COMPARING THE SPATIAL PATTERN OF FIRE AND HARVEST DISTURBANCE IN BOREAL ONTARIO WATERSHEDS

by

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ABSTRACT

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Fire and harvest are both major sources of disturbance in Ontario's boreal forest. They are largely responsible for successional patterns in forest vegetation, and influence regimes of hydrologic change in boreal streams, owing to the relationship between watershed and riparian disturbance and conditions in the stream. These forests and their streams have historically developed under the influence of fire disturbance. However, increased harvest activity and fire suppression have significantly reduced the impact of fire within Ontario's managed boreal forest. The degree to which harvest activity in these regions results in similar spatial patterns of disturbance within watersheds as fire is unclear. Accordingly, the objectives of this study were to assess if harvest disturbance resulted in a similar extent and landscape pattern of impact as fire, both within boreal watersheds and their riparian forests.

In the study's first chapter fire and harvest were compared within 30 km^2 (±20% area) watersheds in the study area. Harvest was the most common of the two, impacting ~30% of the study watersheds during any given period, whereas fire disturbed ~2% of study watersheds. Stark differences were observed between the watershed impacts of the two types. Fire disturbed a greater median percentage of watershed land areas and resulted in a range of impacts, including 100% disturbance. Harvest conversely resulted in lower disturbance percentages, occupying a subset of the variability measured in fire-disturbed watersheds, typically below 20% disturbance. Other contrasts between the types include fire resulting in fewer and more simply shaped patches than harvest, often occurring during a single year of a period compared with multiple years in harvested watersheds.

In the study's second chapter fire and harvest were compared within shoreline riparian buffers, both 30 and 90 m in width around aquatic features. Harvest was the most common for both buffer distances impacting 20% and 25% of the 30 and 90 m buffers respectively, compared with ~1.5% impacted by fire. Fire disturbed a greater percentage of both buffers and resulted in a range of impacts up to 100% buffer area disturbed. Harvest on the other hand resulted in significantly lower disturbance extents, particularly within the 30 m buffer, and only occupied a small subset of the variability resulting from fire, typically <10% area disturbed. Other differences in impact included, more numerous, smaller, and more intricately shaped patches spread over multiple years in harvested buffers over fire.

Differences in the watershed chapter indicate that harvest does not provide for a similar extent and landscape pattern of disturbance and as a result, does not likely result in similar regimes of forest succession and stream flow change as fire. In the riparian chapter it is clear that harvest does not provide similar impacts as fire, particularly with widespread usage of reserve forested buffers in Ontario harvest practices. Accordingly harvest is likely not providing for similar successional patterns as fire within riparian forests, and as a result will not provide for flow and stream temperature changes that would naturally occur.

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1.0 GENERAL INTRODUCTION

Approximately 66% of Ontario is mantled in forests, with an additional ~18% occupied by lakes, wetlands, and streams (Watkins 2011); specifically within the boreal forest, water features occupy around a third of the total area (Pinel-Alloul *et al.,* 2002). These forests face increasing disturbance from anthropogenic sources including mining, construction, fire suppression and forest harvesting (Pinel-Alloul *et al.,* 2002). During the last century harvest disturbance has increased and is now close to exceeding the annual area disturbed by fire (Pinel-Alloul *et al.,* 2002), which has been the dominant natural disturbance during the development of Canada's boreal forests (Flannigan *et al.,* 2005; Perera & Cui 2010). While fire suppression efforts in Ontario have reduced the frequency and annual area burned in some parts of the boreal (Bergeron *et al.,* 2001; Bergeron *et al.,* 2004; McRae *et al.,* 2001), future climate modelling has projected significant increases in annual area burned under a changing climate (Bergeron *et al.,* 2004; Flannigan *et al.,* 2005). The risks of additive effects of fire and harvest activity on Ontario's boreal forests are of concern (Bridge *et al.,* 2005), as are the influence of fire and harvest disturbance on forest hydrological processes (Bowman & Boggs 2006; Buttle *et al.,* 2000; Buttle *et al.,* 2005). Particularly as maintaining forest hydrological processes are currently included in the evaluation criteria of many sustainable forestry certifications (Buttle *et al.,* 2000).

Current forest management activity in Ontario operates under an emulation of natural disturbance (END) based management paradigm (CFSA 1994; OMNR 2010;

OMNR 2014); however this has not always been the case, and differences have been identified in the spatial patterns of disturbance of harvest and fire. Differences between harvest disturbance and fire could disrupt the natural successional regime of the boreal forest (Bergeron *et al.,* 2001; Bouchard *et al.,* 2008), and its riparian areas (Kreutzweiser *et al.,* 2012; Pettit & Naiman 2007). Additionally, differences in watershed and riparian disturbances could affect natural regimes of hydrologic change resulting from fire, owing to the relationship of both the extent (Abdelnour *et al.,* 2011; Carignan & Steedman 2000) and location of watershed disturbance (Abdelnour *et al.,* 2011; Bosch & Hewlett 1982; Burton 1997), and effects on stream environments.

Accordingly, a call for research addressing both the pattern and extent of fire and harvest disturbance within watersheds and their riparian areas has come from the scientific community (Dwire & Kauffman 2003; Moore & Richardson 2012; Schroeder & Perera 2002). Others have emphasized the need to address the effects of fire and harvest disturbance in both headwater catchments (Nitschke 2005), and large scale watersheds (Cui *et al.,* 2012; Pinel-Alloul *et al.,* 2002). Additionally, many have identified the need to address these questions at regional or landscape scales (Lin & Wei 2008; Moore & Richardson 2012; Pickell *et al* 2013; Richardson *et al.,* 2012; Vose *et al.,* 2011). It is therefore important to evaluate and compare the extent and pattern of disturbance resulting from fire and harvest activity in Ontario's boreal forest watersheds and their riparian areas.

2.0 WATERSHED CHAPTER

2.1 INTRODUCTION

Both fire and harvest are major sources of forest disturbance in Ontario's boreal region (Flannigan *et al.,* 2005; Perera & Cui 2010; Pickell *et al.,* 2013; Pinel-Alloul *et al.,* 2002). Fire as the dominant natural disturbance, plays a significant role in the development of the structure and composition of the boreal forest landscape (Arkle & Pilliod 2010; Flannigan *et al.,* 2005). Within the approximately 300 000 km^2 of managed boreal forest in Ontario harvest plays a similar role (Perera & Cui 2010; Schroeder & Perera 2002). During the past century forest area disturbed by harvest has increased and is close to exceeding the area affected by fire (Pinel-Alloul *et al.,* 2002). The two disturbance types result in spatially fragmented and temporary local deforestation, but operate using different mechanisms (Carignan & Steedman 2000). Current forest management activity in Ontario operates under an emulation of natural disturbance (END) based management paradigm (CFSA 1994; OMNR 2010; OMNR 2014); however this has not always been the case, and differences have been identified in the spatial patterns of disturbance of harvest and fire.

Differences between fire and harvest include disparities in the frequency and range of disturbed areas they create. Fire can burn areas ranging from a few hectares to hundreds or thousands of hectares (Bouchard *et al.,* 2008; McRae *et al.,* 2001), and while smaller fires account for a significant majority of fires that occur, larger fires (>200 ha) generally account for ~97% of the total area burned (Cumming 2001; Girardin *et al.,* 2006). In contrast to fire the majority of the area disturbed by forest management is from small harvest events (Pickell *et al.,* 2013). Forest policy in Ontario generally limits the size of clearcuts to <260 ha, although some harvests (20%) are permitted exceeding this limit (Perera & Cui 2010).

Harvest disturbance patch sizes typically represent a small subset of those that can occur from fire (McRae *et al.,* 2001), and median harvest patch sizes are generally smaller than those resulting from fire (Schroeder & Perera 2002). Patch densities are usually greater in clearcut-harvested landscapes, compared with fire disturbed ones (Schroeder & Perera 2002). Other differences are tied to disturbance patch shapes, which are generally elliptical in wind driven fire events with unburnt islands, while harvest disturbances are straight edged non-elliptical shapes (McRae *et al.,* 2001).

Differences in the spatial patterns of fire and harvest disturbance can have important implications for the boreal forest ecosystem, through the influence of large-scale disturbances on the forest age and species composition, structure and spatial arrangement of forests (Bergeron *et al.,* 2001; Bouchard *et al.,* 2008; Cui & Perera 2008). When examined with deference to boreal forest watersheds, differences in spatial pattern could translate into differences in their hydrological effects, owing to the relationship between the extent and location of watershed disturbance and level of hydrological response (Abdelnour *et al.,* 2011; Bosch & Hewlett 1982; Carignan & Steedman 2000). Both peak flows and water yield have been found to increase with greater levels of watershed forest cover removal (Abdelnour *et al.,* 2011; Guillemette *et al.,* 2005; Putz *et al.,* 2003). Although, disturbance levels of 20% (Brown *et al.,* 2005; Buttle 2011; Stednick 1996) or 30% (Guillemette *et al.,* 2005; Kuraś *et al.,* 2012; Lin & Wei 2008) may be necessary for causing measurable increases in flow. The influence of watershed disturbance location is tied to the source areas of streamflow within watersheds (Bosch & Hewlett 1982), and the flow path distance between disturbed areas and the stream (Abdelnour *et al.,* 2011). Increased flow levels following watershed disturbance typically return to normal with the regrowth of vegetation (Putz *et al.,* 2003).

Fire as the dominant natural disturbance in the region has played a significant role in the development of Ontario's boreal forests (Arkle & Pilliod 2010; Flannigan *et al.,* 2005). Given the relationship between watershed disturbance and changes in stream hydrology (Abdelnour *et al.,* 2011; Bosch & Hewlett 1982; Carignan & Steedman 2000), this role would extend to the development boreal stream environments. Watershed disturbance can cause: changes in water quality (Nitschke 2005; Pinel-Alloul *et al.,* 2002; Putz *et al.,* 2003); increases in sedimentation (Kreutzweiser *et al.,* 2012; Waterloo *et al.,* 2007; Zhang & Wei 2012); increases in stream temperatures (Kreutzweiser *et al.,* 2012; Zhang & Wei 2012); changes in the timing, frequency, and magnitude of stream flows (Buttle & Metcalfe 2000; Zhang & Wei 2012); and increases in water yields (Bosch & Hewlett 1982; Brown *et al.,* 2005; Burton 1997; Putz *et al.,* 2003). All these hydrologic changes may have a number of negative effects on aquatic ecosystems and their biota (Burn *et al.,* 2008; Heicher 1993, as cited in Smakhtin 2001). On the other hand some changes in hydrology may have a positive effect; disturbances like fire can contribute to heterogeneity and natural patterns of diversity in aquatic ecosystems (Kreutzweiser *et al.,* 2012). As an example, larger peak flows can alter channel morphology, clean spawning sites, and create new ones (Tremblay *et al.,* 2008). Differences in the spatial patterns of disturbance by fire and harvest within watersheds could result in different successional regimes in the forest, and may affect natural forest hydrologic processes. Comparing the pattern and extent of fire and harvest disturbance within watersheds is a common theme in watershed disturbance studies (Moore & Richardson 2012; Schroeder & Perera 2002). Many point to limited research and the need to assess related questions at regional or landscape scales (Bowman & Boggs 2006; Lin & Wei 2008; Moore & Richardson 2012; Pickell, *et al* 2013; Richardson *et al.,* 2012; Vose *et al.,* 2011).

2.1.1 Objectives

The overall objective of this study is to compare the spatial pattern of watershed disturbance by fire and harvest at a landscape scale. Specifically I will address the question: at a landscape scale is the proportion of stand replacing disturbances within watersheds similar, when comparing natural disturbance to forest management? This question tests the hypothesis that forest management has resulted in spatial patterns of disturbance within watersheds similar to those resulting from fire. If natural disturbance patterns are maintained then natural forests processes, such as hydrological changes may be as well. Additionally I will evaluate the characteristics of harvested and burned watersheds to test if the disturbance types are selecting for different types of watersheds across the landscape.

2.2 Study Details

2.2.1 Study Area

This projects study area was located primarily within Ontario's Canadian Shield ecozone, with a small portion in the Hudson Bay Lowlands ecozone. The area selected extended from Ontario's western to eastern borders and included approximately 629 830 km^2 or 58.5% of Ontario's total area (Figure 1). The study area included Forest Management Units (FMU) within the Ministry of Natural Resources and Forestry's (MNFR) northeast and northwest regions, and a 100 km buffer around their limits. Buffering the northern FMUs allowed for the inclusion of some additional fire disturbed watersheds occurring just beyond the limits of the managed forest.

Ten separate ecoregions were included, in whole or in part, within the study area: 2E James Bay, 2W Northern Boreal, 3E Lake Abitibi, 3S Lake St. Joseph, 3W Lake Nipigon, 4E Lake Temagami, 4S Lake Wabigoon, 4W Thunder Bay, 5E Georgian Bay, and 5S Agassiz Clay Plain (Figure 2). Of these ecoregions nine occurred within the larger Canadian Shield ecozone, while 2E James Bay was part of the Hudson Bay Lowlands ecozone. Additionally, forty separate FMUs were wholly or partially located within the study area (Figure 2), in addition to a small section of crown land on the northwest shore of Lake Nipigon (Government of Ontario 2016).

Climate within the study area can be characterized as humid continental, excepting some areas with a more maritime climate influenced by Hudson Bay (Baldwin *et al.,* 2011). Temperatures in the region generally increase from north to south, with some modification by major water features and topography (Baldwin *et al.,* 2011; Burn *et al.,* 2008). Annual precipitation increases from the northwest to southeast of the study (Baldwin *et al.,* 2011). Summer precipitation appears to be more consistent across the study area, but continental high-pressure systems, which dominate its western portions, reduce precipitation in early to mid summer (Baldwin *et al.,* 2011). Notably there is a trend toward greater amounts of time spent in a water deficit state toward the extreme west and north of the study area; excepting a few small pockets, comparatively long periods of water deficit are not evident travelling eastward through the study area (Baldwin *et al.,* 2011).

Active fire suppression in Ontario has increased over the last 50 years, particularly with the use of water bomber aircraft beginning in 1970, which has reduced the annual frequency and area burned by fires (Bergeron *et al.,* 2001; Bergeron *et al.,* 2004; McRae *et al.,* 2001). Efforts have been concentrated and most effective in more southerly regions, where fire poses the greatest risk to the public, infrastructure, and timber resources (Girardin *et al.,* 2006; McRae *et al.,* 2001). Ontario's fire management zones reflect the level of suppression effort and are described from north to south as extensive, measured, and intensive (Bridge *et al.,* 2005).

