0002**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0001**	

A Levene's test was conducted to test whether the variability of the numbers of Bridge–Bridge joins differ among the years 2001 through 2014 in Norwest Territories. The result of this test showed that the effect of the temporal grouping by year was significant $F(13, 826) = 18.81$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Bridge–Bridge occurrences for 2014 are significantly higher than in all other years (Table 41).

Table 40. Tukey HSD results of the Levene's test for Bridge–Bridge joins from the years 2001 through 2014 in Northwest Territories, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.1462													
2003	0.3645	0.9999												
2004	0.0414	1.0000	1.0000											
2005	0.2015	0.9956	1.0000	0.9995										
2006	0.0032	1.0000	0.9941	0.9996	0.8013									
2007	0.2630	0.9999	1.0000	1.0000	1.0000	0.9937								
2008	0.7243	0.9770	1.0000	0.9915	1.0000	0.6906	1.0000							
2009	0.0171	1.0000	1.0000	1.0000	0.9890	1.0000	1.0000	0.9504						
2010	0.3159	0.9999	1.0000	1.0000	1.0000	0.9917	1.0000	1.0000	1.0000					
2011	0.4116	0.9978	1.0000	0.9999	1.0000	0.9204	1.0000	1.0000	0.9975	1.0000				
2012	0.9753	0.7977	0.9903	0.7528	0.9907	0.2134	0.9791	1.0000	0.5436	0.9872	0.9979			
2013	0.7272	0.9799	1.0000	0.9935	1.0000	0.7197	1.0000	1.0000	0.9590	1.0000	1.0000	1.0000		
2014	**0.0404**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	

A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Loop–Loop joins differ among the years 2001 through 2014 in Norwest Territories. The result of this analysis confirmed that the effect of the spatial grouping by province and/or territories was significant $F(8, 837) = 6.668$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the Loop–Loop occurrences for 2014 are significantly higher than in 2003-2006 and 2009-2012 (Table 42).

Table 41. Tukey HSD results of the ANOVA test for Loop–Loop joins from the years 2001 through 2014 in Northwest Territories, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	0.9857													
2003	0.9489	1.0000												
2004	0.5810	1.0000	1.0000											
2005	0.9880	1.0000	1.0000	0.9908										
2006	0.2863	1.0000	0.9999	1.0000	0.8606									
2007	1.0000	0.9999	0.9997	0.9699	1.0000	0.8165								
2008	1.0000	0.9984	0.9937	0.8070	0.9998	0.4863	1.0000							
2009	0.4285	1.0000	1.0000	1.0000	0.9598	1.0000	0.9248	0.6636						
2010	0.8038	1.0000	1.0000	1.0000	0.9996	1.0000	0.9952	0.9460	1.0000					
2011	0.8707	1.0000	1.0000	1.0000	1.0000	0.9996	0.9988	0.9752	1.0000	1.0000				
2012	0.9882	1.0000	1.0000	0.9988	1.0000	0.9566	1.0000	0.9997	0.9926	1.0000	1.0000			
2013	1.0000	0.9971	0.9886	0.7616	0.9993	0.4395	1.0000	1.0000	0.6122	0.9228	0.9606	0.9991		
2014	0.8760	0.2848	**0.0187**	**0.0000**	**0.0003**	**0.0000**	0.3358	0.3219	**0.0000**	**0.0008**	**0.0006**	**0.0047**	0.4870	

A Levene's test was conducted to test whether the variability of the numbers of Loop–Loop joins differ among the years 2001 through 2014 in Norwest Territories. The result of this test showed that the effect of the temporal grouping by year was significant $F(13, 837) = 8.746$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Loop–Loop occurrences for 2014 are significantly higher than in 2003-2006 and 2009-2011, and the variability of the Loop–Loop occurrences for 2006 are significantly higher than in 2001, 2007, 2008, 2013, and lower in 2014 (Table 43).

Table 42. Tukey HSD results of the Levene's test for Loop–Loop joins from the years 2001 through 2014 in Northwest Territories, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.9991													
2003	0.9712	1.0000												
2004	0.2834	0.9999	0.9996											
2005	0.6415	1.0000	1.0000	0.9998										
2006	**0.0246**	0.9669	0.8659	0.9991	0.7662									
2007	1.0000	0.9961	0.9255	0.1884	0.4852	**0.0140**								
2008	1.0000	0.9956	0.8978	0.1048	0.3248	**0.0045**	1.0000							
2009	0.1087	0.9983	0.9909	1.0000	0.9875	1.0000	0.0658	**0.0270**						
2010	0.8378	1.0000	1.0000	1.0000	1.0000	0.9267	0.7189	0.6269	0.9983					
2011	0.7505	1.0000	1.0000	1.0000	1.0000	0.9253	0.6111	0.4932	0.9986	1.0000				
2012	1.0000	1.0000	0.9997	0.6115	0.9413	0.0787	0.9996	0.9994	0.2986	0.9876	0.9698			
2013	1.0000	0.9817	0.7699	0.0506	0.1754	**0.0018**	1.0000	1.0000	**0.0115**	0.4372	0.3130	0.9915		
2014	0.9144	0.5935	**0.0401**	**0.0000**	**0.0000**	**0.0000**	0.9874	0.9405	**0.0000**	**0.0018**	**0.0003**	0.1308	0.9967	

A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Bridge–Bridge joins differ among the years 2001 through 2014 in Saskatchewan. The result of this analysis confirmed that the effect of the spatial grouping by province and/or territories was significant $F(8, 1077) = 7.903$, $p = 0.048$. Post hoc analyses using Tukey's HSD for significance indicated that the Bridge–Bridge occurrences for 2014 are significantly higher than in all other years (Table 44).

Table 43. Tukey HSD results of the ANOVA test for Bridge–Bridge joins from the years 2001 through 2014 in Saskatchewan, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.9830													
2003	0.9946	1.0000												
2004	1.0000	0.9984	0.9998											
2005	1.0000	0.9094	0.9670	1.0000										
2006	0.8092	1.0000	1.0000	0.8947	0.4795									
2007	1.0000	0.9759	0.9946	1.0000	1.0000	0.6457								
2008	1.0000	0.9929	0.9988	1.0000	1.0000	0.7804	1.0000							
2009	0.9976	1.0000	1.0000	1.0000	0.9781	0.9989	0.9976	0.9997						
2010	0.8600	1.0000	1.0000	0.9365	0.5683	1.0000	0.7358	0.8515	0.9997					
2011	0.9667	1.0000	1.0000	0.9947	0.8347	1.0000	0.9411	0.9791	1.0000	1.0000				
2012	1.0000	0.8991	0.9679	1.0000	1.0000	0.3870	1.0000	1.0000	0.9778	0.4844	0.8005			
2013	0.9990	1.0000	1.0000	1.0000	0.9940	1.0000	0.9995	0.9999	1.0000	1.0000	1.0000	0.9956		
2014	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	

A Levene's test was conducted to test whether the variability of the numbers of Bridge–Bridge joins differ among the years 2001 through 2014 in Saskatchewan. The result of this test showed that the effect of the temporal grouping by year was significant $F(13, 1077) = 18.86$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Bridge–Bridge occurrences for 2014 are significantly higher than in all other years, (Table 45).

Table 44. Tukey HSD results of the Levene's test for Bridge–Bridge joins from the years 2001 through 2014 in Saskatchewan, in which the bold numbers represent the values that are significantly different at $\alpha = 0.05$.

	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**
2001														
2002	0.7479													
2003	0.7229	1.0000												
2004	1.0000	0.8334	0.8141											
2005	1.0000	0.2723	0.2723	0.9998										
2006	0.3374	1.0000	1.0000	0.3288	**0.0360**									
2007	1.0000	0.4337	0.4311	1.0000	1.0000	0.0652								
2008	1.0000	0.3660	0.3666	1.0000	1.0000	**0.0478**	1.0000							
2009	0.8382	1.0000	1.0000	0.9132	0.3590	0.9996	0.5476	0.4713						
2010	0.2882	1.0000	1.0000	0.2704	**0.0266**	1.0000	**0.0483**	**0.0350**	0.9988					
2011	0.6761	1.0000	1.0000	0.7482	0.1833	1.0000	0.3083	0.2493	1.0000	1.0000				
2012	1.0000	0.3853	0.3883	1.0000	1.0000	**0.0458**	1.0000	1.0000	0.4943	**0.0331**	0.2576			
2013	0.7802	1.0000	1.0000	0.8764	0.3991	1.0000	0.5778	0.5156	1.0000	1.0000	1.0000	0.5481		
2014	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	

A one-way analysis of variance (ANOVA) was conducted to test whether the average numbers of Loop–Loop joins differ among the years 2001 through 2014 in Saskatchewan. The result of this analysis confirmed that the effect of the spatial grouping by province and/or territories was significant $F(8, 1104) = 5.07$, $p = 0.048$. Post hoc analyses using Tukey's HSD for significance indicated that the Loop–Loop occurrences for 2014 are significantly higher than in all other years, except in 2003 and 2013 (Table 46).