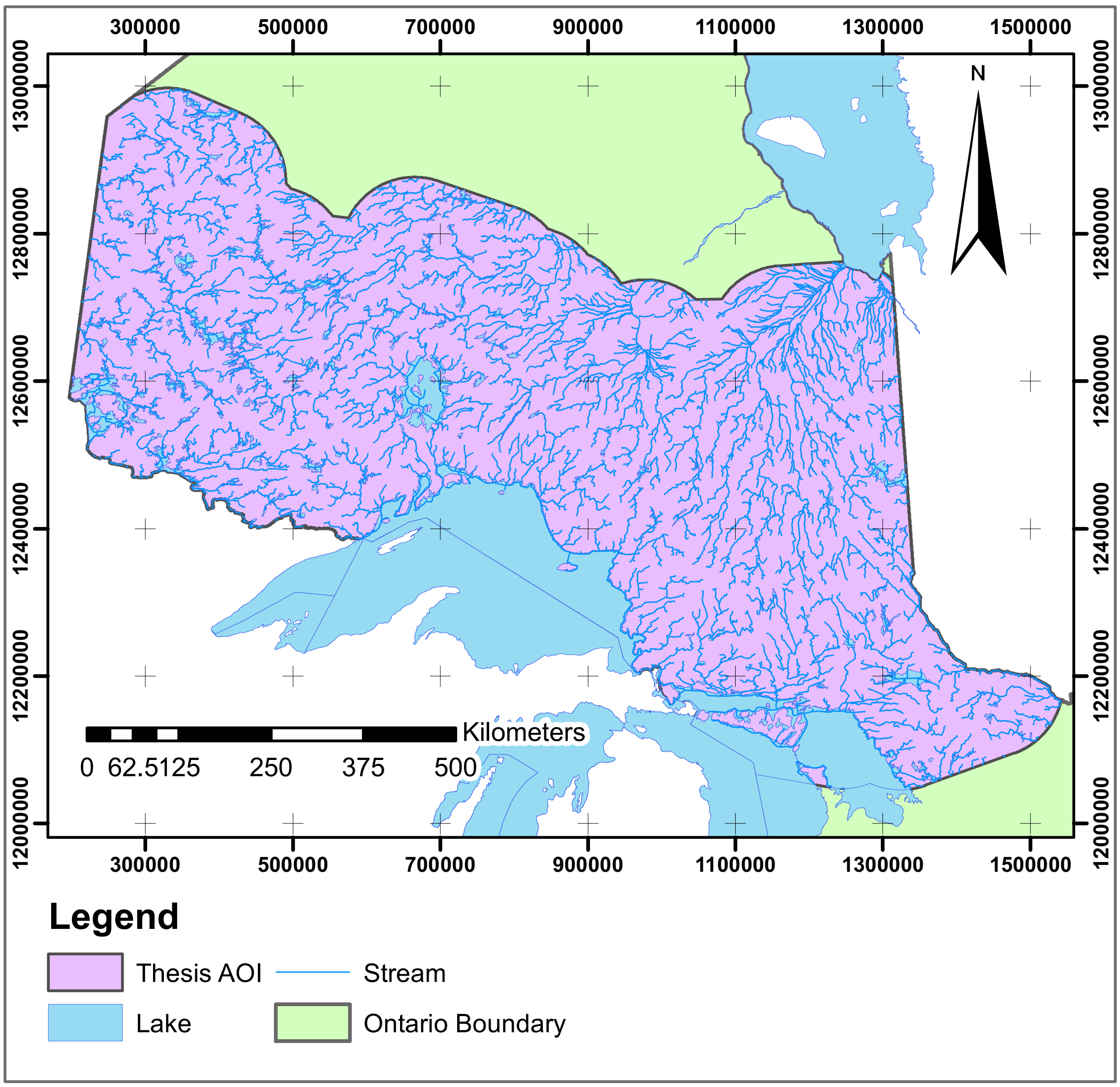

Figure 1: Overview map of study area showing provincial boundaries and large-scale water features.

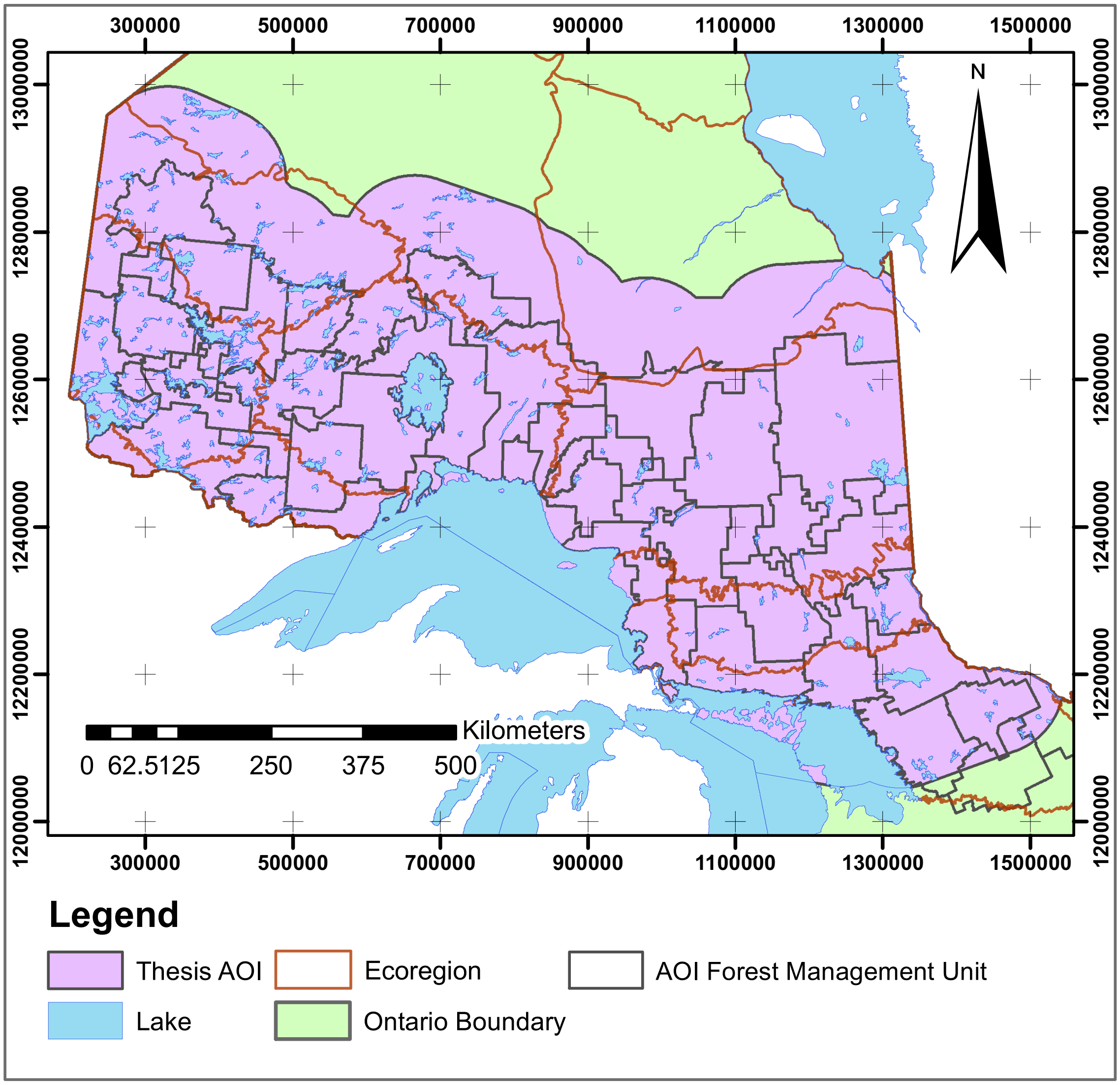

Figure 2: Overview map of study area showing ecoregion and FMU boundaries.

2.2.2 Study Disturbance Records

Study disturbance records used in this study were sourced from Ontario's Forest Resource Inventory (FRI) geospatial data. Study fire records were collected as part of Ontario's FRI natural disturbance mapping and harvest data included Ontario's FRI annual reporting (pers. comm., Larry Watkins, forest analyst MNRF). Raw fire disturbance geospatial data included mapped fires >40 ha in area from 1960-2013 (1 846 records); fires <40 ha were not digitized. Raw harvest disturbance geospatial data was compiled from two overlapping datasets described as Harvest-Estimate and Harvest-All, covering the years 1990-2003 and 2002-2012, and including 93453 and 147807 records respectively.

Raw geospatial fire and harvest data were filtered by location, time period, and disturbance type, using the Environmental Systems Research Institutes' (ESRI) Geographic Information System (GIS) software ArcGIS. This was done in order to select a subset of the disturbance records that were: within the study area, during the greatest period of temporal overlap between the datasets, and included only clearcut harvests, as partial or selective harvest systems were viewed to be innately different than fire. Filtering reduced the 1 846 records of fire disturbance to 320 records within the study area, during the 1990-2009 period, and overlapping study watersheds (Figure 3). The two sets of harvest data were combined before being filtered to include 62 799 records of harvest disturbance within the study area during the 1990-2009 time period, that overlapped study watersheds and were conducted using clearcut silviculture systems (Figure 3).

The use and combination of the two harvest disturbance datasets revealed both a two-year overlap of their records (2002-2003) and a number of errors in the geospatial data. Errors were most prevalent in the overlapped years and during those immediately before and after (2001-2004). For a more detailed description of the study error correction methods, as well as examples of the types of errors encountered see Appendix A. Fire disturbance records employed in the study also suffered from limitations.

Spatial and historic records of fire disturbance have been widely used to characterize fire regimes, however, there are a number of issues and limitations in these records. For one, in Ontario fires <40 hectares in area are generally not spatially represented. Fires below this threshold likely do not significantly contribute to annual area burned, particularly as fires >200 hectares represent a small percentage of total fires but account for ~97% of area burned in Canada (Girardin *et al.,* 2006). These small fires do however represent a significant percentage of total fire number. Provincial records from 1976 to 1990 included 21176 fires <10 hectares in the intensive and measured protection zones (Bridge *et al.,* 2005). Other issues arise from the digitization of fire records reflecting inconsistencies in digitization methods; older fires digitized by hand are generally less accurate than newer fires digitized after the advent of satellite imagery and GPS (Bridge *et al.,* 2005), leading to variability in fire data quality over space and time (Girardin *et al.,* 2006).

The filtered geospatial records of fire and harvest disturbance were then combined to provide a complete record of disturbances within the study area during the 1990-2009 period. Attribute fields were included in the combined record describing the disturbance type, year, source area, and area. Combined disturbance records were then split into four 5-year subsets (*i.e.* 1990-1994, 1995-1999, 2000-2004, and 2005-2009) for later use in analysis of watershed and shoreline riparian disturbance. The 5-year period is reflective of the revision period for forest management guides set up in the EAA, in order to ensure management practices are reviewed and reflective of current scientific knowledge (EAA 1990; OMNR 2010).

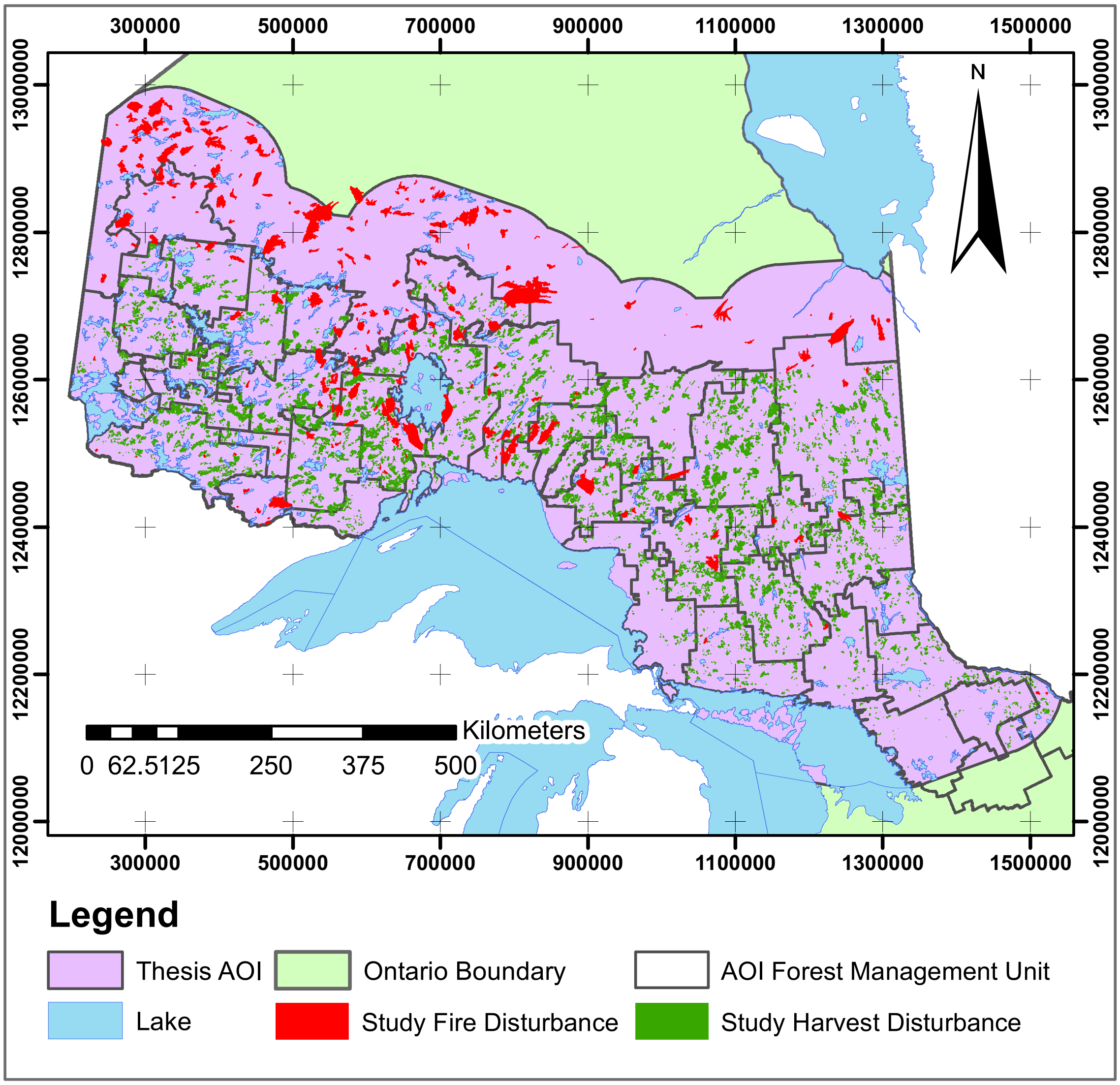

Figure 3: Overview map of fire and harvest disturbance records within the study area.

2.3 Methodology

2.3.1 Watersheds and Hydrology

Watersheds were delineated using Hydrology Tools in the Spatial Analyst extension of ArcGIS software (ESRI v10), along with a variety of geospatial data as inputs to delineate all 30 km^2 (±20% area) watersheds in Ontario. A catchment area of 30 km^2 will support fish populations year round while the ±20% range in areas increased the total number of watersheds available for analysis. Input data included an Enhanced Flow Direction Grid (EFDIR), along with Ontario Integrated Hydrology (OIH) watercourse and Ontario Hydrologic Network (OHN) water body shapefiles. The EFDIR is an updated D8 flow direction grid that incorporates mapped hydrologic features (e.g. lakes and streams) and flow directions from a Digital Elevation Model (DEM) created using methods described in Kenny and Matthews (2005), and sourced from OIH data. The Select by Location tool was used to filter the delineated watersheds include only those within the study area, resulting in 4933 watersheds for analysis (Figure 4). A unique ID field was added to separately identify each study watershed. All geospatial data required or produced during the watershed study methodology are briefly described along with their source in Table 1.

Descriptive attribute fields were added to the study watersheds in order to characterize disturbed watersheds. Hydrologic characteristics were included to assess the potential for hydrologic change; specifically the factors were stream, lake, and wetland density within the watershed. Higher drainage ratios have been associated with greater potential for stream flow change following disturbance, drainage ratios in stream-dominated watersheds are generally greater than in lake dominated (Luke *et al.,* 2007; Pinel-Alloul *et al.,* 2002). Hydrologic characteristics were calculated by combining lake, stream, and wetland shapefiles with the study watersheds using the Intersect tool (Figure 5). Watershed topographic characteristics were also added to study watershed attribute table; these included watershed mean elevation (metres above sea level, m.a.s.l.), range in elevation (m), and roughness (coefficient of variation for elevation points within the watershed). Watershed topography can influence both fire and harvest activity, respectively by influencing fuel moisture and affecting accessibility by harvest equipment (McRae *et al.,* 2001). Additionally topography influences the location of hydrologically sensitive areas, such as convergent slopes with high upslope contributing area (Buttle 2002; Jencso *et al.,* 2009). These factors were calculated using the Zonal Statistics tool in the Spatial Analyst extension, using the DEM and study watersheds as inputs. Easting and northing values for the centroid of each study watershed were included using the Add and Calculate field tools. The geographic position of the study watersheds will influence both the climate conditions they experience (Baldwin *et al.,* 2011), and the level of fire suppression they undergo, with the greatest efforts concentrated toward the south of the study area (Bridge *et al.,* 2005; Girardin *et al.,* 2006; McRae *et al.,* 2001).

Table 1: Descriptions and sources of GIS data employed and produced in the watershed methodology.