Table 45. Tukey HSD results of the ANOVA test for Loop–Loop joins from the years 2001 through 2014 in Saskatchewan, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	0.9766													
2003	0.9619	1.0000												
2004	1.0000	0.5201	0.4908											
2005	1.0000	0.9286	0.9008	1.0000										
2006	0.9485	1.0000	1.0000	0.3285	0.8503									
2007	1.0000	0.6869	0.6507	1.0000	1.0000	0.4889								
2008	1.0000	0.9922	0.9845	0.9971	1.0000	0.9714	0.9998							
2009	1.0000	0.9993	0.9978	0.9792	1.0000	0.9962	0.9968	1.0000						
2010	0.9420	1.0000	1.0000	0.3241	0.8392	1.0000	0.4814	0.9667	0.9950					
2011	1.0000	0.9995	0.9983	0.9690	0.9999	0.9971	0.9944	1.0000	1.0000	0.9961				
2012	1.0000	0.6049	0.5744	1.0000	1.0000	0.3897	1.0000	0.9995	0.9935	0.3855	0.9890			
2013	0.9663	1.0000	1.0000	0.5917	0.9212	1.0000	0.7347	0.9880	0.9980	1.0000	0.9985	0.6772		
2014	**0.0007**	**0.0170**	0.0607	**0.0000**	**0.0000**	**0.0089**	**0.0000**	**0.0000**	**0.0001**	**0.0140**	**0.0001**	**0.0000**	0.1944	

A Levene’s test was conducted to test whether the variability of the numbers of Loop–Loop joins differ among the years 2001 through 2014 in Saskatchewan. The result of this test showed that the effect of the temporal grouping by year was significant $F(13, 1104) = 11.06$, $p < 0.05$. Post hoc analyses using Tukey's HSD for significance indicated that the variability of the Loop–Loop occurrences for 2014 are significantly higher than in all other years except in 2013, and the variability of the Loop–Loop occurrences for 2002 are significantly higher than 2004, 2005, 2007, 20012, and lower in 2014, and the variability of the Loop–Loop occurrences for 2013 are significantly higher than in 2004, 2005, 2007, 2008, and 2012 (Table 47).

Table 46. Tukey HSD results of the Levene’s test for Loop–Loop joins from the years 2001 through 2014 in Saskatchewan, in which the bold numbers represent the values that are significantly different at α = 0.05.

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
2001														
2002	0.8461													
2003	0.9088	1.0000												
2004	0.8262	**0.0004**	**0.0019**											
2005	0.9965	**0.0334**	0.0722	1.0000										
2006	0.9995	0.9950	0.9988	0.0165	0.3555									
2007	0.9519	**0.0017**	**0.0069**	1.0000	1.0000	0.0549								
2008	1.0000	0.0750	0.1595	0.9658	1.0000	0.6263	0.9982							
2009	1.0000	0.7807	0.8870	0.2452	0.8899	0.9999	0.4922	0.9911						
2010	0.9746	1.0000	1.0000	**0.0019**	0.1041	1.0000	**0.0074**	0.2221	0.9697					
2011	1.0000	0.2524	0.4130	0.7333	0.9981	0.9236	0.9322	1.0000	1.0000	0.5565				
2012	0.9802	**0.0027**	**0.0106**	1.0000	1.0000	0.0820	1.0000	0.9998	0.6173	**0.0113**	0.9751			
2013	0.3407	0.9984	0.9979	**0.0001**	**0.0041**	0.6593	**0.0002**	**0.0097**	0.2333	0.9422	0.0393	**0.0004**		
2014	**0.0001**	**0.0138**	**0.0220**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0000**	**0.0005**	**0.0000**	**0.0000**	0.7217	

3.5.1 Review of the results of morphological connectors' joins

Reviewing the results of the join count analysis on the morphological connectors' join for Canada in the year 2014 revealed that the number of Bridge–Bridge and Loop–Loop joins in Northwest Territories and Saskatchewan are significantly higher in that year in terms of mean and variability. Furthermore, after looking into these two provinces and territories individually and examining their results of Bridge–Bridge and Loop–Loop joins throughout the years of study, Bridge–Bridge joins in Northwest Territories and Saskatchewan confirmed that 2014 is significantly higher than all other years, however, the results if Loop–Loop joins for both provinces and territories are only showing that 2014 is significantly higher than some of the years.

4. Discussion

In order to fully comprehend the results of the join count analysis that were mentioned in the previous section, the discussion section looks at how different numbers of joins in morphological classes (e.g., Core–Core, Islet–Islet) can explain some of the aspects of the disturbances in terms of their size, shape, and complexity. Large extent of the study area which multiplied by 14 years of disturbance data resulted in a a massive number of pixels for each of the morphological classes that make it impossible to have a framework in which each of the patches are compared to each other without losing all spatial aspects. However, investigating the results of the join count analysis on the outputs of the morphological analysis reveal insights into what would the number of joins reveal about the size, shape, and complexity of patches.

Before getting into each of the morphological classes and their joins, a brief, yet tangible overview of the meaning of the distributions of the joins using Core–Core as an example, is provided. As it has been mentioned in Section 2.3, the join count analysis was performed on the MSPA results for each province and/or territory and year combination by extracting subsamples 500 times based on a kernel of 200 × 200. For the sake of the demonstration, the Figure 31 is provided as a simplified version of that analysis that represents subsamples with 18 x 18 window size in which subsample A and subsample B captured two different sets of disturbance patches where A has four patches with various numbers of Core pixels (and subsequently Edge pixels) and B represents only one compact Core patch.

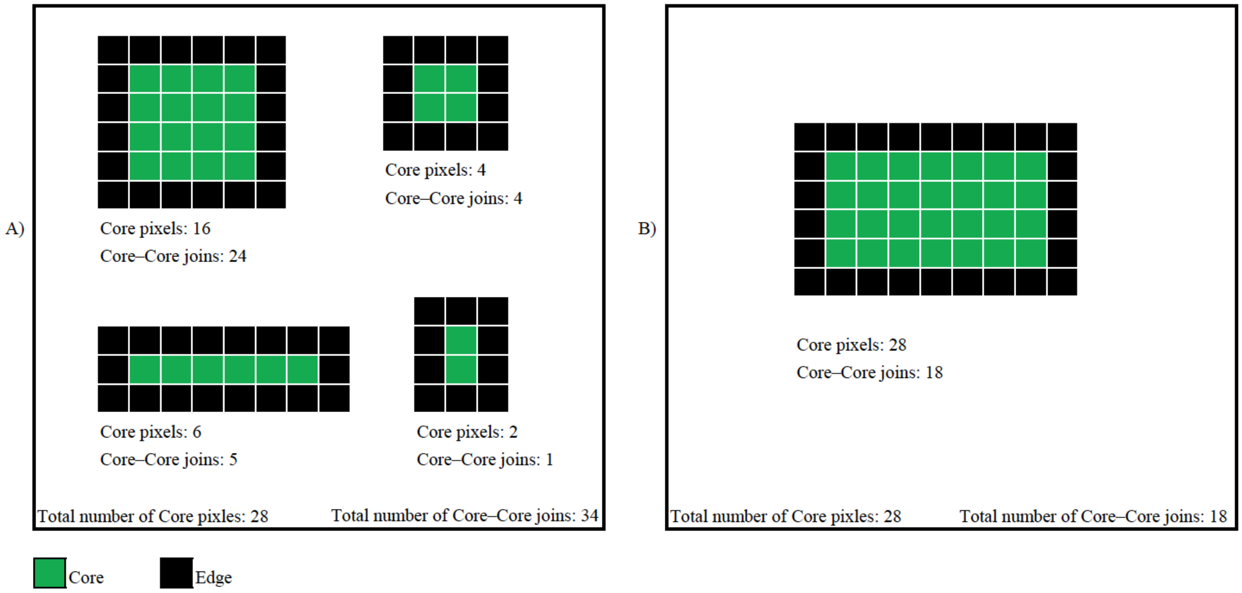


Figure 31. The explanation of the join count analysis on MSPA files using a simplified version with a window size of 18 x 18. A is the first window that captured four patches and B is the second window that captured one patch.

While both subsamples contain the same number of Core pixels, the number of Core–Core joins are very different, the variability of the frequency of Core–Core joins in the subsample A is from 1 to 24 which has a bigger range in comparison to subsample B that is only 28. In conclusion, while details on how the number of joins can be explained for different morphological classes will be provided separately later on, it is important to understand that based on the Figure 31, a higher variability in the frequency of the number of joins can be interpreted as inconsistency in the shape of the disturbances, and the mean is an indicator of the average of the number of joins. In the next parts of the discussion section, the explanations on how the number of joins can be interpreted for each of the morphological classes are provided.

4.1 Core–Core joins

Core pixels are the first morphological class that are classified and includes the pixels that are surrounded by four orthogonal adjacent neighbors or rook's case (Sawada, 1999). Understanding the results this class and what a certain number of joins mean would potentially disclose meaningful insights into the main bodies or patches of forest disturbances. Three aspects of the disturbances can possibly be explained by looking at the number of Core–Core joins, size, compactness/linearity, and complexity. The following Figure represents four examples of Core patches with different number of pixels and joins and how those numbers can reflect the size of the patches.