Data Name	Source	Data Description
Watercourse	OIH	Enhanced watercourse/stream shapefile covering Ontario (MNRF 2015).
DEM	OIH	Stream enforced digital elevation model, 30 m resolution continuous for Ontario (MNRF 2015).
EFDIR	OIH	Enhanced flow direction grid, covering Ontario (MNRF 2015).
Waterbody	OHN	Waterbody/lake shapefile covering Ontario (MNRF 2013a).
Wetland	LIO	Wetland shapefile covering Ontario (MNRF 2013b)
Fire and Harvest Disturbance Records	FRI	Records of fire and harvest disturbance within the study area sourced from FRI natural disturbance mapping and annual reporting by forest management companies
Study watersheds	Generated	4933 watershed records within the study AOI generate through study methodology
Intersect watersheds	Generated	Study watersheds with lake areas erased from their extent for intersection with study disturbance records
Watershed disturbance	Generated	Results of intersections between study FRI disturbance records and the intersect watersheds during all four study time periods

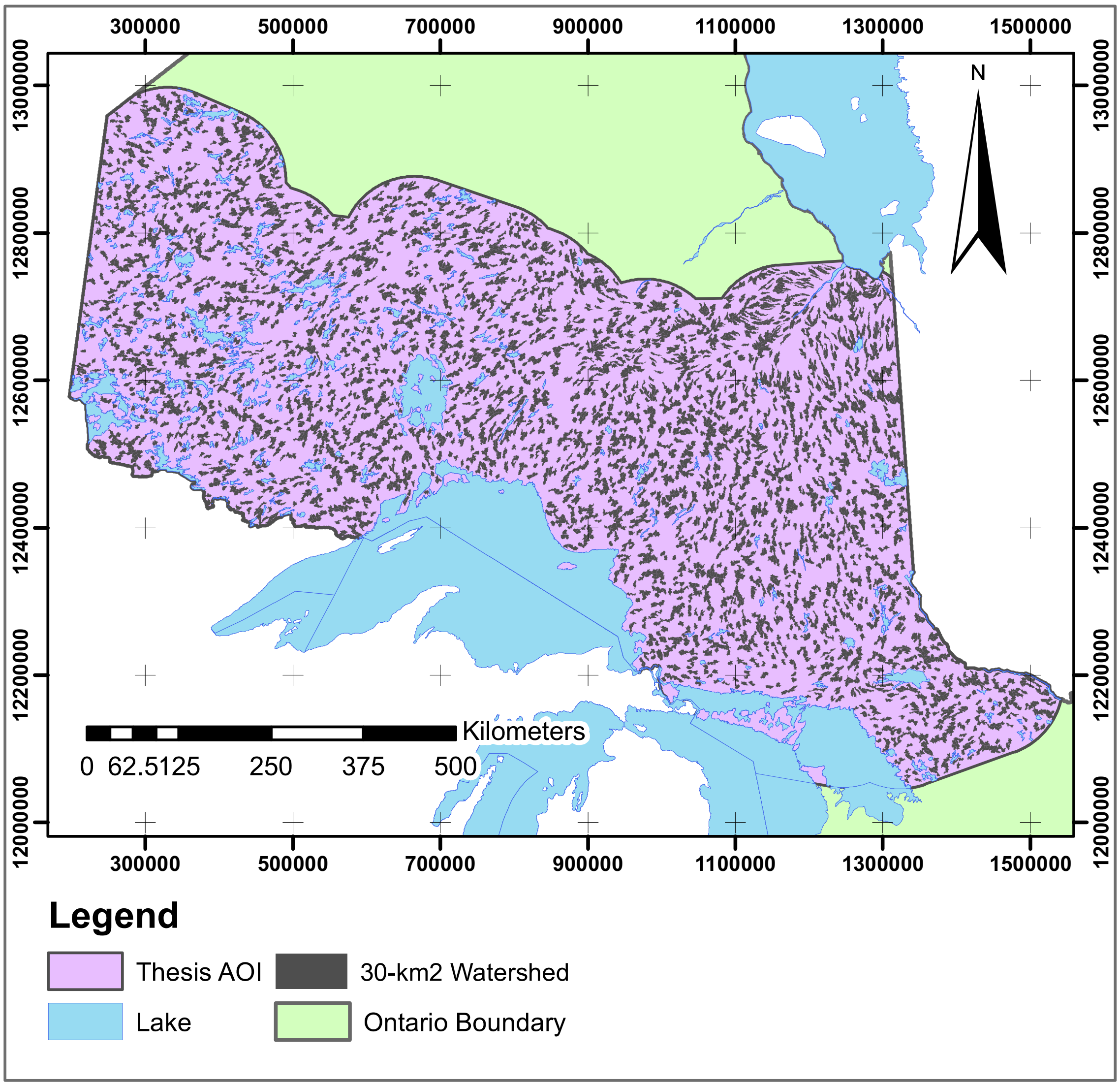

Figure 4: Overview map of study watersheds with the study AOI.

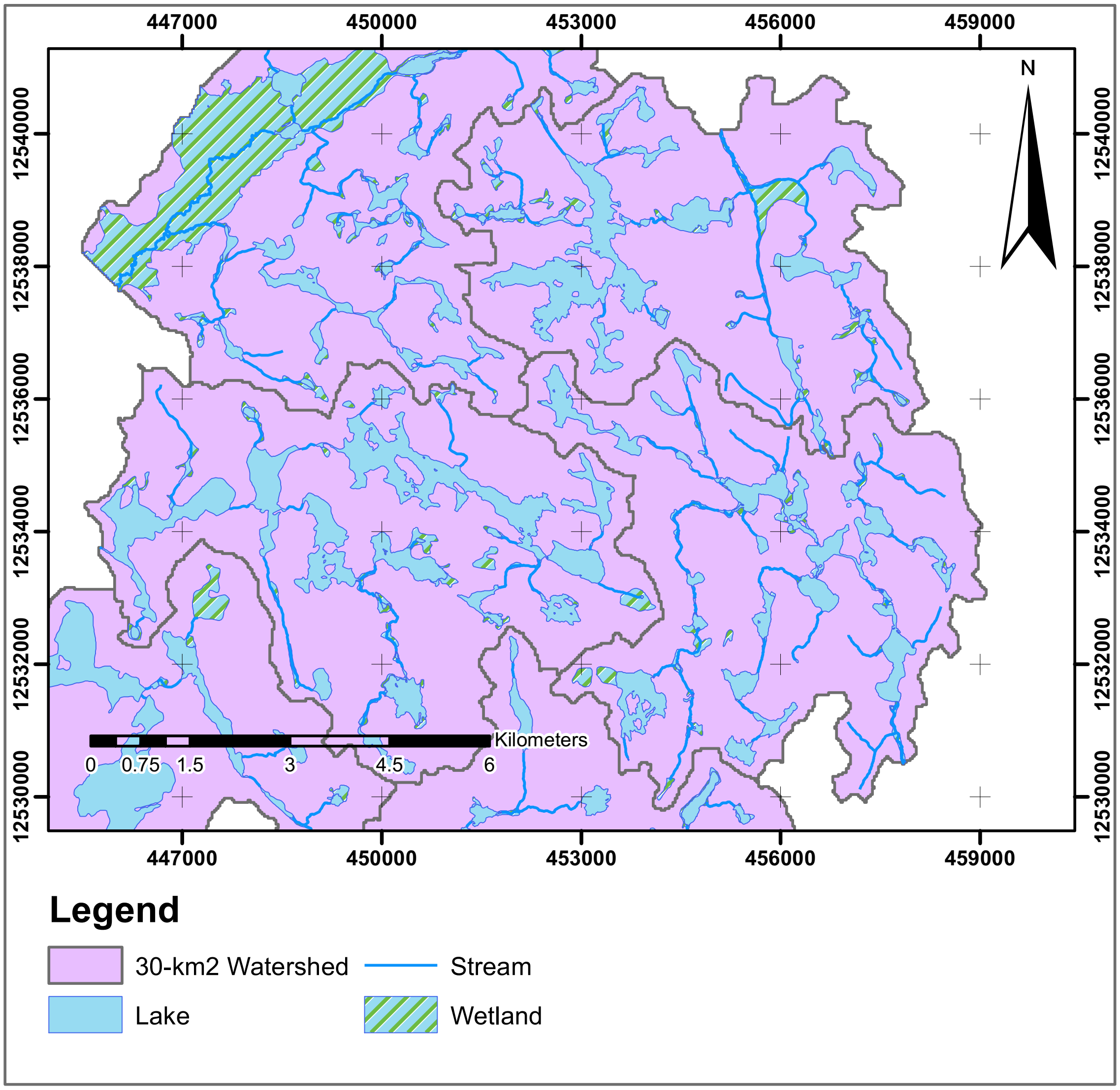

Figure 5: Sample study watersheds showing intersected watercourses, water bodies and wetlands. Numerous watersheds are depicted, with their limits denoted by the dark grey lines in the figure.

2.3.2 Watershed Disturbance

The extent of disturbance within watersheds was calculated by combining spatial information on disturbance by fire and harvest with watershed boundaries using the Intersect tool in the Analysis extension (Figures 6 & 7). Prior to these intersects lake areas within the study watersheds removed using the Erase tool, so that water feature areas could not be counted as disturbed land area. Attribute tables resulting from these intersections were output to Microsoft Access. To summarize the data into a single record per study watershed, and describe various aspects of how each watershed was disturbed, watershed disturbance records for each time period were subjected to successive queries in Access. Fields were added to describe the disturbance category of each study watershed for each time period (e.g. no disturbance, both types, fire, or harvest), along with characteristics of the disturbance's spatial pattern including: the number of years with disturbance, the number of disturbance patches, the percentage of watershed land area disturbed, and the perimeter to area ratio of the disturbance. Two separate datasets were produced for each of the four time periods. The first described percentages of study watersheds within each disturbance category, along with the percentage of fire and harvest disturbed watersheds that underwent disturbance in multiple years of the time period. The second was developed for statistical analysis using the IBM Statistical Package for the Social Sciences (SPSS v23). It included study watersheds experiencing only fire or harvest disturbance during the period, and described: the number of years with disturbance, the number of disturbance patches, the percentage of watershed land area disturbed, and the perimeter to area ratio of the disturbance.

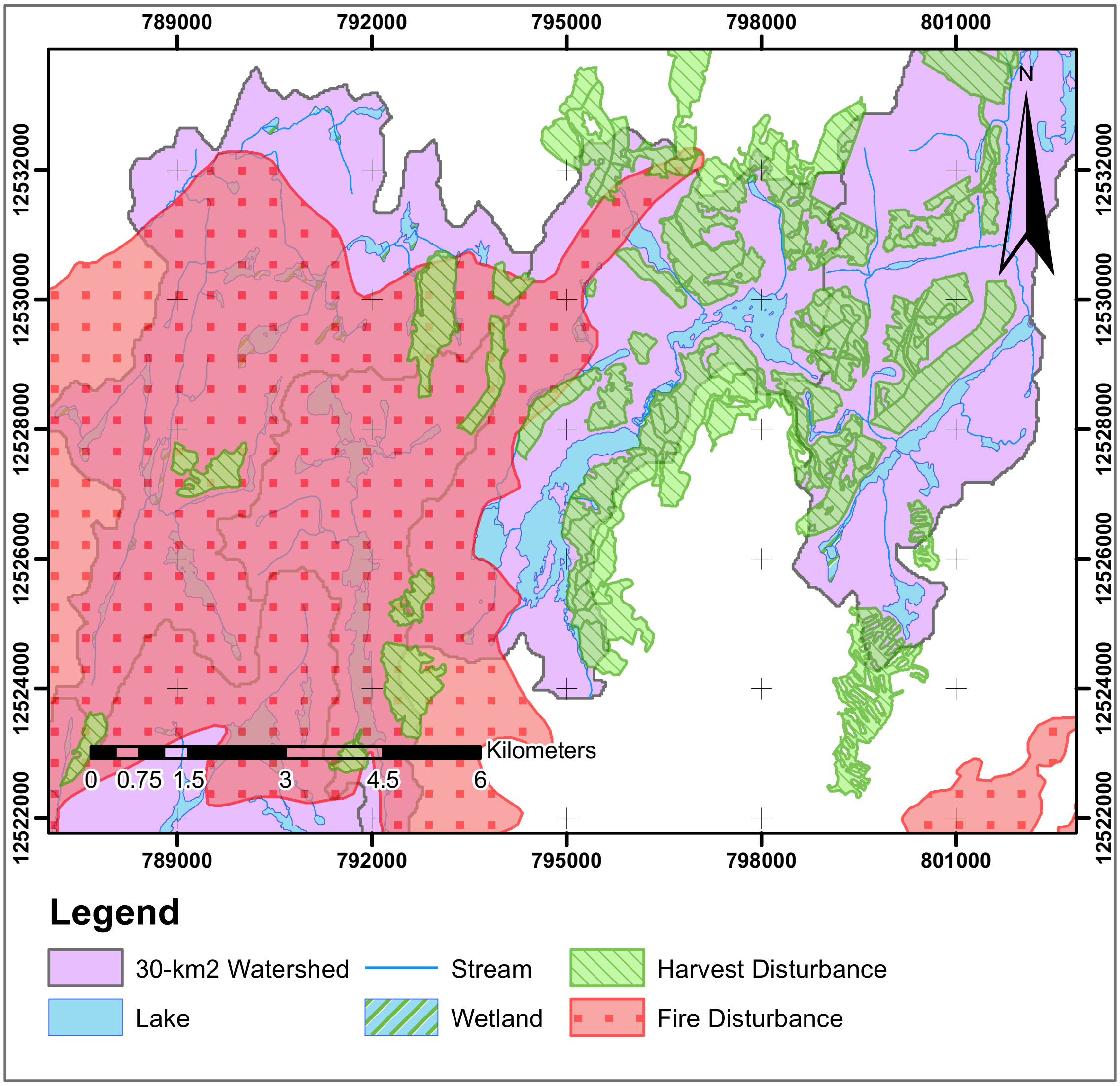

Figure 6: Sample fire and harvest disturbances overlapping study watersheds.

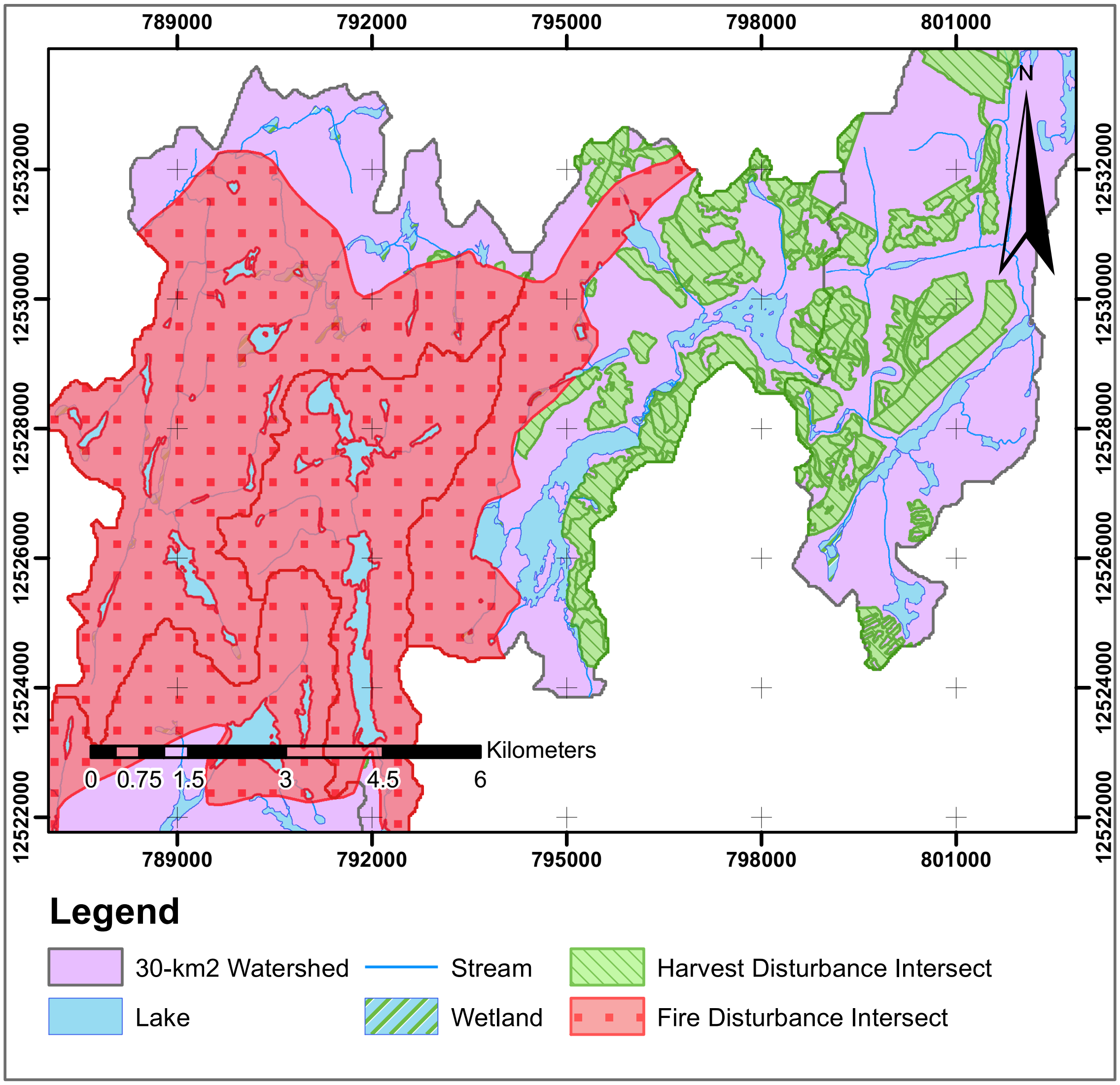

Figure 7: Sample fire and harvest disturbances intersected with study watersheds.

2.3.4 Watershed Analysis

Fire and harvest disturbance within watersheds were compared during each study time period using metrics, which collectively described the spatial pattern of each disturbance type across the landscape. The metrics included: the prevalence of each disturbance type, the median levels of disturbance and disturbance variability within watersheds, the landscape pattern of watershed disturbance, and the characteristics of disturbed watersheds. To determine appropriate statistical procedures for analysis watershed disturbance metrics were assessed for normality using Shapiro-Wilk testing and visual inspection of their histograms. For both fire and harvest disturbance during all study time periods the metrics describing watershed disturbance characteristics including, disturbance years, disturbance patches, percentage land area disturbed, and disturbance perimeter to area ratio, were all assessed as non-normal $p < 0.01$. Disturbed watershed characteristics (hydrologic, topographic, and geographic) were also assessed as non-normal during all periods $p < 0.05$; excepting stream density within fire disturbed watersheds during the 2005-2009 period where $p = 0.061$. Employing non-normal data for statistical analyses required that non-parametric procedures be employed for all hypothesis testing (Lin & Wei 2008), although in some instances trends in the data were examined using parametric statistics.

The prevalence of the disturbance types was assessed as the percentage of the total number of watersheds that experience each disturbance type. During each time period the percentage of watersheds within each disturbance category (Fire, Harvest, Both, None) were calculated and compared. For watersheds with a single disturbance type (Fire or Harvest) during a time period additional comparisons were made examining the percentage of harvest-disturbed watersheds with harvests occurring in multiple years of the period to the percentage of fire-disturbed watersheds with fires occurring in multiple years.

Median levels of disturbance were compared between watersheds that experienced only fire or harvest disturbance during a time period using the Mann-Whitney U test. This is a non-parametric test rank sum test that measures significant differences in the median values between groups (Pickell *et al.,* 2013). A number of metrics were compared to characterize differences in the spatial pattern of each disturbance type within watersheds including: the number of years of the period where disturbance occurred, the resulting number of disturbance patches, the total percentage of watershed land area disturbed, and the watershed disturbance perimeter to area ratio.

The landscape pattern of watershed disturbance was assessed using the percentage of watershed land area disturbed metric and Kolmogorov-Smirnov (KS) two sample testing. This is a non-parametric test that measures statistical differences in the cumulative distribution functions between groups (Pickell *et al.,* 2013; Young 1977). During each study time period the cumulative distributions for percentage of watershed land area disturbed were compared within single disturbance type watersheds, using visual inspection of their cumulative frequency distributions and KS testing. Testing was completed for the landscape as a whole and repeated within individual ecoregions.

Disturbed watersheds during each study time period were assessed to determine if particular watershed characteristics were associated with fire or harvest disturbance. Characteristics examined include geographic (centroid easting and northing), hydrologic (stream, lake, and wetland density), and topographic (average and range of elevation, roughness) information on each study watersheds. Principle Components Analysis (PCA) was used to visually represent differences in the disturbed watersheds in terms of assorted combinations of these variables. Discriminant Function Analysis (DFA) was used to statistically test for differences in the watershed characteristics between the two disturbance types.

2.4 Results

2.4.1 Prevalence of Watershed Disturbance

Harvest disturbance affected a greater percentage of the study watersheds than fire during all study time periods (Table 2). Most watersheds were not disturbed during a given time period, ranging from 62.05 to 69.93% of the 4933 study watersheds. Harvest disturbance prevalence varied between 28.20 to 31.79% of the watersheds among time periods, with >30% of watersheds affected during three of the four time periods. Fire disturbance was far less common, affecting 4.09% of watersheds during the 1995-1999 period, and only 1.62 to 1.84% during the remaining periods. Watersheds undergoing both disturbance types were the least common occurring in only 0.20 to 0.62% of study watersheds during three time periods, and 2.13% during the 1995-1999 period, when fire was more common.

As well as being more prevalent, harvest disturbance within a watershed occurred more frequently within time periods than disturbance by fire (Table 2). Between 48.02 and 56.36% of the harvest affected watersheds had harvest occurring in multiple years of a study time period. During three time periods >54.9% of harvested watersheds had harvest occur in multiple years. Comparatively, the percentage of watersheds with fire disturbance occurring in multiple years within a time period was far lower, between 1.49 and 5.49% from 1990-2004, and 0.0% in 2005-2009.

Table 2: Prevalence of watershed disturbance by time period, and percentage of watersheds with disturbance in multiple years.

Time Period	Disturbance Category	Watershed Disturbance		Disturbance in Multiple Years	
		Count	Percentage of Total Watersheds	Count	Percentage of Disturbed Watersheds
1990-1994	None	3325	67.40	n/a	n/a
	Both	10	0.20	n/a	n/a
	Fire	91	1.84	5	5.49
	Harvest	1507	30.55	848	56.27
1995-1999	None	3061	62.05	n/a	n/a
	Both	105	2.13	n/a	n/a
	Fire	202	4.09	3	1.49
	Harvest	1565	31.73	882	56.36
2000-2004	None	3253	65.94	n/a	n/a
	Both	30	0.61	n/a	n/a
	Fire	82	1.66	3	3.66
	Harvest	1568	31.79	862	54.97
2005-2009	None	3435	69.63	n/a	n/a
	Both	27	0.55	n/a	n/a
	Fire	80	1.62	0	0.00
	Harvest	1391	28.20	668	48.02

2.4.2 Extent of Watershed Disturbance

Median levels of watershed disturbance, including the number of years of each period with disturbance, the number of disturbance patches, the percentage of watershed land area disturbed, and the perimeter to area ratio of the disturbance, by fire and harvest were significantly different during all study time periods (Table 3). Harvest disturbed watersheds had a significantly greater median number of disturbed years than fire, this metric was also more variable in harvest over fire disturbed watersheds as indicated by their respective interquartile ranges (IQRs) (Table 3). Differences between the disturbance types are clearly evident in boxplots of this metric (Figure 8), but are most pronounced during the three periods covering 1990-2004, where harvest resulted in a median value of 2 years and a IQR of 2, compared with fire (median = 1, IQR = 0) (Table 3, Figure 8). The two types were also significantly different during the 2005-2009 period despite both resulting in a median value of 1 disturbance year; differences between the types were attributed to the greater variability of harvest (IQR = 1) over fire (IQR = n/a) (Table 3, Figure 8).

Harvest disturbed watersheds had a significantly greater median number of disturbance patches than fire disturbed watersheds during all study time periods (Table 3, Figure 9). During corresponding time periods the median number of disturbance patches within harvested watersheds was between 3.5 and 8.7 times greater than patch counts resulting from fire (Table 3). Patch counts in harvested watersheds were also far more variable than in fire disturbed watersheds, with IQR values between 4.7 and 13 times greater than fire during corresponding time periods (Table 3, Figure 9).

Table 3: Mann-Whitney U results and significance values comparing median watershed disturbance by fire and harvest in each study time period.

Test Statistic	Disturbance Descriptor	Time Period	Fire		Harvest		Mann-Whitney U	p value
			Median	IQR	Median	IQR		
Mann-Whitney U	Years with disturbance during time period	1990-1994	1	0	2	2	104467.5	< 0.01
		1995-1999	1	0	2	2	245437	< 0.01
		2000-2004	1	0	2	2	97890	< 0.01
		2005-2009	1	n/a	1	1	83360	< 0.01
Mann-Whitney U	Number of disturbance patches during time period	1990-1994	2	3	7	14	101910	< 0.01
		1995-1999	2	3	9	16	251808	< 0.01
		2000-2004	1.5	2	13	26	114668.5	< 0.01
		2005-2009	2.5	5	13	25	90933.5	< 0.01
Mann-Whitney U	Percentage of watershed land area disturbed during time period	1990-1994	16.72	36.69	2.93	7.42	28905	< 0.01
		1995-1999	9.97	34.36	3.47	7.72	101062	< 0.01
		2000-2004	14.05	33.90	4.00	7.22	45061	< 0.01
		2005-2009	7.98	31.92	2.97	5.80	35875	< 0.01
Mann-Whitney U	Disturbance perimeter to area ratio during time period	1990-1994	4.15	3.65	16.76	11.38	125393	< 0.01
		1995-1999	5.48	6.90	16.77	10.23	269461	< 0.01
		2000-2004	4.78	6.19	19.56	10.22	110743	< 0.01
		2005-2009	6.57	5.87	22.89	9.90	99990	< 0.01

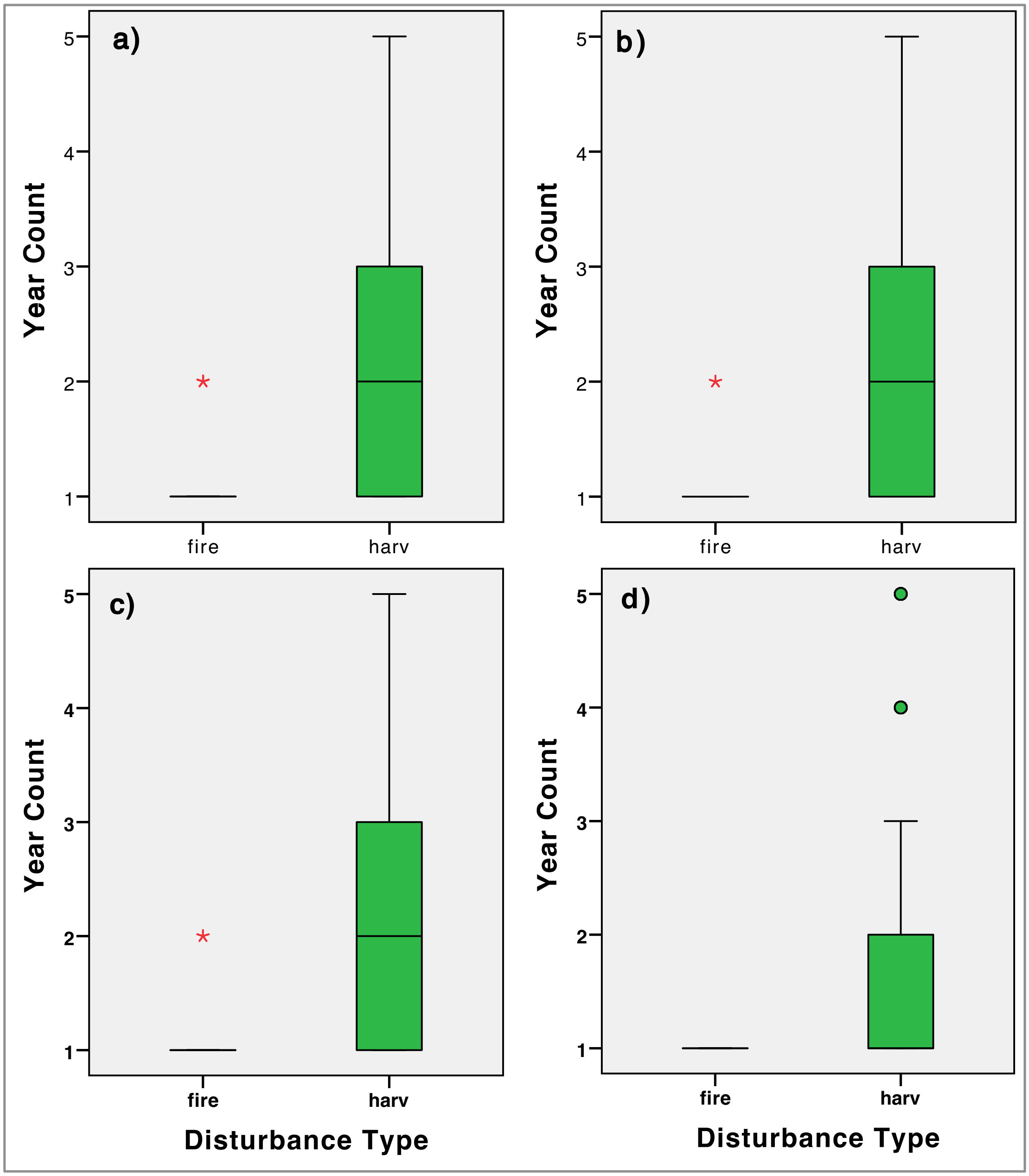

Figure 8: Boxplots depicting disturbed year counts for watersheds with a single watershed disturbance type. Subfigures represent study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. The horizontal line represents median year count. Boxes represent the IQR; whiskers represent 1.5 times the IQR from the first and third quartile; hollow circles represent outlier data, and stars represent extreme outliers.

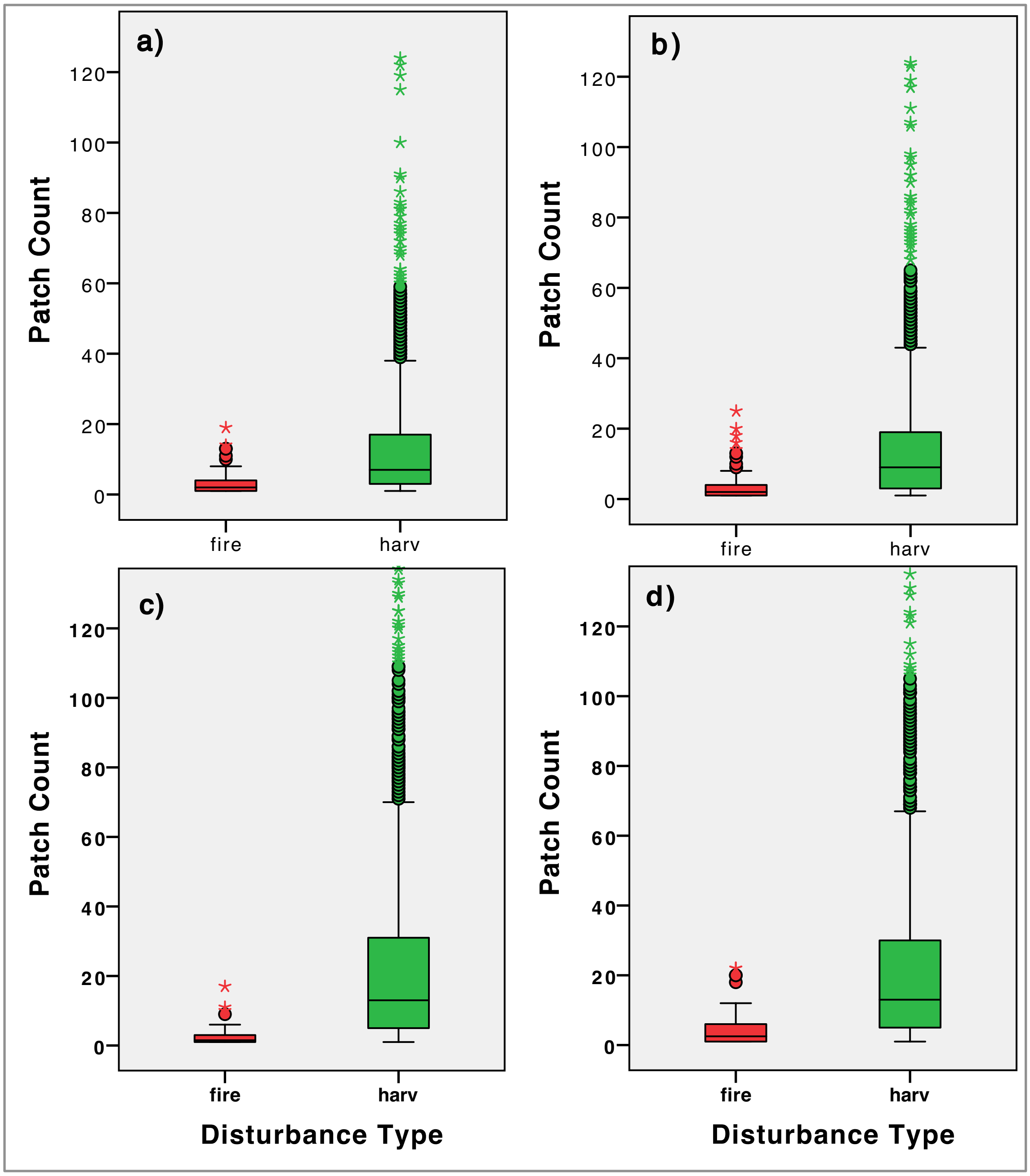

Figure 9: Boxplots depicting disturbance patch count for watersheds with a single disturbance type. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Patch count axis truncated to better view the disturbance IQR's, number of extreme outliers removed from figure: a) 4 harvest, b) 14 harvest, c) 52 harvest, d) 5 harvest. Boxplot elements are described in Figure 8.