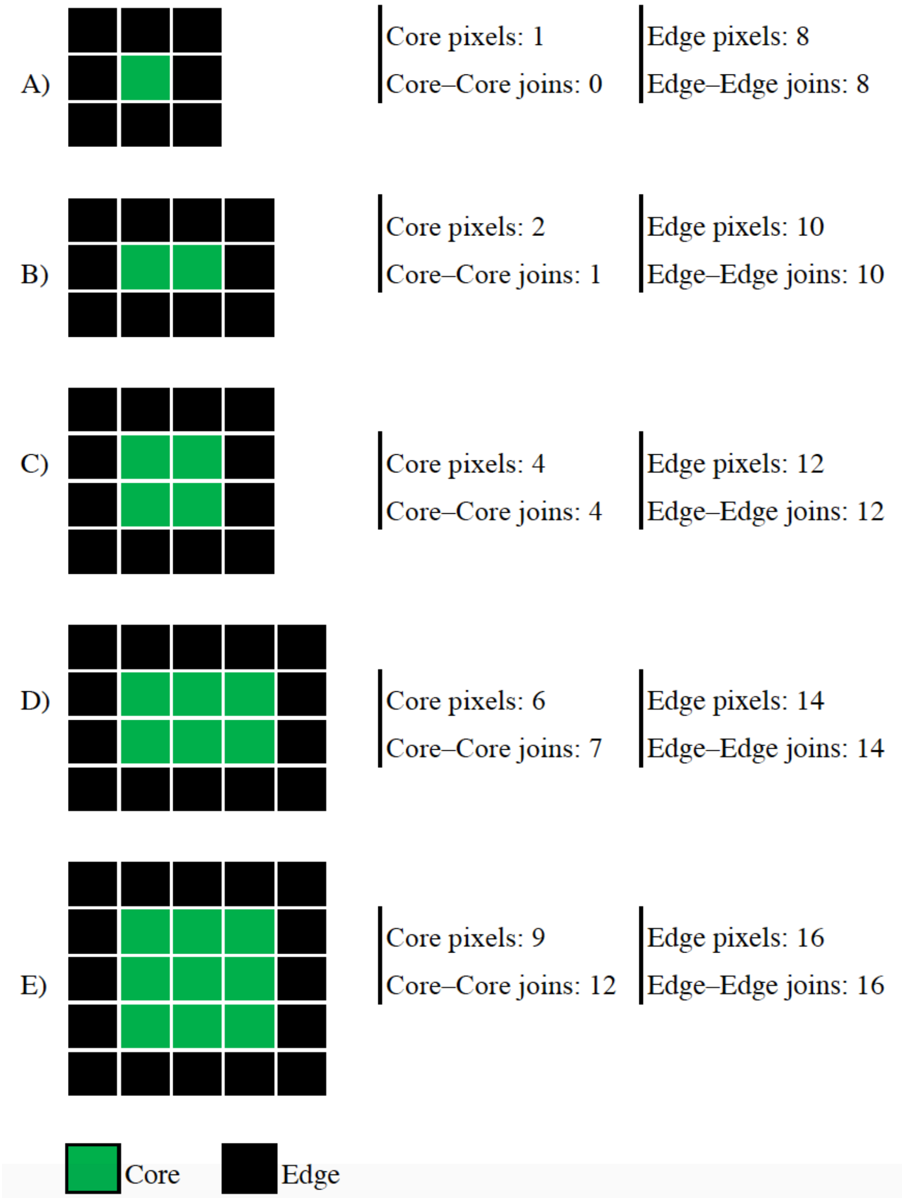


Figure 32. Representation of four examples of Core patches with different number of pixels and joins and how those numbers can reflect the size of the patches.

According to the Figure 32, as the size of the patches increases, the number of Core–Core increases, therefore a higher number of joins can be interpreted as a bigger disturbed patch. The second characteristics of disturbances can be explained by the number of joins is their compactness/linearity. The patch A and B in the following Figure both have 60 foreground pixels but as we can see, A looks more linear than B, in other words, in spite of their visible differences, we are not able to differentiate these two patches by only counting the number of pixels. However, looking at the number of Core–Core joins can reveal more information about the shape of the patches. Therefore, in can be concluded that a higher number of Core–Core joins can be interpreted as a sign of compactness of the shape of the disturbance patches.

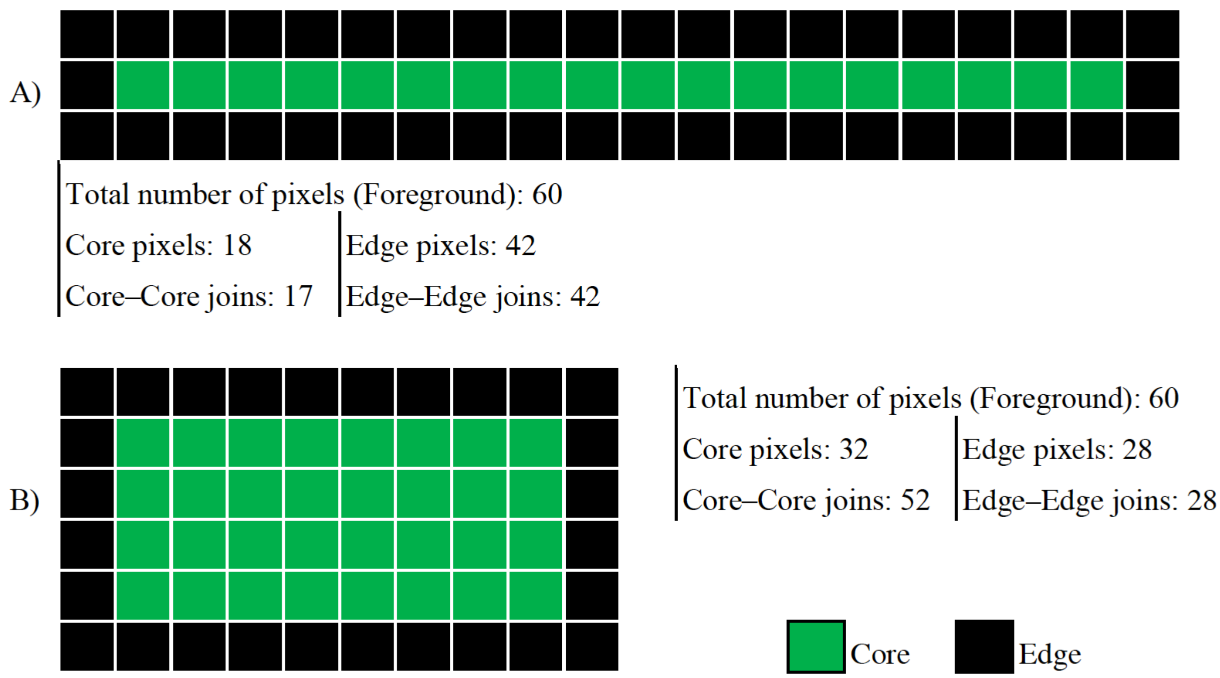


Figure 33. Representation of two examples of Core patches with the same number of total pixels but different Core–Core and Edge–Edge joins and how the number of joins can explain the level of compactness/linearity of the Core patches.

The last characteristics of disturbances can be explained by the number of joins is the level of complexity of the patches. The Figure 34 represents two patches that have 60 Core pixels with different level of complexity. However, the number of Core–Core joins can be used as an indicator of their level of complexity, therefore in can be concluded that a higher number of Core–Core joins can be interpreted as a sign of complexity of the shape of the disturbance patches.

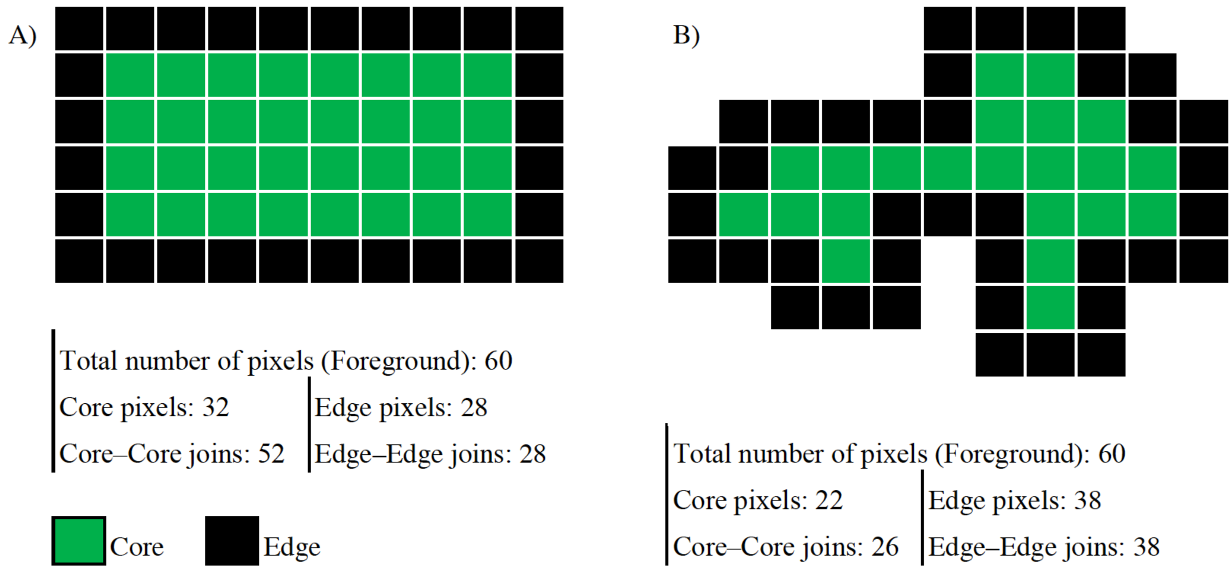


Figure 34. Representation of two examples of Core patches with the same number of total pixels but different number of Core–Core and Edge–Edge joins and how the number of joins can explain the level of complexity of the Core patches.

The following map which is produced from MSPA results of Manitoba in the year 2013, overlaid on Landsat TM 5 images, represents how big and compact disturbances resulted into a higher number of Core–Core join that was highlighted in Table 20 and 21. While this is just a small portion of the entire MSPA output, but the output contains Core patches with the same characteristics all across the province and/or territory in that year.