Fire disturbance affected a significantly greater median percentage of watershed land area than harvest during all study time periods (Table 3, Figure 10). During corresponding periods the median percentage of land area disturbed by fire was between 2.7 and 5.7 times greater than in harvested watersheds (Table 3). Fire disturbance was also far more variable in its s, with IQRs during corresponding periods between 4.5 and 5.5 times greater than those resulting from harvest (Table 3). The difference between the types is evident when they are plotted together, where fire includes a wide range of disturbance percentages harvest is concentrated almost entirely below 20% land area disturbed (Figure 10).

Harvest occurring within the study watersheds was more complex in shape, with median perimeter to area ratios significantly greater than fire during all study time periods (Table 3, Figure 11). Median values for this metric were between 3 and 4.1 times greater in harvested watersheds over fire during corresponding periods (Table 3). This ratio was also far more variable in harvest disturbed watersheds, with IQR values between 1.6 and 3.1 times greater than fire, and a large number of outlying values well beyond the limits of fire (Figure 11).

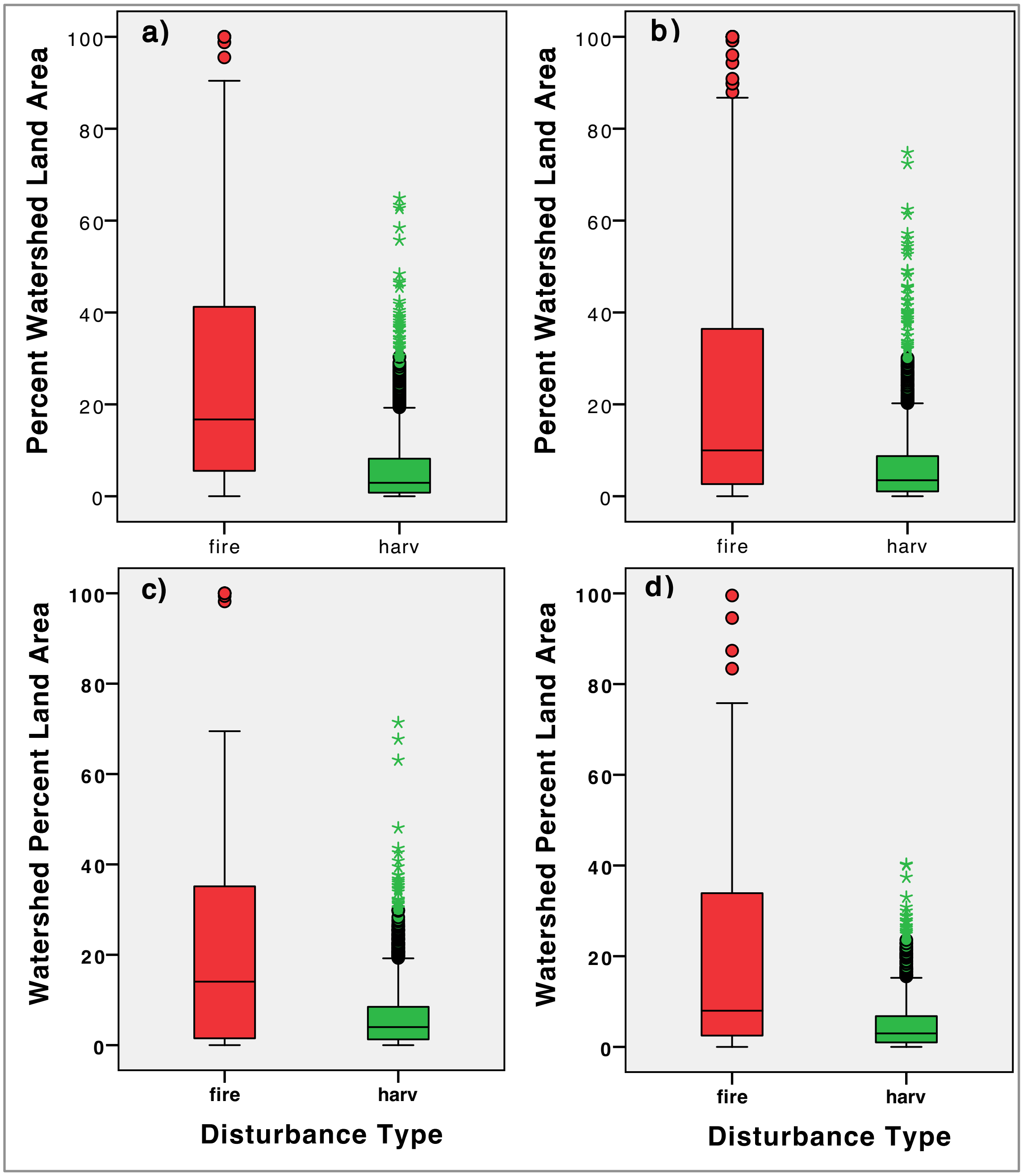

Figure 10: Boxplots depicting the percentage of watershed land area disturbed in single disturbance type watersheds. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Boxplot elements are described in Figure 10.

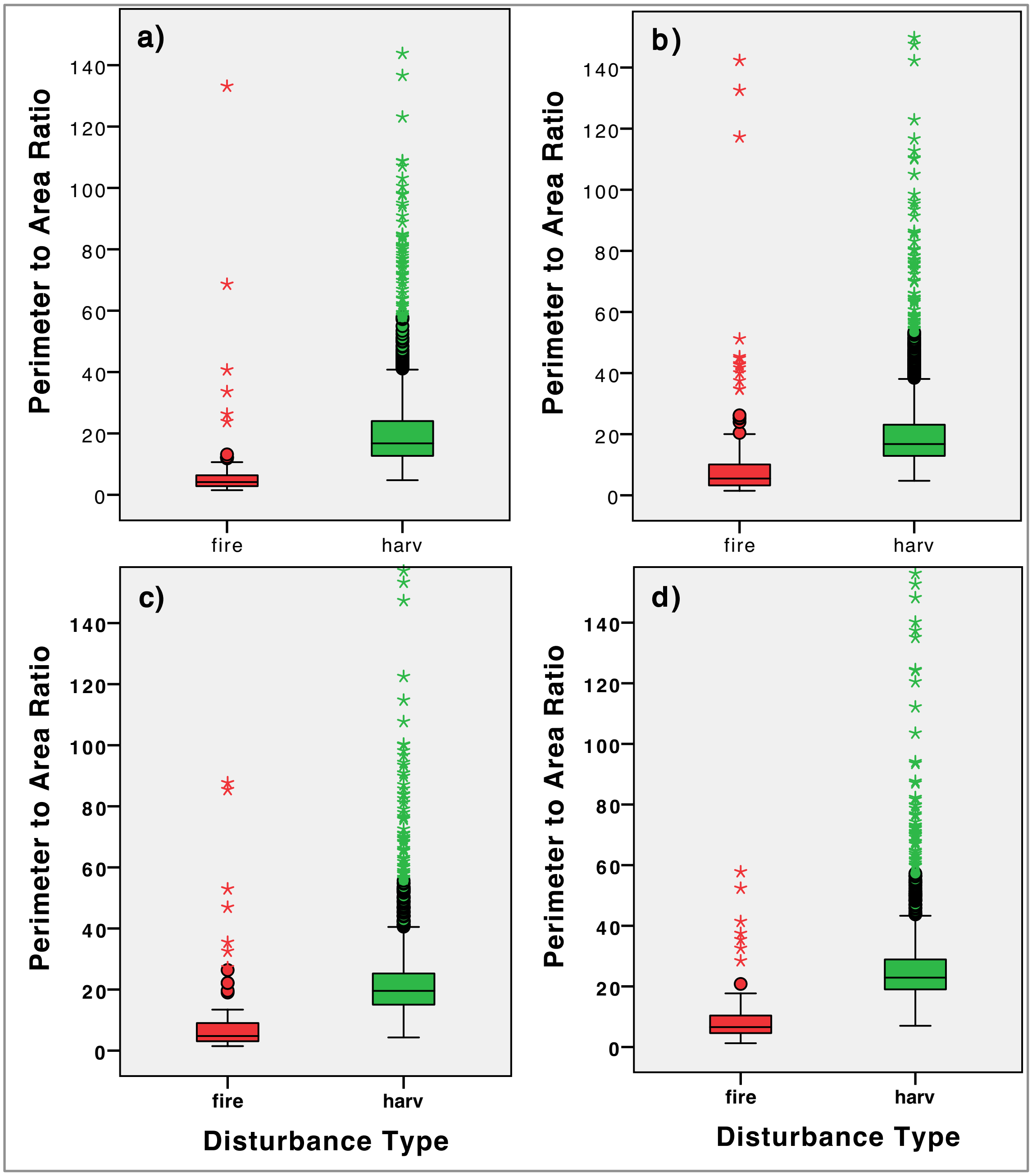

Figure 11: Boxplots depicting the perimeter to area ratio for watersheds with a single disturbance type. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Perimeter to area ratio axis truncated to better view disturbance IQR's, number of extreme outliers removed from figure: a) 1 fire 14 harvest, b) 3 fire 13 harvest, c) 1 fire 14 harvest, d) 1 fire 8 harvest. Boxplot elements are described in Figure 10.

2.4.3 Landscape Pattern of Watershed Disturbance

At a landscape scale, fire and harvest disturbance within watersheds resulted in significantly different landscape patterns of disturbance based on the frequency distributions of percent land area disturbed (Table 4). Fire disturbed watersheds across a wide range of percentages, including watersheds disturbed in <=10% of their land area, ranging up to and including 100% watershed land area (Figures 12 & 13). Contrasting this, harvest disturbance, while far more frequent than fire, most commonly resulted in a <=10% disturbance level (Figs. 12 & 13). Resultantly, the cumulative percent frequency distributions differed between the types, with fire gradually approaching its maximum as the disturbance percentage approaches 100% land area, whereas harvest almost immediately maxes out due to the large number of watersheds (>1000) disturbed in <=10% land area (Figs. 12 & 13). The spatial patterns for each disturbance type were generally consistent, regardless of the study time period examined. The results of KS tests comparing the landscape pattern of watershed disturbance within each ecoregion included in the study area can be found in Appendix B.

Table 4: KS test statistics for comparisons of the frequency distributions of percent watershed area disturbed by fire and harvest within the full study area, during each study time period.

Time Period	Num. Fire	Num. Harvest	Abs. Difference	Test Statistic	p value
1990-1994	91	1507	0.461	4.271	**< 0.001**
1995-1999	202	1565	0.337	4.508	**< 0.001**
2000-2004	82	1568	0.386	3.407	**< 0.001**
2005-2009	80	1391	0.32	2.785	**< 0.001**

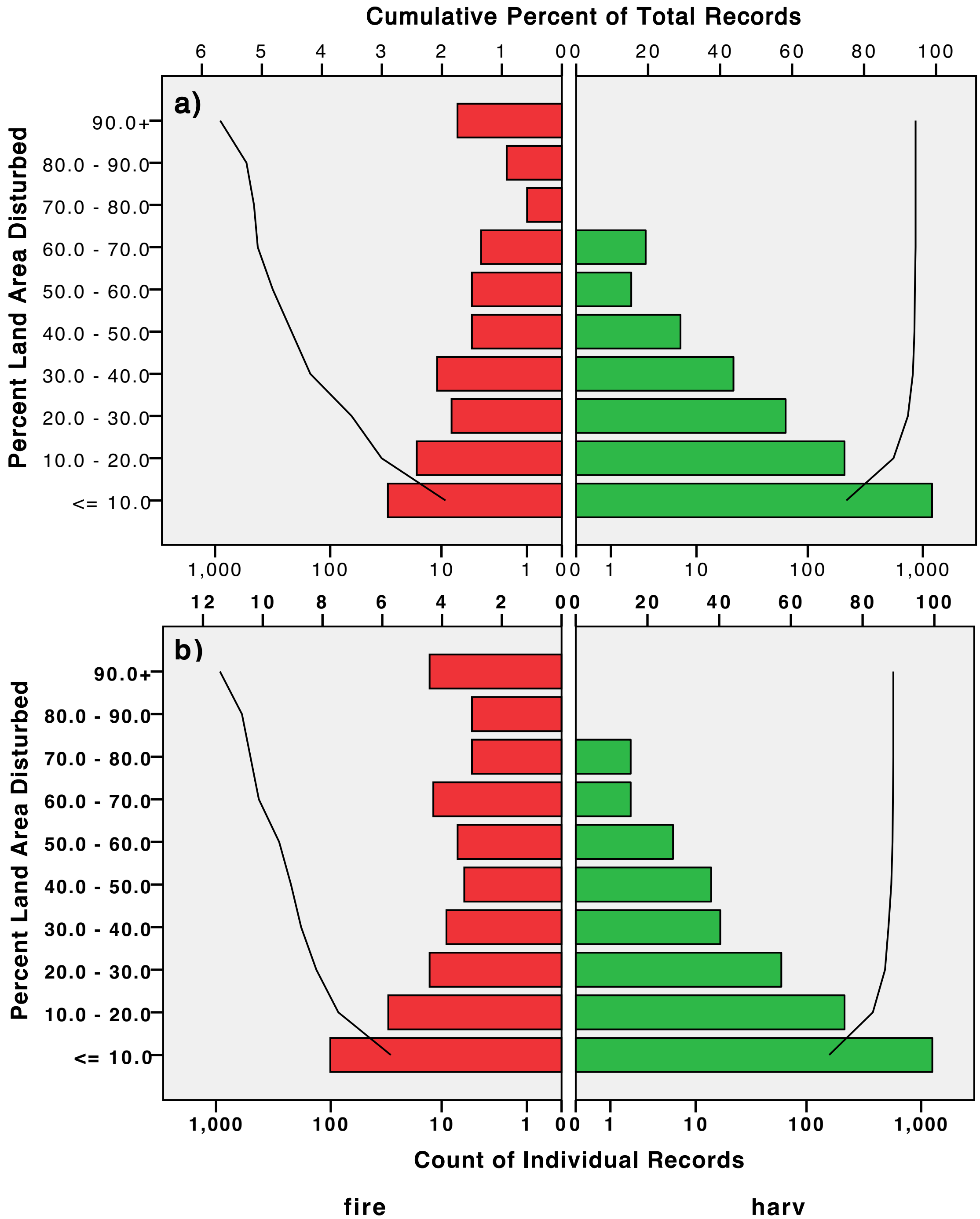

Figure 12: Frequency distributions and cumulative percent frequency distributions of the percent land area disturbed by fire and harvest within watersheds for study time periods a) 1990-1994, b) 1995-1999.