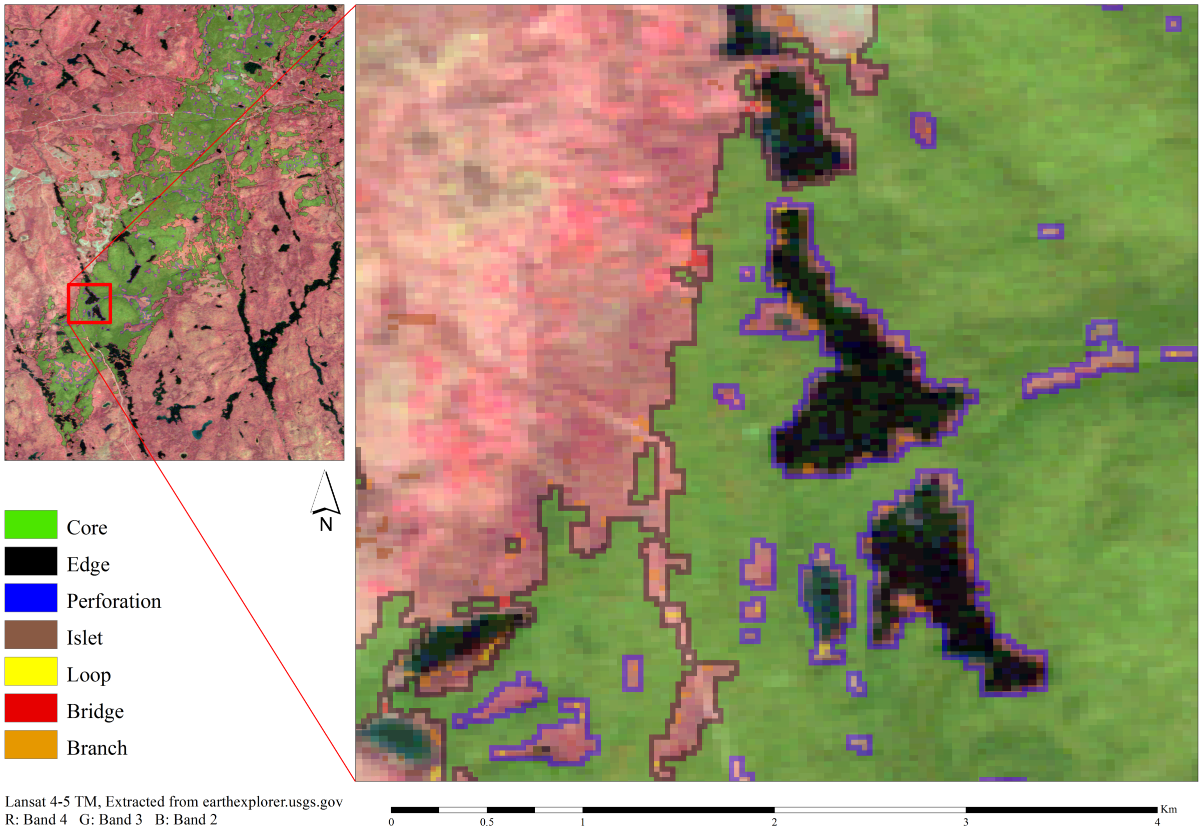


Figure 35. A small portion of MSPA output of the province of Manitoba in the year 2013, in which the Core–Core occurrences are significantly higher than in all other years. This represents how big and compact disturbances resulted into a higher number of Core–Core joins.

Based on the understanding from this section regarding Core–Core joins, it can be discussed that the average and the variability of the Core–Core joins is an indicator of size, compactness, linearity, and complexity of the shape of the disturbances.

4.2 Islet–Islet joins

Islet pixels include the pixels that are not big enough to be considered as Core. Understanding the results this class and what a certain number of joins mean would potentially disclose meaningful insights into small fires, sparks, and so on. Figure 36 represents how different Islets might look as the number of Islet pixels increase.

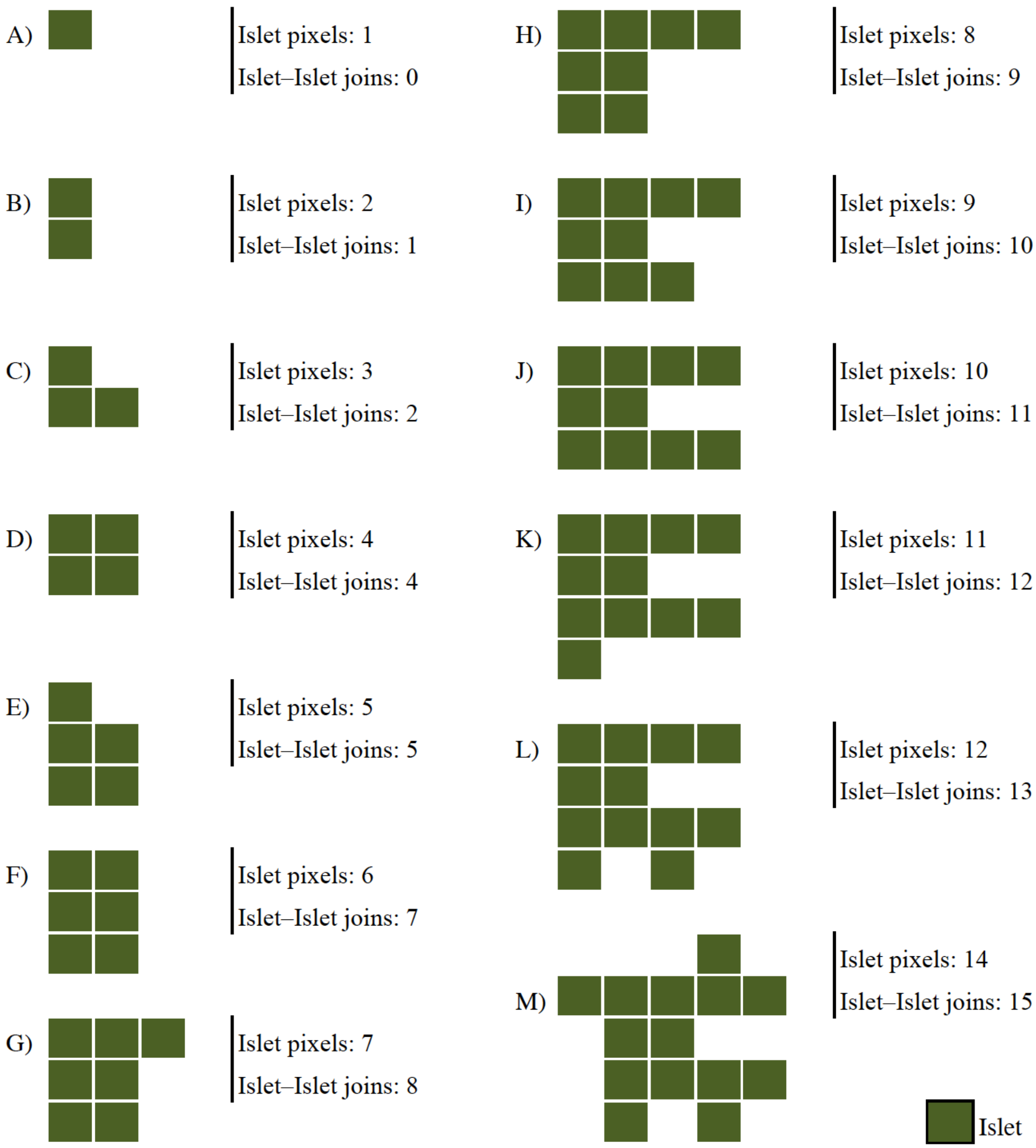


Figure 36. Representation of 13 examples of Islets with various number of pixels and Islet–Islet joins and how the number of joins can reflect the different shapes of Islets.

The simplest form of Islet is represented in A which is only one pixel without any joins, as the number of Islet increases, the number of Islet–Islet increases. Looking at the shape of the Islets and how it grows reveals the most important characteristic of Islet pixels which is their restrictions in terms of the shape it can form as the number of pixels increases. Figure 37 is another representation of how the shape of Islet changes if we keep adding pixels to it and those pattern styles are some of the possible ways that the Islet can grow into.

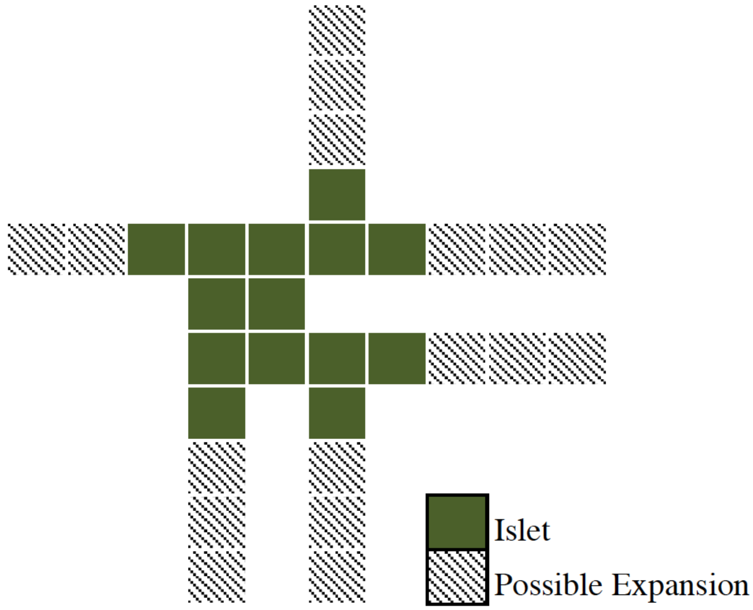


Figure 37. Representation of how Islets are limited in terms of expanding because as they increase in size, they cannot increase in width or otherwise they would contain Core area or Edge.

From the Figures 36 and 37, it can be concluded that as the number of pixels increase, Islet pixels tend to be more linear, because the compactness in the shape would require pixels appear next to each other in each of the 4-directions which is not possible, as if one foreground pixel is surrounded by other foreground pixels, they would be labeled as Core or Edge, not Islets anymore, therefore A very large Islet would could have a very spider-web like pattern.

The aforementioned Figures provided a basic understanding of what Islet–Islet joins mean and how they can look like, now we can go back to the MSPA outputs and look into the province/year that were significantly different in terms of mean and variability of Islet–Islet joins as an attempt to reveal more insights about the disturbances that occurred in that certain province/year which resulted into a higher mean or variability of the number of joins.

The number of Islet–Islet joins in the province of Ontario in the year 2002 is significantly different in terms of mean and variability that the other years (Table 10 and 11). The following map represents a small part of Ontario 2002 in which we can see how a high average and variability of number of Islet–Islet joins are explained by excessive number of small burned areas. It should be mentioned that while this is only a small part of the entire province, but there are many areas in the MSPA output of that year that have these small Islets.

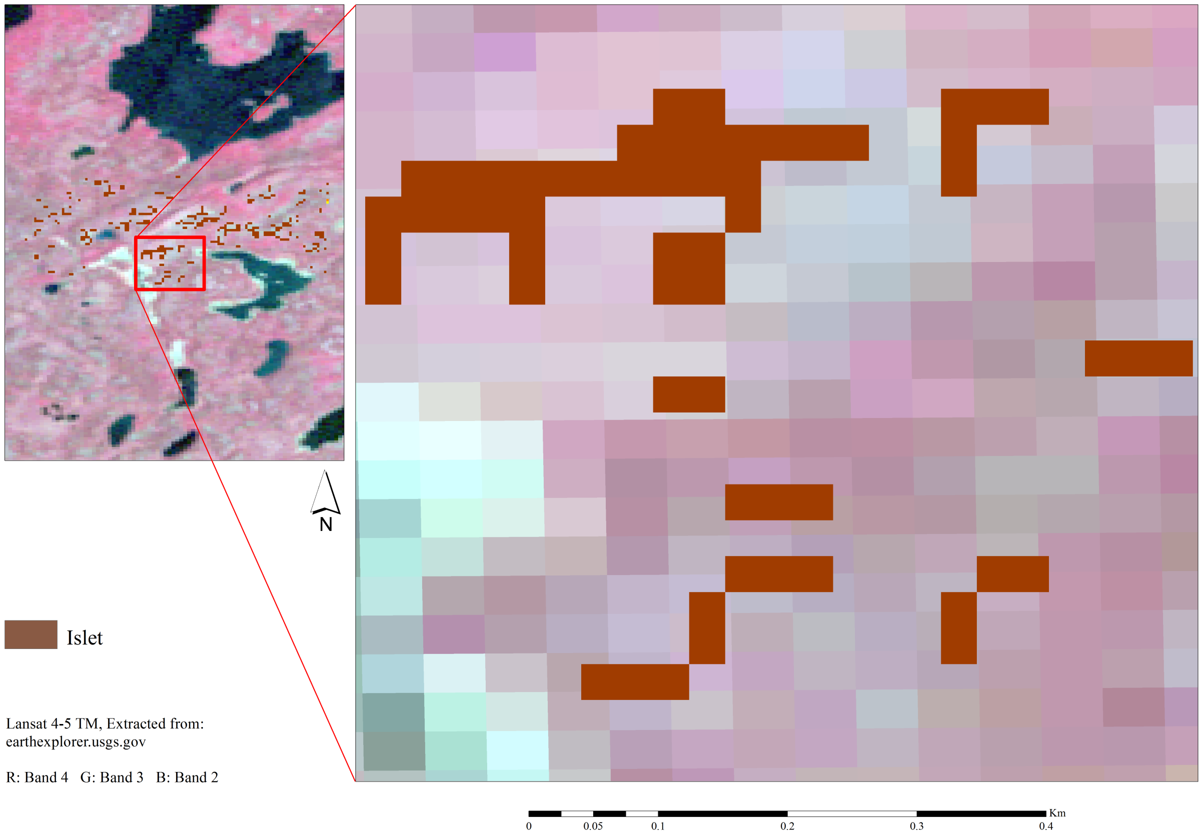


Figure 38. A small portion of MSPA output of the province of Ontario in the year 2002, in which the Islet–Islet occurrences are significantly higher than in all other years. This represents how excessive number of small Islets resulted into a high average number of Islet–Islet joins in Ontario 2002.

The year 2014 is another interesting year in the province of Ontario in terms of Islet–Islet joins. While this year is not significantly different when it comes to the average number of joins, but it is different in terms of variability (Table 11). The Figure 39 represents two small parts of the MSPA output of Ontario 2014 in order to demonstrate that how having a large number of Islet pixels which result into a linear set of Islet pixels, explain a higher variability of the number of Islet–Islet joins.

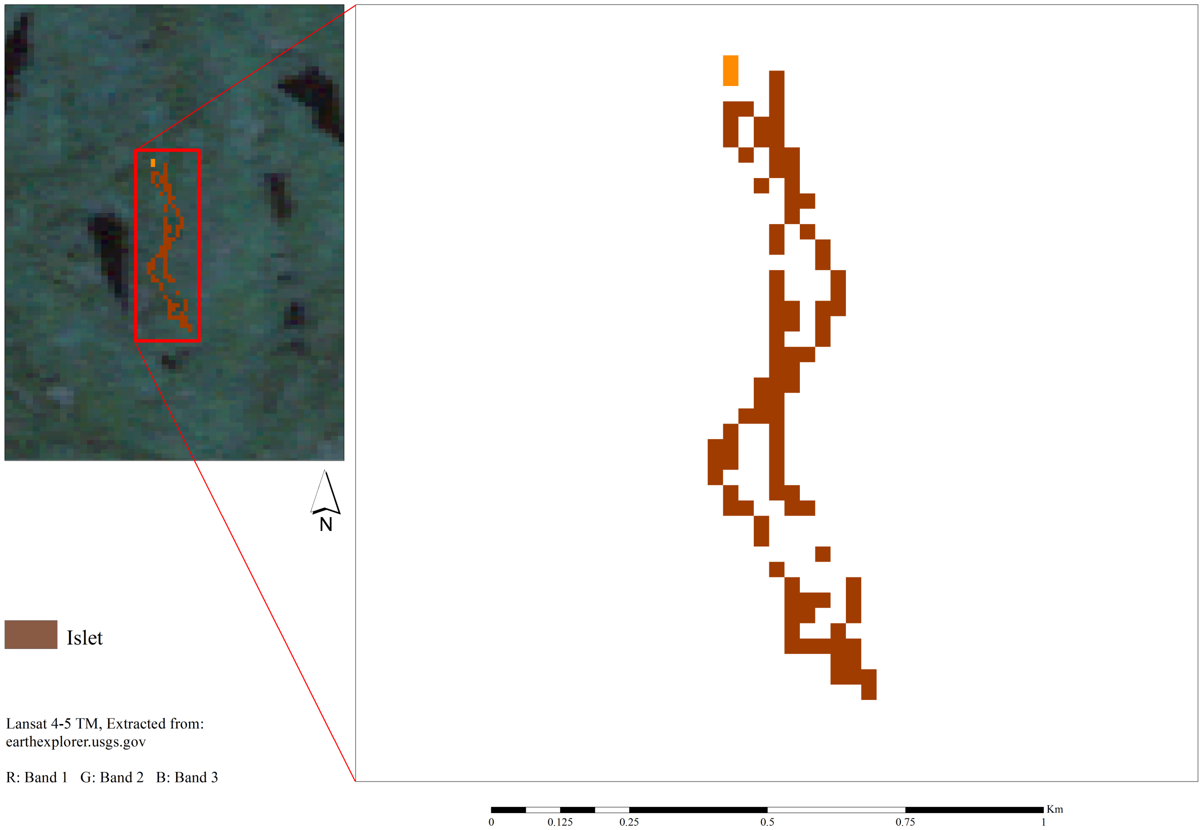


Figure 39. A small portion of MSPA output of the province of Ontario in the year 2014, in which the variability of the Islet–Islet occurrences are significantly higher than in all other years. This represents a large number of Islet pixels which result into a linear set of Islet pixels and how that explains a higher variability of the number of Islet–Islet joins.

a) The disturbances in Ontario in 2002, Alberta in 2004 include more Islets, or in other words, smaller and narrower patches, than the rest of the years.
b) The disturbances in Ontario in 2002 and 2014, Northwest Territories in 2005 and 2014, and Yukon in 2004-2006, 2010 and 2014 include more linear Islets, or in other words, longer patches of narrow disturbed areas, than the rest of the years.

4.3 Perforation–Perforation joins

There are many similarities in explanation of Perforation pixels and the Core and Edge pixels (Section 4.1). Perforation pixels are the boundary of holes in the Core patches. Understanding the results this class and what a certain number of joins mean would potentially disclose meaningful insights into the areas that are left undisturbed in the middle of disturbance patches. Similar to Section 4.1, three aspects of the disturbances can possibly be explained by looking at the number of Perforation–Perforation joins, size, compactness/linearity, and complexity. The following Figure represents four examples of Perforation patches with different number of pixels and joins and how those numbers can reflect the size of the patches.