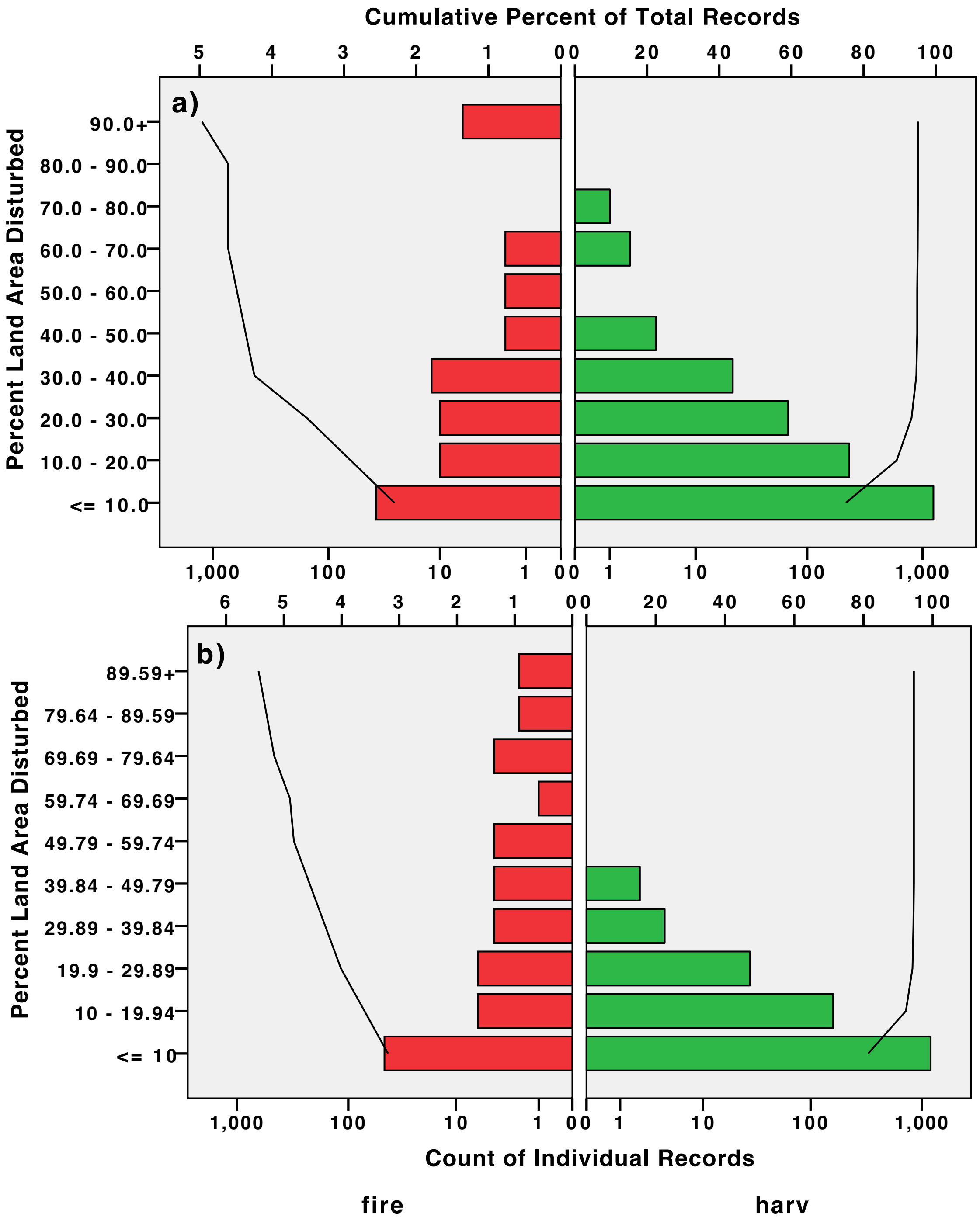

Figure 13: Frequency distributions and cumulative percent frequency distributions of the percent land area disturbed by fire and harvest within watersheds for study time periods a) 2000-2004, b) 2005-2009.

2.4.4 Characteristics of Disturbed Watersheds

The characteristics of disturbed watersheds, when summarized by PCA showed similar patterns during each study time period. The first two components generated by PCA summarized between 57.1 and 58.3% of the variability among the watersheds. The watershed characteristics with the strongest influence on component scores were generally the same across all the study time periods, with a few exceptions. The first component represented a gradient between watersheds with a large variability in topography, and higher drainage density in the southern and eastern parts of the study area, on the positive end, and watersheds with less topographic variability and lower stream drainage density in the northwest on the negative end of the axis (Table 5). In recent time periods, proportion of lake area was negatively correlated with PC1 with watersheds with high a proportion of lakes being associated with the negative end of the first component. The second component represented a gradient of watersheds with higher average elevation and large lake area in the west of the study area on the positive end, and on the negative end, watersheds with a higher proportion of wetlands in the east of the study area (Table 5). In recent time periods, range in elevation contributed to PC2 scores with watersheds with a high range being associated with the positive end of the second component. Eigenvalues, percentages of variance explained, and complete component scores generated by PCA during each study time period can be found in Appendix C.

During all study time periods fire disturbed watersheds were clustered toward the negative end of component 1. This indicates that these watersheds are mainly in the northwest portion of the study area and tended to have lower topographic variability and lower stream drainage density (Figures 14 & 15); although fire disturbed watersheds did show more spread on component 1 during the 1995-1999 and 2005-2009 periods. In contrast, harvest disturbed watersheds were spread out along component 1 indicating the characteristics of these watersheds were more variable than fire disturbed watersheds (Figures 14 & 15). There was, however a tendency for harvested watersheds not to have high negative scores on PC1 likely because there are fewer in the northern portion of the study area. Fire and harvest disturbed watersheds were each spread out along component 2 during each study time period, and resultantly there was very little separation between the types on this component. This indicates that fire and harvest disturbed watersheds occurred from the east to west of the study area, and included both watersheds with high average elevation and high proportions of lake area, and those with a higher proportion of wetlands (Figures 14 & 15).

Table 5: Component matrix values for PCA components 1 and 2 during each study time period.

Time Period		1990-1994		1995-1999		2000-2004		2005-2009	
Component Num.		1	2	1	2	1	2	1	2
Watershed Centroid	Easting	0.496	-0.622	0.624	-0.539	0.642	-0.522	0.667	-0.474
	Northing	-0.704	0.020	-0.721	-0.076	-0.711	-0.003	-0.713	-0.011
Watershed Elevation	Average (masl)	0.082	0.790	-0.114	0.787	-0.165	0.745	-0.180	0.708
	Range (m)	0.834	0.348	0.759	0.498	0.760	0.507	0.756	0.528
	Roughness	0.792	0.044	0.787	0.175	0.793	0.228	0.784	0.272
Watershed Density	Lake Area (total area)	-0.224	0.641	-0.358	0.557	-0.397	0.526	-0.464	0.511
	Stream Length (land area)	0.565	-0.191	0.566	-0.091	0.547	-0.007	0.603	0.012
	Wetland Area (land area)	-0.267	-0.692	-0.143	-0.739	-0.138	-0.736	-0.070	-0.749

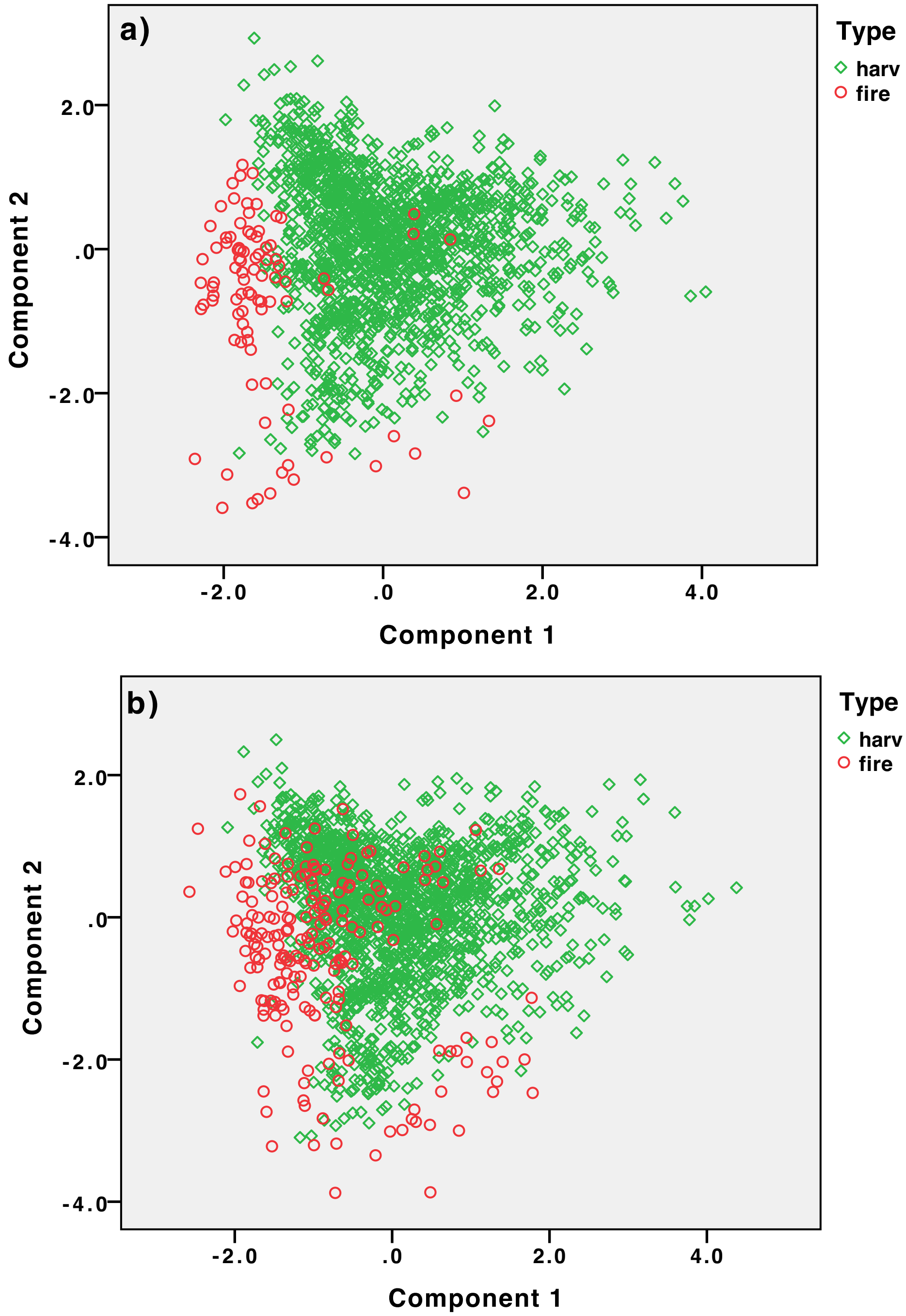

Figure 14: PCA ordination plots summarizing variability in watershed characteristics among watersheds. Disturbance type is overlaid showing harvest (green) and fire (red) disturbed watersheds. Major contributing factors to the components can be found in Table 5. Subfigures represent different study time periods a) 1990-1994, b) 1995-1999.

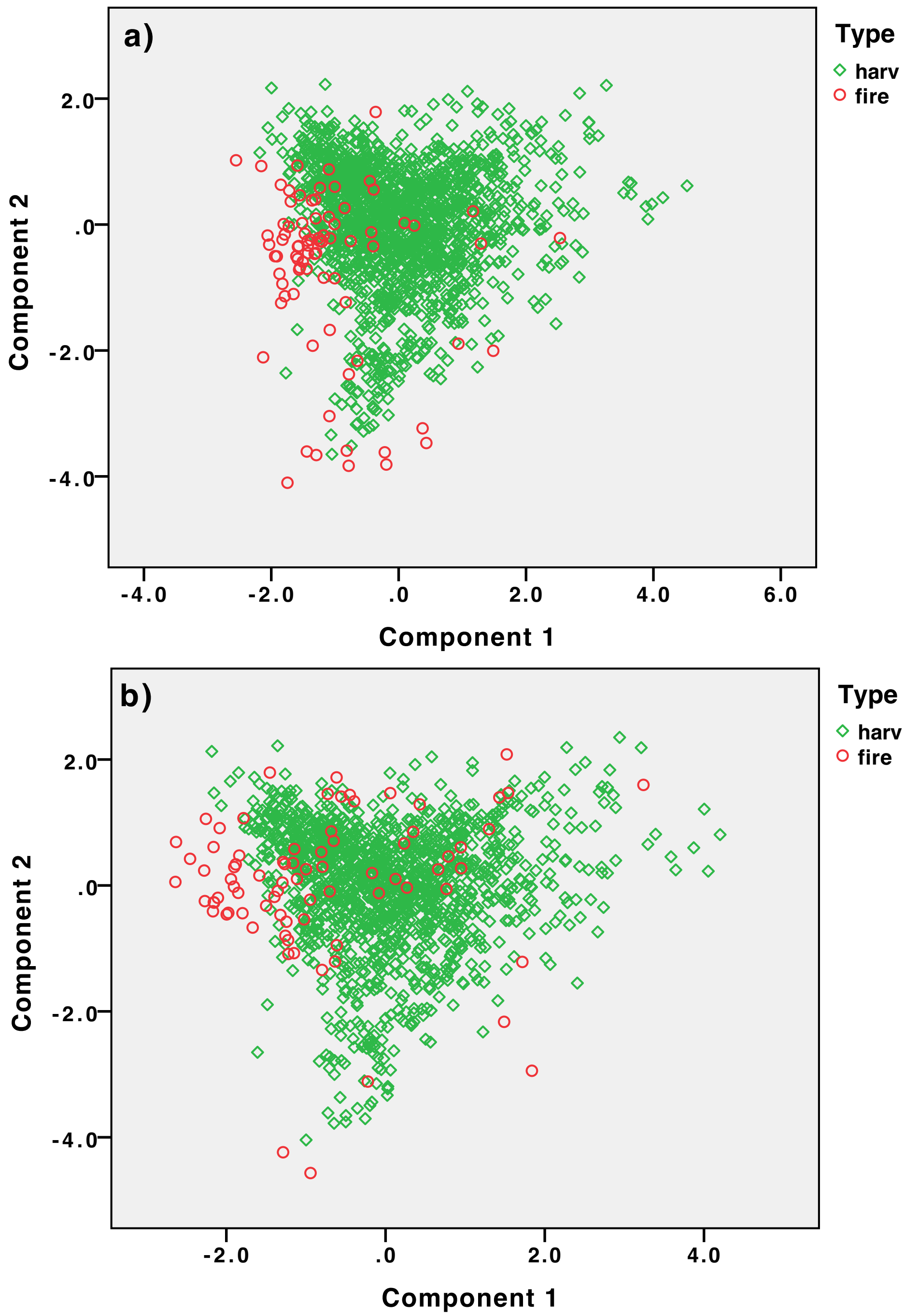

Figure 15: PCA ordination plots summarizing variability in watershed characteristics among watersheds. Disturbance type is overlaid showing harvest (green) and fire (red) disturbed watersheds. Major contributing factors to the components can be found in Table 5. Subfigures represent different study time periods a) 2000-2004, b) 2005-2009.

There was a small but significant difference in watershed characteristics between fire and harvest watersheds found by the DFA during each study time period (Tables 6 & 7). However, the disturbance type only explained 14.3 – 36.9% of the variability among watershed characteristics, based on canonical correlation coefficients of 0.379 – 0.608, across the study time periods. The single discriminant function axis described a gradient of watersheds with a higher proportion of wetlands in the northern part of the study area, on the positive end, to watersheds with a higher stream drainage density in the southern part of the study area, on the negative end. During all study time periods fire disturbed watersheds tended to have positive DFA scores with centroid values between 1.708 and 3.117, while harvest disturbed watersheds tended to be negative, centroid values -0.098 to -0.247 (Table 7). This demonstrates consistency with the patterns observed in the PCA ordination plots (Figures 14 & 15), where fire disturbance was clustered toward watersheds in the north of the study area, and harvest disturbance while harvest disturbance was clustered toward watersheds with high stream drainage density in the southern part of the study area. Fire disturbed watersheds were correctly classified 80% of the time by the 8 watershed characteristic variables contributing to the discriminant function, while harvest disturbed watersheds were classified correctly 89% of the time. These values changed little between original and cross-validated classification attempts. Overall 88.8% of the original watershed disturbances were classified correctly, this number falls slightly to 88.7% of cross-validated cases. Canonical discriminant Function coefficients and structure matrix values generated by DFA, as well as, classification results during each study time period are available in Appendix C.

Table 6: DFA eigenvalues, Wilks' lambda, and significance values during each study time period.