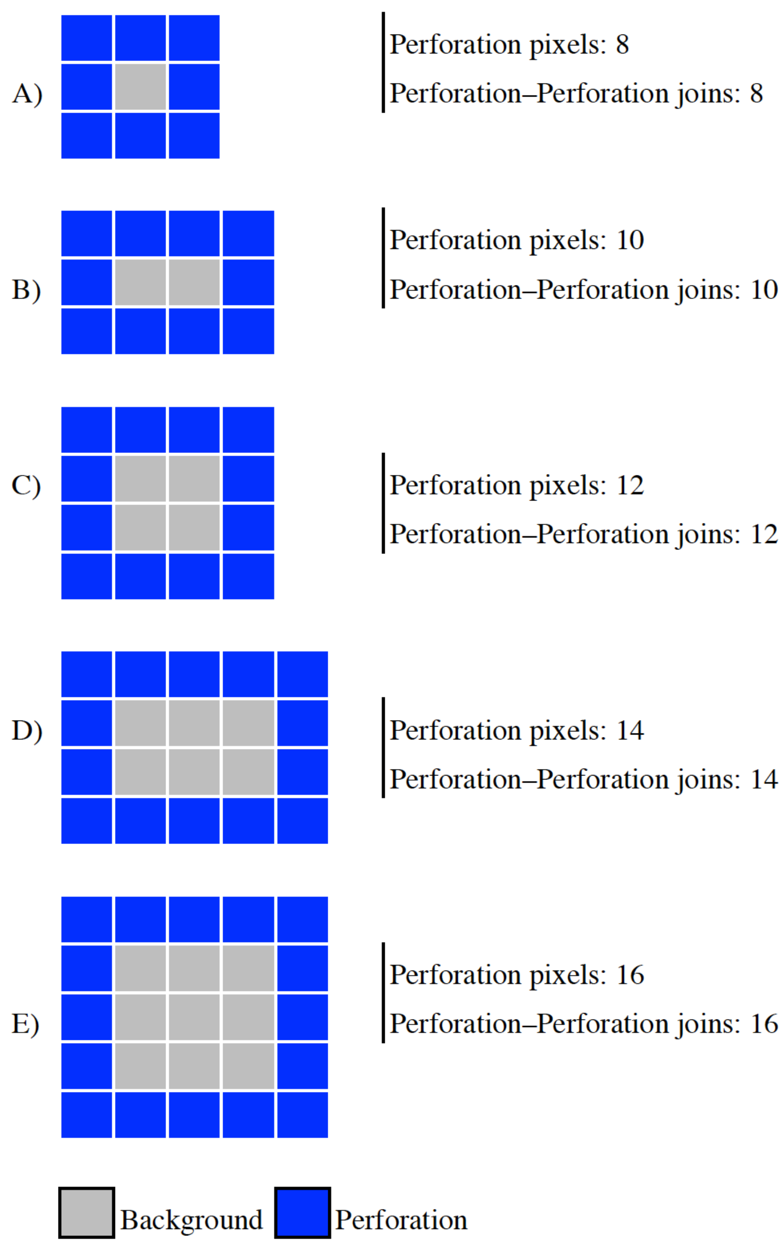


Figure 40. Representation of four examples of Perforation patches with different number of pixels and joins and how those numbers can reflect the size of the patches.

Perforation A is the simplest form of Perforation in which the hole (background pixel in the middle of a Core, refer to section 1.5.5 for further explanations). According to the Figure 40, as the size of the hole increases, the number of Perforation, and subsequently the number of Perforation–Perforation joins increases as well, therefore, higher number for the Perforation–Perforation joins could be interpreted as a bigger area in the middle of a disturbance patch that was not burned and left undisturbed for some reasons that could be explored in other studies and ultimately are labelled as background. Similar to the Core and Edge pixels (Section 4.1), an increase in the number Perforation–Perforation joins could also be explained by either compactness/linearity (Figure 41) or complexity (Figure 42) of the hole pixels.

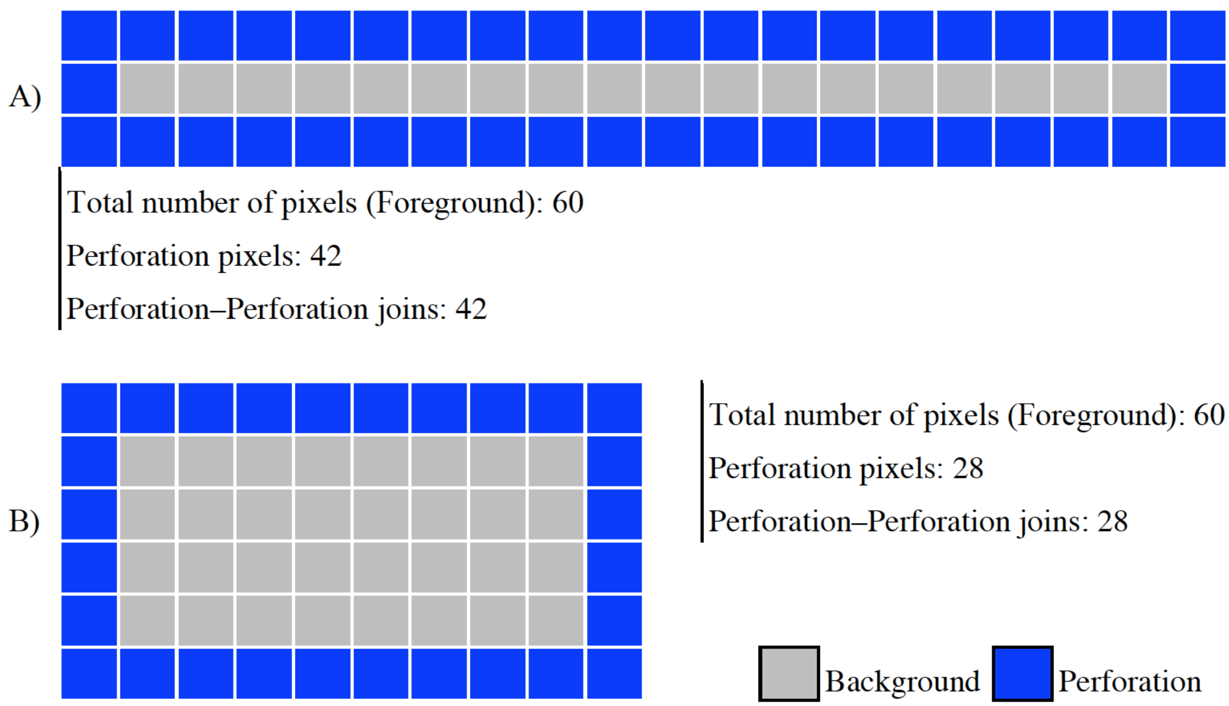


Figure 41. Representation of two examples of Perforation patches with the same number of total pixels but different Perforation–Perforation joins and how the number of joins can explain the level of compactness/linearity of the Perforation patches.

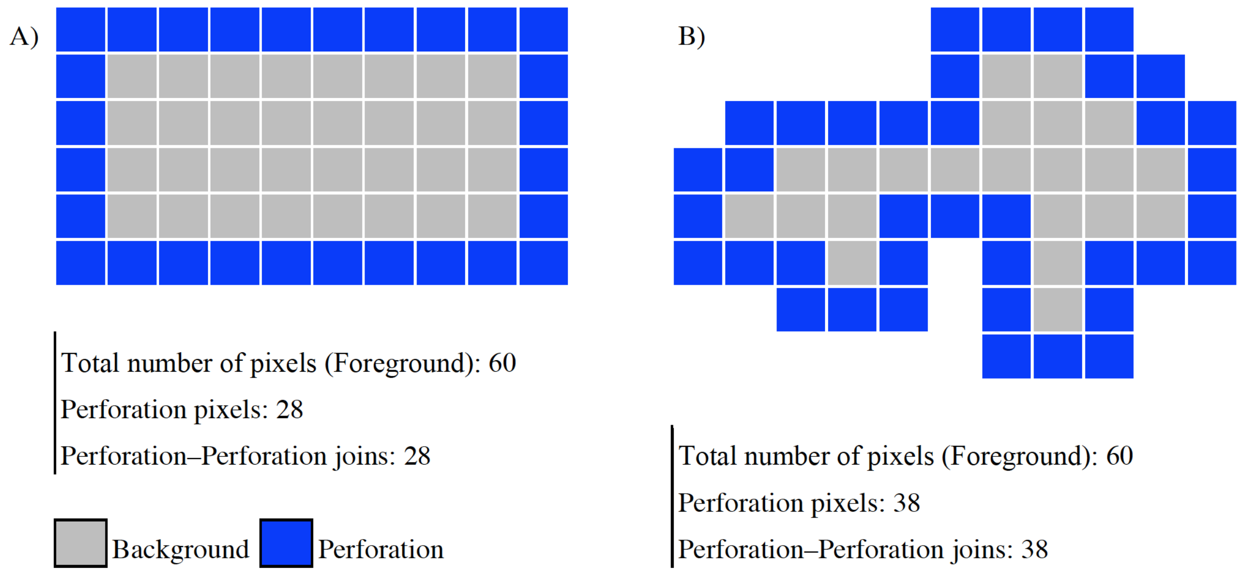


Figure 42. Representation of two examples of Perforation patches with the same number of total pixels but different number of Perforation–Perforation and how the number of joins can explain the level of complexity of the Perforation patches.

It is logical to assume that one of the main reasons causing Perforations is small lakes in the middle of a forest patch (Figure 35), however, water is not the only reason. As it can be seen in Figure 43 that is map that is produced from MSPA results of Yukon in the year 2011 overlaid with Landsat 5 images, in which Perforation–Perforation joins were significantly different that the other years, those Perforations in the locator map are not caused due to the existence of water, therefore other features were left undisturbed in the middle of a disturbed patch. That being said, it needs to be mentioned that a) Specifying what all the features are needs a more local approach, concentrating on specific part of a province and year, B) While this is just a small portion of the entire MSPA output, but the output contains Core patches with the same characteristics all across the province in that year.

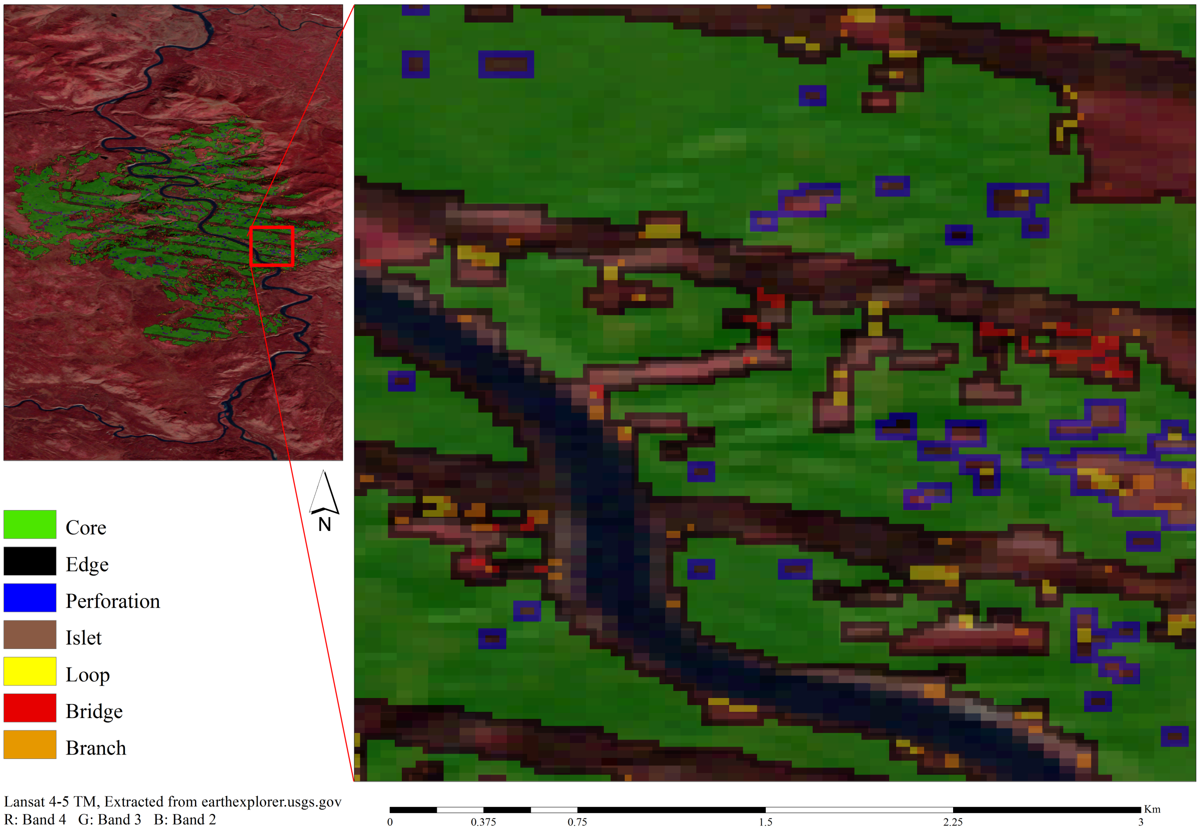


Figure 43. A small portion of MSPA output of the territory of Yukon in the year 2011, in which the Perforation–Perforation occurrences are significantly higher than in all other years.

Based on the understanding from this section regarding Perforation–Perforation joins, it can be discussed that the average and the variability of the Perforation–Perforation joins is an indicator of size, compactness, linearity, and complexity of the shape of the holes within the disturbances, however, those holes could be caused by many reasons, such as existence of a lake and so on. Then again, while only Yukon 2011 is explored here, but after going through the other provinces/years that were highlighted in the Section 3.5, the aforementioned points apply to every province/year that exhibits significant differences in terms of Perforation–Perforation joins.

4.4 Morphological connectors' joins (Bridge and Loop)

There are two classes that are called the morphological connectors, Bridge and Loop. The pixels that are labeled as Bridge are the ones that connect two Core patches together. Connectors' pixels are harder to perceive in comparison to the rest of the morphological classes; however, Figure 44 aims at providing a basic understanding of how Bridge pixels could be formed and how different number of joins can be explained with the size, shape, and the complexity of the disturbance patches.

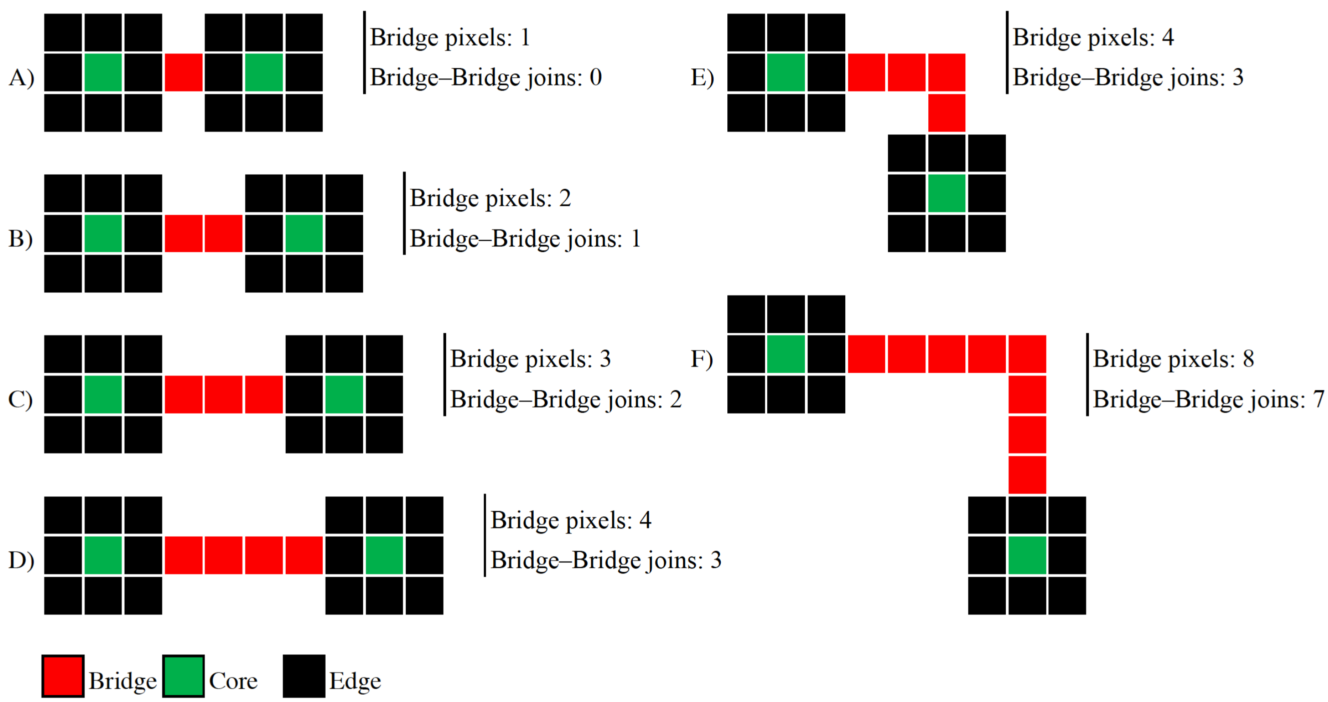


Figure 44. Representation of six examples of Bridge with different number of pixels and joins and how those numbers can reflect the size/shape of the Bridges.

The first example (A) in the above Figure represents a simple one-pixel Bridge that is connecting the two Core patches to each other. It is important to emphasize that these six cases are examples and not the only possible cases. According to Figure 44, a larger number of Bridge–Bridge joins might mean longer Bridge pixels, in other words, in the context of disturbances, a larger number of Bridge–Bridge joins could be interpreted as longer set of pixels between two disturbed patches that are not disturbed. However, when looking into the other possibilities that might have resulted into a higher number of joins, E and F might explain that there are other forms that Bridge pixels can get into that are not necessarily linear or easy to interpret.

The second morphological connector is Loop, which defines the pixels that connect a Core patch to itself. Following the interpretation of Bridge–Bridge joins, Figure 45 is attempting to provide a basic understanding of how Loop pixels could be formed and how different number of joins can be explained with the size, shape, and the complexity of the disturbance patches.