Time Period	1990-1994	1995-1999	2000-2004	2005-2009
Function Num.	1	1	1	1
Eigenvalue	0.587	0.474	0.261	0.168
% of Var.	100	100	100	100
Cum. %	100	100	100	100
Cannonical Correlation	0.608	0.567	0.455	0.379
(Cannonical Correlation)^2	36.9664	32.1489	20.7025	14.3641
Wilks' Lambda	0.63	0.678	0.793	0.856
Chi-Square	735.567	683.606	380.933	227.477
df	8	8	8	8
p value	< 0.001	< 0.001	< 0.001	< 0.001

Table 7: Standardized canonical discriminant function coefficients and function centroid values for disturbed watersheds during each study time period.

Time Period		1990-1994	1995-1999	2000-2004	2005-2009
Function Num.		1	1	1	1
Watershed Centroid	Easting	0.452	0.644	0.202	0.392
	Northing	1.075	1.255	0.990	1.215
Watershed Elevation	Average (masl)	0.328	0.316	0.071	0.135
	Range (m)	-0.072	-0.214	0.050	0.161
	Roughness	0.368	0.516	0.224	0.401
Watershed Density	Lake Area (total area)	-0.048	0.091	-0.063	0.199
	Stream Length (land area)	-0.344	-0.251	-0.253	-0.333
	Wetland Area (Land Area)	0.564	0.342	0.510	0.225
Function Centroid	Fire	3.117	1.916	2.232	1.708
	Harvest	-0.188	-0.247	-0.117	-0.098

2.5 Discussion

At a landscape scale, the proportion of stand replacing disturbance within watersheds is a critical indicator to compare among disturbance types because of the importance of maintaining natural hydrologic function. It is clear from the analyses conducted that forest management activities in Ontario's boreal forest do not result in similar patterns of disturbance as fire within forested watersheds. This is true in terms of the prevalence of the disturbance, the extent of disturbance, and their landscape pattern of disturbance. The differences observed have important implications in terms of forest successional patterns, and may influence hydrological processes in boreal streams.

Harvest disturbance, despite being far more prevalent and repetitive within watersheds resulted in a far lower extent of disturbance when compared with fire. Harvest disturbed a lower percentage of watershed land area, typically disturbed less than 10 or 20%, and generally resulted in more numerous disturbance patches, which were more complex in their shape, and often spread out over a number of years during each study time period. Fire disturbance within watersheds was far less common, generally only affecting a watershed during a single year of any study period, and resulted in far greater levels of disturbance when compared with harvest with up to 100% of a watershed land area being burned. Fire disturbance affected a greater percentage of watershed land area, generally through fewer individual disturbance patches with a more simple shape, and in most cases only disturbed watersheds during a single year of a study time period.

Differences observed between the disturbance types are largely in agreement with other studies that describe the disturbance regimes of fire and harvest, and those that compare their spatial patterns of disturbance. Patch densities have been shown to be greater in harvested versus fire disturbed landscapes (Schroeder & Perera 2002), which is consistent with my observation of greater median disturbance patch numbers and variability in patch numbers within harvested watersheds. McRae and others (2001) described fire disturbances as having a general ellipse pattern compared with straight edged non-ellipse shapes in harvest disturbance patches. I observed higher perimeter to area ratios in the harvest disturbed watersheds because the straight edged block like shapes of harvest disturbance have higher ratios than ellipses. Finally, the range of fire disturbance sizes has been described as covering a few to hundreds or thousands of hectares in area (Bouchard *et al.,* 2008; McRae *et al.,* 2001); conversely harvest has been described as representing only a small subset of the potential range of fire (McRae *et al.,* 2001). The difference in disturbance area within watersheds was one of the major differences observed in this study with frequency and cumulative frequency distributions of harvest watersheds predominantly clustered towards the lowest levels of disturbance (10-20% land area disturbed), whereas fire disturbance resulted in a wider range, from 1 to 100% land area disturbed.

One possible explanation for the difference between disturbance patterns of harvest and fire is that they occur in different types of watersheds. Typically fire disturbance occurred in watersheds with low topographic variability and stream density located in the northwest portion of the study area. In contrast, harvested watersheds had higher topographic variability and stream density and were located towards the southeast. Harvested watersheds were present throughout the north-south range of the study area, although not as far north as fire. These differences are not likely because different types of watersheds are different in their susceptibility to disturbance but instead that the disturbance types were primarily separated by their geographic location within the study area, which happened to line up with low relief, high percent wetland watersheds in the north and high relief, high drainage density wetlands in the south. The concentration of harvested watersheds towards the southeast of the study area makes sense considering the location of population centres and wood processing facilities in the south of the province. Conversely, lower annual precipitation and longer periods of time in a state of water deficit towards the northwest of the study area (Baldwin *et al.,* 2011) would contribute to greater potential for dry fuels in that area, and resultantly greater potential for fire activity. Additional to this, fire suppression efforts are concentrated in and are more effective in the southerly regions of the AOU, where fire presents as a significant risk to the public, infrastructure, and timber resources (Girardin *et al.,* 2006; McRae *et al.,* 2001). It follows then that greater levels of fire activity would be found towards the north of the study area, where fire poses the lowest threat to people and timber interests.

Another factor contributing to the observed differences in the extent of watershed disturbance by fire and harvest may be limitations placed on their size distributions through management actions, or spatial data quality. Forest management direction that limits the size of the majority of clearcuts to below 260 ha (Perera & Cui 2010) has likely resulted in a legacy of smaller harvest disturbance patches and very few larger disturbances. Additionally, the quality of spatial data available for fire may result in an under-representation of smaller disturbance patches. Only fires larger than 40 ha in area were spatially represented in the dataset employed in this study, and while large fires compose the majority of area disturbed (Cumming 2001; Girardin *et al.,* 2006) small fires represent the vast majority of fires that occur. As an example, 1976 to 1990 provincial records in Ontario included 21176 fires below 10 ha in area (Bridge *et al.,* 2005) compared with 1 846 fires >40 ha in area from 1960-2013 in the raw data of this study. The inclusion and digitization of some of the fires <40 ha would likely reduce the difference between fire and harvest patch counts, as well as differences in the frequency of disturbances affecting <20% watershed land area. Additionally, the inclusion of small fires and improvements to the digitization accuracy of fires will potentially reduce the difference in perimeter to area ratios between the types. In particular correcting the reduced accuracy of older fires identified by Bridge and others (2005), and more accurately representing the ragged edges and unburnt islands described by McRae and others (2001).

The observed differences in the spatial extent and landscape pattern of disturbance within watersheds have a number of consequences both for boreal forest succession and stream environments. Disturbances in the boreal forest directly affect the age, species composition, structure and spatial arrangement of forest types in the landscape (Bergeron *et al.,* 2001; Bouchard *et al.,* 2008; Cui & Perera 2008). I found that harvest resulted in a lower level of disturbance within watersheds, and a narrower range of watershed disturbance extents. Considering the relationship between boreal forest structure and composition, harvest disturbance resulting in a small amount of disturbance within a large number of watersheds will certainly result in a different successional regime compared with fire; fire resulted in a range in disturbance percentages, and a few watersheds disturbed at a very high level. Additionally, temporal differences between the disturbance types and differences in disturbance patch numbers indicate that while fire will typically result in even aged regrowth in a few larger disturbed patches, harvest will result in regrowth in a larger number of small patches, often with a variety of ages within a single watershed, further differentiating their successional impacts across the landscape.

The potential differences in boreal forest succession are particularly relevant if fire suppression efforts are believed to be largely successful within the AOU. A significant reduction in the incidence and spread of large fires in the intensive zone (Bridge *et al.,* 2005), means that harvest will be largely responsible for the successional regime of boreal forests in the AOU. Considering the differences identified in this study harvest is unlikely to provide for a successional regime within forested boreal watersheds similar to what would have historically been provided by natural regimes of fire disturbance (Arkle & Pilliod 2010; Flannigan *et al.,* 2005). This result has implications for END in Ontario; future management activities may take greater consideration of watersheds and attempt to spatially and temporally concentrate harvest activities to result in a more natural disturbance pattern in the AOU.

In consideration of the relationship between watershed disturbance and increases in water yield and peak flows (Abdelnour *et al.,* 2011; Carignan & Steedman 2000), differences in the spatial extent and landscape pattern of disturbance within boreal watersheds will have a number of implications for boreal streams. In the majority of cases (>1000 watersheds) harvest disturbance resulted in disturbance in less than 10 or 20 percent of the watersheds land area. If disturbances at these levels result in proportionally small increases in streamflow it is unlikely that harvest is providing for similar flow regime changes as fire. Instead harvest is likely resulting in a small amount of flow increases within a very large number of disturbed watersheds. Conversely, fire appears to result in a range of flow increases, including a few large flow increases within highly disturbed watersheds, but within fewer watersheds across the landscape. Potential differences in flow regime changes resulting from fire and harvest may be more drastic considering the disturbance thresholds identified in the literature of 20% (Brown *et al.,* 2005; Buttle 2011; Stednick 1996) or 30% of watershed area (Guillemette *et al.,* 2005; Kuraś *et al.,* 2012; Lin & Wei 2008). With the majority of watershed disturbance in this study occurring below these thresholds harvest disturbance may not be resulting in any measurable increases in flow in a large number of affected watersheds. In either case harvest disturbance is unlikely to provide for the potentially large increases in flow resulting from the high levels of watershed disturbance (50-100% land area) caused by fire. Large flow increases may be responsible for changes in channel morphology, cleaning and creating of spawning sites (Tremblay *et al.,* 2008); while watershed disturbances likely provided for habitat heterogeneity and natural patterns of diversity in aquatic ecosystems (Kreutzweiser *et al.,* 2012). Results observed in this study indicate that harvest is not likely to result in flow changes that naturally occur as a result of fire disturbance.

The temporal differences in disturbances between fire and harvest reveal other potential changes in their hydrologic response. Fire typically only disturbed a watershed during a single year of any of the study time periods, and will therefore likely result in a proportional response in streamflow. Conversely, harvest frequently disturbed watersheds over multiple years of each time period. So, even in cases where disturbance thresholds are exceeded the total area disturbed by harvest is likely to be comprised of numerous smaller disturbed patches in various states of regrowth and recovery, reducing the potential increases in streamflow as vegetation re-establishes (Putz *et al.,* 2003).

The results of this study show that the pattern of stand replacing disturbance within watersheds differs between natural and managed disturbances. While the risk of hydrologic disturbance within a watershed may be less for harvest disturbances, due to the generally smaller proportion of the watershed affected relative to fire, there may be other cumulative effects of a higher frequency of disturbance for both forest succession and boreal stream environments. In addition, the relatively infrequent but large potential hydrologic changes associated with fire may play an important natural role in boreal stream ecosystems. In order for forest management to result in more natural spatial patterns of disturbance there should be additional consideration of watersheds in management planning, maintaining natural patterns of disturbance may provide for other natural processes in the forest, including hydrological changes.

3.0 SHORELINE RIPARIAN CHAPTER

3.1 Introduction

Fire and harvest represent major sources of disturbance in Ontario's boreal forest region (Flannigan *et al.,* 2005; Pickell *et al.,* 2013; Pinel-Alloul *et al.,* 2002; Schroeder & Perera 2002). As the dominant natural disturbance fire has played a significant role in structuring forest ecosystems (Arkle & Pilliod 2010; Flannigan *et al.,* 2005). This is also true for the riparian areas of these forests (Silbey *et al.,* 2012), where fire regularly burns to the stream edge (Buttle 2002; Lamb *et al.,* 2003; Sibley *et al.,* 2012). Within the ~300 000 km^2 of managed boreal forest in Ontario harvest also influences forest structure (Perera & Cui 2010; Schroeder & Perera 2002) and during the past century has increased its annual area disturbed near to the point of surpassing fire (Pinel-Alloul *et al.,* 2002). Forest management direction in Ontario includes reserve forested strips, 30 to 90 m in width around mapped water features, which restrict nearly all shoreline harvest activity (Lamb *et al.,* 2003; OMNR 2010). This practice has resulted in an abnormal landscape of mature forest strips surrounding boreal water features (Buttle 2002) and the suppression of natural forest renewal in riparian forests (Kreutzweiser *et al.,* 2012) that would otherwise be naturally affected by fire activity (Buttle 2002; Lamb *et al.,* 2003; Sibley *et al.,* 2012). In addition to the successional effects, restricting harvest activity in these areas may reduce changes in the aquatic environment that would naturally occur following riparian fire. Hereafter, the term 'buffer' will refer to an area of shoreline forest delineated along hydrologic features, which reflect the reserve forested strips employed in forest management policy, unless specifically noted.

The reason for using riparian buffers during harvest activity is to reduce the potential for upland harvesting to affect the stream environment (Luke *et al.,* 2007; Macdonald *et al.,* 2004; Richardson *et al.,* 2012). Buffers provide habitat, reduce direct insolation of streams, intercept sediments, and provide woody material input for streams, along with protecting aesthetic values (Bren 2000; Richardson *et al.,* 2012). Although intended to provide protection, buffer strips generally fail to prevent many of the potential harvest effects on water quality and the stream environment (Moore & Richardson 2012; Pinel-Alloul *et al.,* 2002). Ontario's forest management direction on buffer width relies on shoreline slope measurements, often applying a single buffer width to an entire length of stream or lake shoreline regardless of local slope variations and without accounting for significant hydrologic features such as flow pathways, convergence areas, and recharge zones (Buttle 2002; Buttle *et al.,* 2005). Accordingly, buffers may overprotect aquatic features in some areas and under protect them in others resulting in a situation that that does not satisfy protection requirements for of boreal aquatic systems and prevents forest managers from accessing high value timber within the protected areas (Buttle 2002; Buttle *et al.,* 2005).

Differences in the spatial pattern of disturbance by fire and harvest on boreal forests include: significant variation in fire sizes (Bouchard *et al.,* 2008; McRae *et al.,* 2001) versus limited clearcut areas (Perera & Cui 2010); a tendency for large fire events to include the majority of area burned (Cumming 2001; Girardin *et al.,* 2006) versus numerous small events constituting the majority of harvested areas (Pickell *et al.,* 2013); smaller median patch sizes and greater patch densities in harvested areas versus fire disturbed landscapes (Schroeder & Perera 2002); and harvest only resulting in a subset of the range of disturbances resulting from fire (McRae *et al.,* 2001). Other differences are tied to disturbance patch shapes, which are generally elliptical in wind driven fire events with unburnt islands, while harvest disturbances are straight edged non-elliptical shapes (McRae *et al.,* 2001). Given these differences, the riparian forest is probably differentially influenced by fire and harvest; however, the primary difference is likely the usage of forested riparian buffer strips that restrict most shoreline harvest activity (Lamb *et al.,* 2003; OMNR 2010). Fire in the boreal forest regularly burns to the stream edge (Buttle 2002; Lamb *et al.,* 2003; Pettit & Naiman 2007; Sibley *et al.,* 2012). Studies examining watershed disturbance by fire have found that the amount of riparian area disturbed by fire was proportional to the amount of upland area burned (Arkle & Pilliod 2010), although the study was not conducted within the boreal forest.

Disturbance within riparian forests has the potential to cause a number of changes in the stream environment including: increases in sediment depositions and inputs of woody debris (Kreutzweiser *et al.,* 2012; Pettit & Naiman 2007); increases in water temperatures (Kreutzweiser *et al.,* 2012; Moore *et al.,* 2005; Pettit & Naiman 2007); and changes in streamflow (Abdelnour *et al.,* 2011). Changes in temperature and stream flow are respectively related to increases in solar insolation reaching the stream (Kreutzweiser *et al.,* 2012; Moore *et al.,* 2005; Pettit & Naiman 2007), and the close proximity of riparian areas to the stream; modelling has indicated that shorter flow paths between disturbed areas and streams will result in greater levels of flow increase (Abdelour *et al.,* 2011). Both stream temperature and flow changes have the potential to negatively affect stream biota (Burn *et al.,* 2008; Heicher 1993, as cited in Smakhtin 2001). However, given the fact that they result naturally from fire disturbance, and contribute to habitat heterogeneity and natural patterns of diversity in aquatic ecosystems (Kreutzweiser *et al.,* 2012), restricting harvest activity in these areas could negatively affect boreal streams.

Studying the spatial pattern of fire and harvest disturbance within riparian areas is required to both develop our scientific understanding of aquatic systems (Dwire & Kauffman 2003; Moore & Richardson 2012) and evaluate whether harvest has resulted in similar spatial patterns of disturbance as fire. Concerns over the widespread application of shoreline riparian buffers, including a lack of consideration of significant hydrologic features in their application (Buttle 2002; Buttle *et al.,* 2005) have led to suggestions that forest management include landscape level planning for riparian harvest (Macdonald *et al.,* 2004; Richardson *et al.,* 2012).