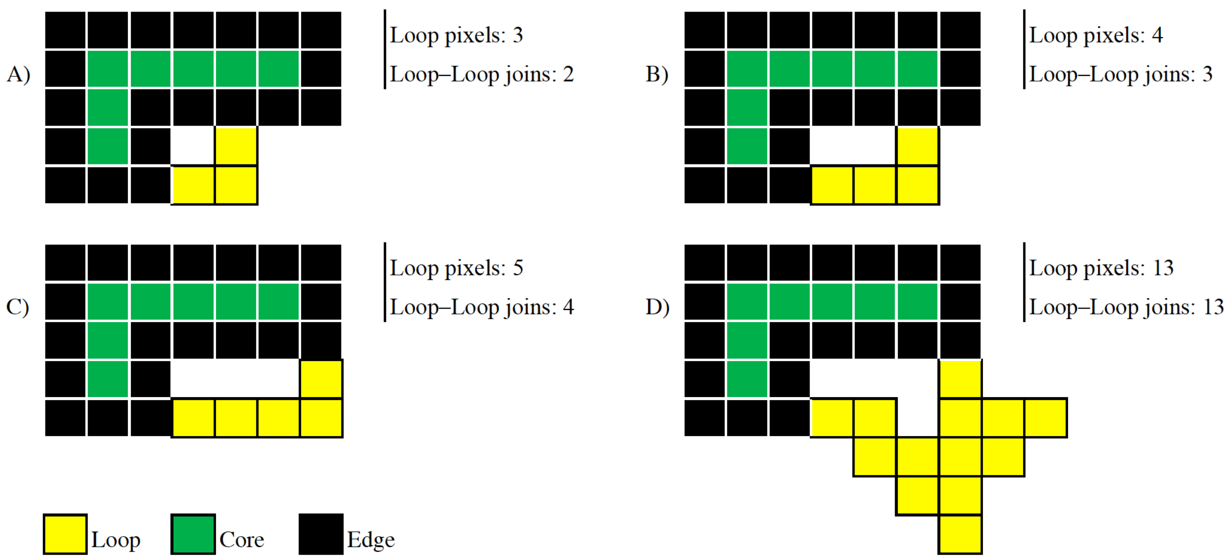


Figure 45. Representation of four examples of Loop with different number of pixels and joins and how those numbers can reflect the size/shape of the Loops.

There are four examples of how different number of Loop pixels might look like and how that would affect the number of Loop–Loop joins. It is important to emphasize that these four cases are examples and not the only possible cases. The example A represents three-pixel Loop that resulted into 2 Loop–Loop join. According to the Figure 45. a larger number of Loop–Loop joins can be interpreted as longer and irregular, yet narrow shapes.

Not only the connectors' joins are harder to perceive but also their number of joins are harder to interpret. For instance, the following map that is produced from MSPA results of Saskatchewan in the year 2014, in which Bridge–Bridge joins as well as Loop–Loop joins were significantly different that the other years, show how the morphological connectors form in association with the Core patches. While this is just a small portion of the entire MSPA output, but the output contains Core patches with the same characteristics all across the province of Saskatchewan in the year 2014.

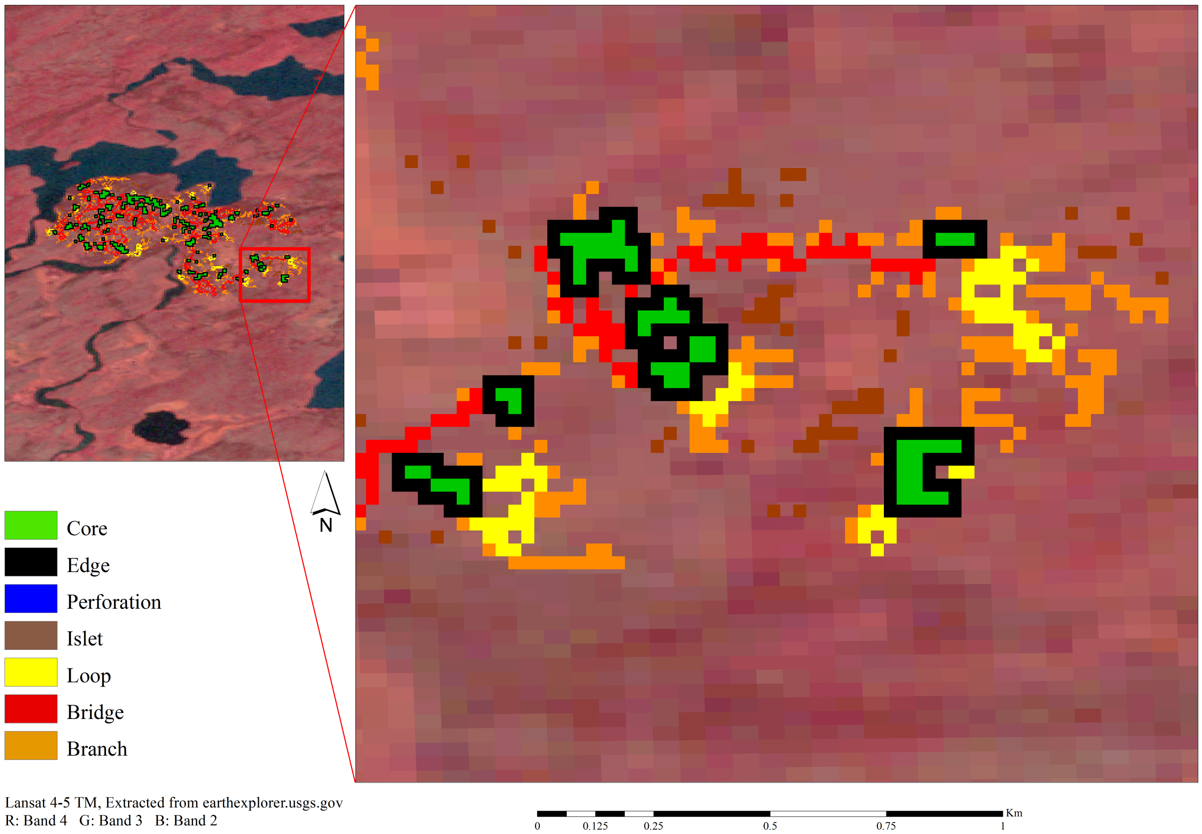


Figure 46. A small portion of MSPA output of the province of Saskatchewan in the year 2014, in which Bridge–Bridge and Loop–Loops joins occurrences are significantly higher than in all other years.

It can be said that the higher average and variability of the number of Bridge–Bridge joins in the province of Saskatchewan in the year 2014 could be interpreted that there are longer and irregular, yet narrow set of pixels between Core patches. When it comes to discussing the causing factors of the morphological connectors, similar to the rest of the classes, specifying what all the features are needs a more local approach, concentrating on specific part of a province and year.

5. Conclusions

Quantification and comparison of the forest cover change over vast geographic extents and long periods of time is a challenging task. The first challenge is the lack of a theoretical framework that embeds a consistent approach to characterize and compare those changes which makes it impossible to have a broad understanding on how these changes manifest themselves through time and geographic spaces while maintaining all the spatial elements.

This study aimed at analyzing temporal morphological pattern changes and spatial differences in forest disturbance within the boreal biome of Canada among the years 2001 through 2014 and it utilized a standardized morphological approach (MSPA) and bootstrapped join count statistics to compare spatial distributions of the morphological elements among the geographic and temporal groupings.

The use of join count statistics enabled assessing the composition and configuration of the spatial patterns on binary maps, where fire disturbances were not mapped as objects but by individual and independent. Bootstrap resampling produced empirical distributions that facilitated the comparisons of the join count analysis outcomes among the factor groups: (1) spatially groupings (i.e., Canadian provinces and territories) and (2) temporal groups (i.e., years 2001 through 2014). In order to answer the questions and statistically test the effect of spatial and temporal groupings, ANOVA and Levene's tests were used to compare means and variances of join count outcomes for each of the morphological classes, respectively.

There were two research questions that this study attempted to answer. The first question concerns with whether the spatial and temporal morphology of forest disturbance pattern within the boreal biome of Canada differ through time. The simplest answer to the first question is yes, the spatial and temporal morphology of forest disturbance pattern within the boreal biome of does Canada differ through time and these differences manifest themselves in various provinces/territories and morphological classes.

The second question is whether the spatial morphologies of forest disturbance patterns in the boreal biome of Canada differ among provinces and/or territories. The answer to this question yes as well, the spatial morphologies of forest disturbance patterns in the boreal biome of Canada does differ among provinces and/or territories and these differences manifest themselves in various years and morphological classes.

The main findings of this study can be divided into two categories based on the extent of which the analyses were taken place at: a) entire boreal biome of Canada b) provinces/territories. This study investigated all the morphological classes in all the years of study for the entire Canadian boreal biome. The Core–Core and Edge–Edge joins for the entire boreal portion of Canada identified the years of 2004, 2005, and 2013 as the time points that have significantly higher occurrences and the Perforation–Perforation joins revealed pointed out the years of 2003 and 2013.

The second category is organized by the morphological classes and the occurrences of joins within them, and it needs to be mentioned that while several cases were examined for each class, the main case would be mentioned as the finding of this study and the rest are the supplementary cases that might reveal similarities with the main case. The Islet–Islet joins identified the provinces of Ontario and Québec as curious cases to investigate, particularly in year 2002 and 2014 as the occurrences of the joins are significantly higher in those two years. The Core–Core and Edge–Edge joins raised compelling irregularities in the province of Ontario in years 2004, 2011, and 2012, as these three years presented higher occurrences of Core–Core and Edge–Edge joins. The next morphological class is perforation and the joins within this class spotted highly curious and excessive number of occurrences in the territory of Yukon in year 2011. The last classes that were studied are morphological connectors (i.e., Loop and Bridge) in which the occurrences pointed out to Northwest Territories and Saskatchewan in year 2014.

The finding of this study points out a few of the curious pattern changes in the Canadian boreal biome throughout 14 years using a standardized approach. Although several possible explanations as to why the differences in the aforementioned cases for each of the morphological classes, how their shape and size can be explained using the number of joins as well as how they could be interpreted in the context of disturbances are provided in the discussion section, but due to the large extent of the study area, a more local approach to understand the morphological patterns and their alterations in more detail, was not possible and is outside of the scope of this study. However, this study sets a promising direction for future studies in which each of the curious irregularities in the pattern that was mentioned hold a potential to be a topic for another study and be explored in more detail with consideration of influential factors.

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