3.1.1 Objectives

The objective of this study is to compare the spatial pattern of riparian forest disturbance by harvest and fire at a landscape scale. Specifically I will address the question: at a landscape scape is the proportion of stand replacing disturbances within riparian forest similar when comparing natural disturbance to forest management? If harvest is resulting in similar spatial patterns of disturbance as fire within these areas, then there should be little difference in the spatial disturbance metrics between the types. In addition to disturbance patterns I will also compare the relationship between the percentage of riparian and watershed land area disturbed in harvest and fire disturbed riparian forests to test if the differ in other ways. The riparian forest in this case will be represented by the buffers generated around study water features, these areas will not necessarily represent the true location and extent riparian areas with each watershed, but will provide a means of assessing disturbance occurring close to water features.

3.2 Methodology

3.2.1 Shoreline Riparian Buffers

Shoreline riparian buffers areas of 30 and 90 m were delineated within the study watersheds using the Buffer tool in the Analysis extension of ArcGIS. Widths of 30 m and 90 m were selected based on widths prescribed by Ontario forest management policy (OMNR 2010; OMNR 2014). Hydrologic features buffered to the same distance (i.e. 30 m watercourse, 30 m water body) were combined using the Merge tool in the Data Management extension, before having lake areas removed from their extents using the Erase tool. Removing the 30 m buffer from the extent of the 90 m using the Erase tool developed an additional outer 60 m buffer, covering the difference in area between the outer limits of the 30 and 90 m buffer. The majority of analyses were conducted for the 30 and 90 m buffer areas, while additional testing evaluated differences between the buffers using the outer 60 m buffer width. In total 4866 buffers were produced for analysis at the 30 and 90 m levels (Figure 16) and the outer 60 m level (Figure 17). All data employed or produced in this chapter is generally described in Table 8. Any tools or extensions referred to in this chapter can be found in ESRI's ArcGIS software. Both the study area and disturbance records employed in this chapter are the same as those used in the watershed chapter, details on each can be found in Section 2.2 Study Details.

Table 8: Descriptions and sources of GIS data produced during the shoreline riparian methodology.

Data Name	Source	Description
Fire and Harvest Disturbance Records	FRI	Records of fire and harvest disturbance within the study area sourced from FRI natural disturbance mapping and annual reporting by forest management companies
Intersect watercourse	Produced	Result of intersect between study watersheds and the OIH watercourse shapefile. (MNRF 2015)
Intersect waterbodies	Produced	Result of intersect between study watersheds and the OHN waterbody shapefile (MNRF 2013a)
30 m Buffer	Produced	Result of merged 30 m buffers of the OIH intersect watercourse and OHN waterbody shapefiles, with lake areas erased
90 m Buffer	Produced	Result of merged 90 m buffers of intersect OIH watercourse and OHN waterbody shapefiles, with lake areas erased
Outer 60 m Buffer	Produced	Result of 30 m buffer areas being erased from the 90 m buffer, covers the difference in area between the two buffer widths
Buffer Disturbance	Produced	Result of intersections between study shoreline riparian buffers (30, 90, outer 60 m) and study FRI disturbance records during all four study time periods

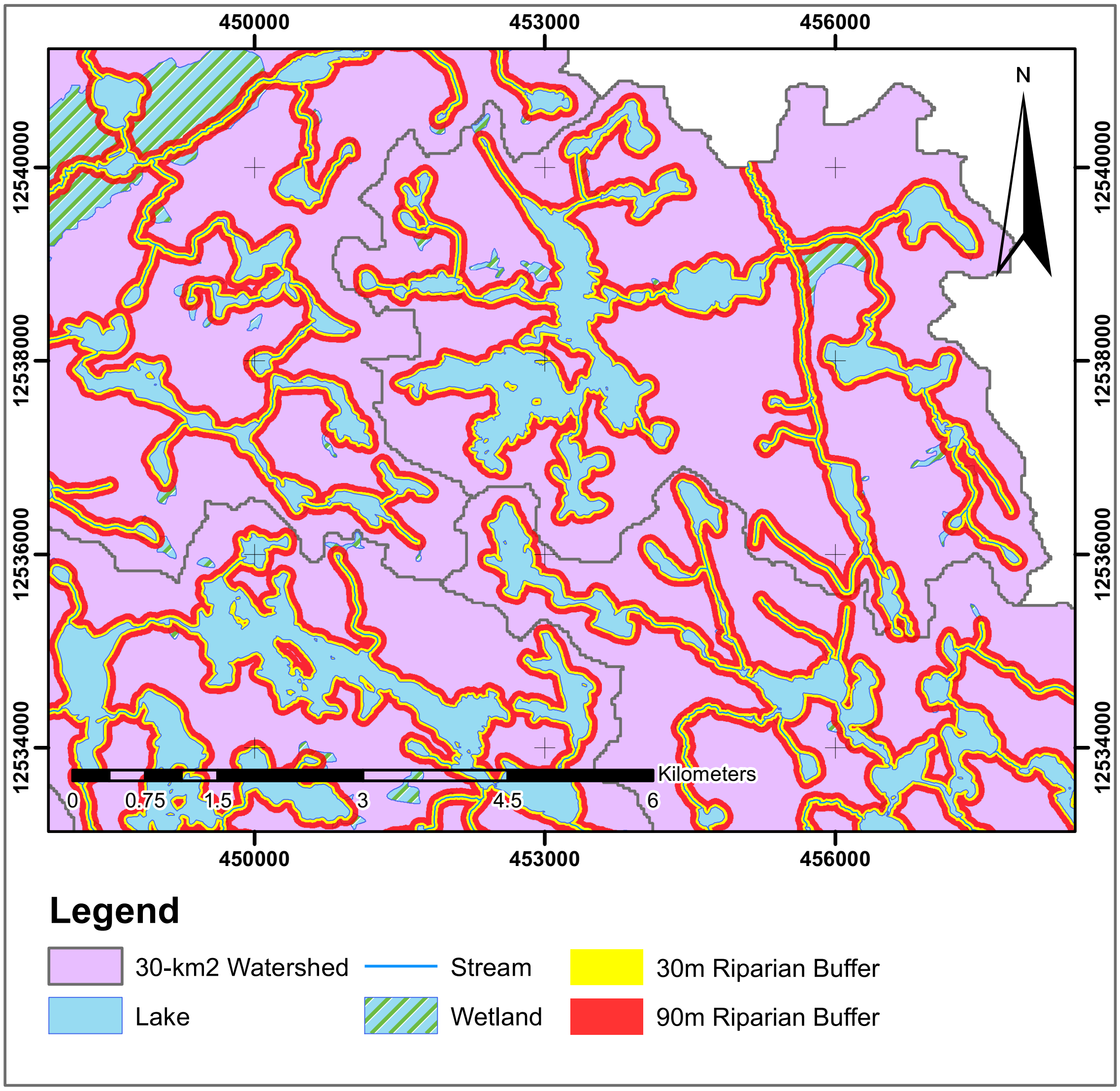

Figure 16: Sample study 30 m and 90 m shoreline riparian buffers, and watershed hydrologic features.

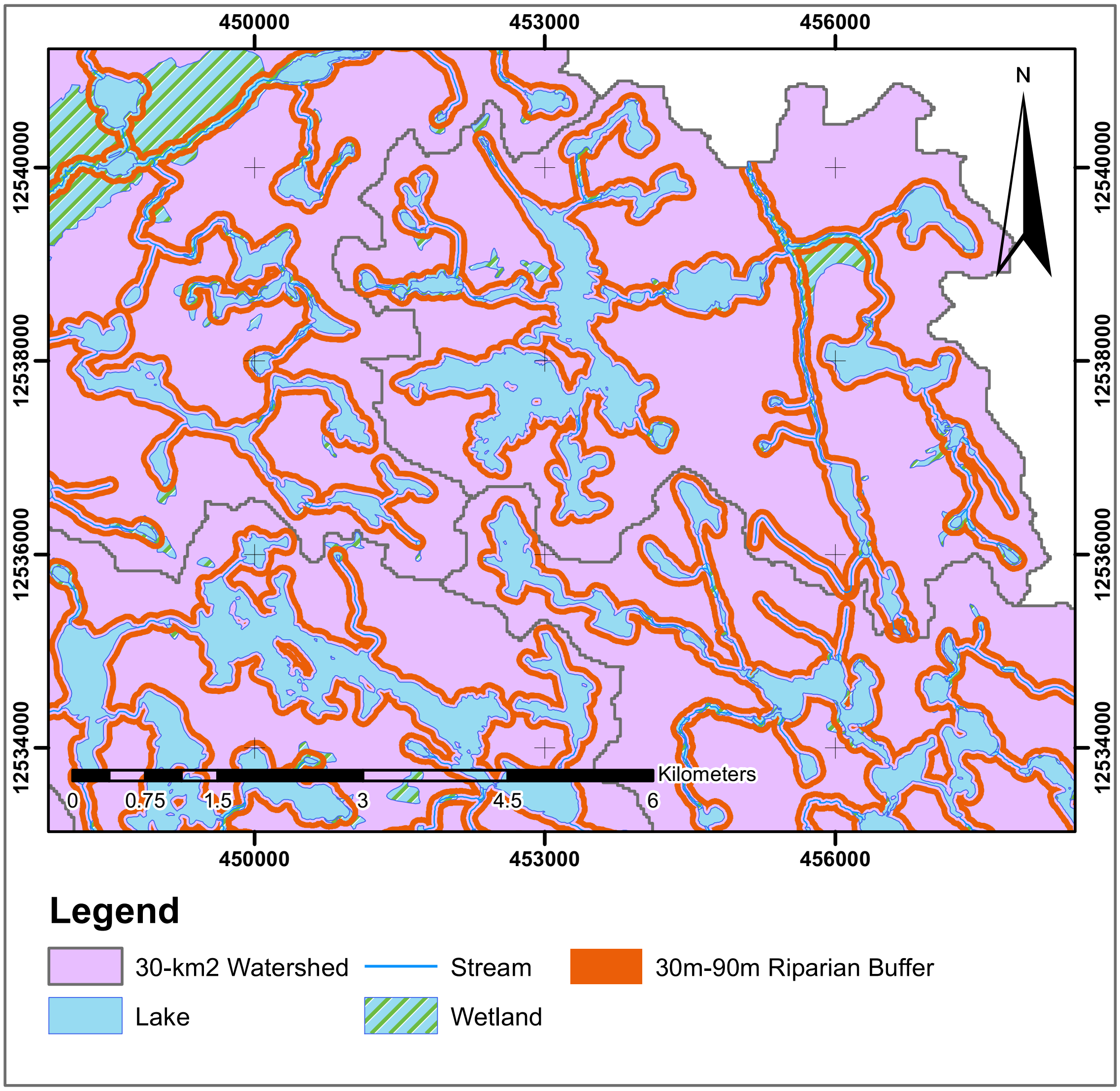

Figure 17: Sample study outer 60 m shoreline riparian buffers and watershed hydrologic features.

3.2.2 Shoreline Riparian Disturbance

Fire and harvest disturbance within riparian areas was quantified by intersecting disturbance records with the study buffers during each time period, using the Intersect tool in the Analysis extension (Figure 18 & 19). Patch Analyst (Rempel *et al.,* 2012) was used to calculate the median disturbance patch size within each disturbed buffer. Results from the intersection and patch analyst processes were joined and output to Microsoft Access. Access queries were used to summarize disturbance information for each buffer including the disturbance category (e.g. no disturbance, both types, fire, or harvest), the number of years with disturbance, the number of disturbance patches, the group median of median disturbance patch sizes, the percentage of buffer area disturbed, and the perimeter to area ratio of the disturbance. Disturbance records for the outer 60 m buffer were also summarized in Access, describing the disturbance category and percentage of buffer area disturbed. Separate data tables were developed in order to address this study's questions. The first detailed the number and percentage of 30 and 90 m buffers within each disturbance category, and the percentage of disturbed buffers experiencing disturbance in multiple years. The second was developed for statistical analysis in SPSS (v23). It included study 30 and 90 m buffers experiencing only fire or harvest during the period, and described: the number of years with disturbance, the number of disturbance patches, the group median of median disturbance patch sizes, the percentage of buffer area disturbed, and the perimeter to area ratio of the disturbance. A third table developed for comparison between the buffer distances included the percentage of 30, 90, and outer 60 m buffers disturbed along with the percentage of the containing watershed disturbed.

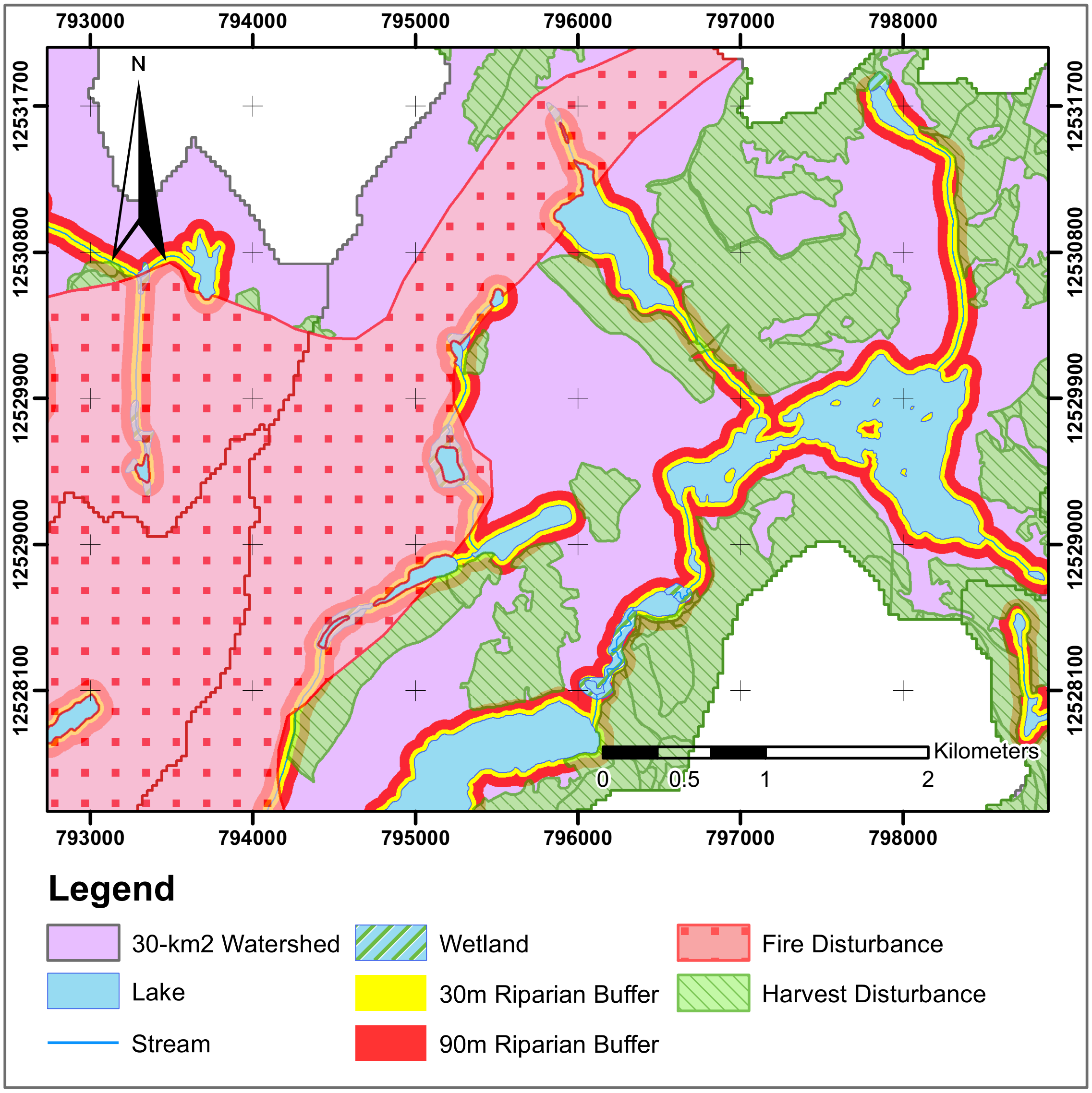

Figure 18: Sample fire and harvest disturbances overlapping study 30 m and 90 m shoreline riparian buffers.

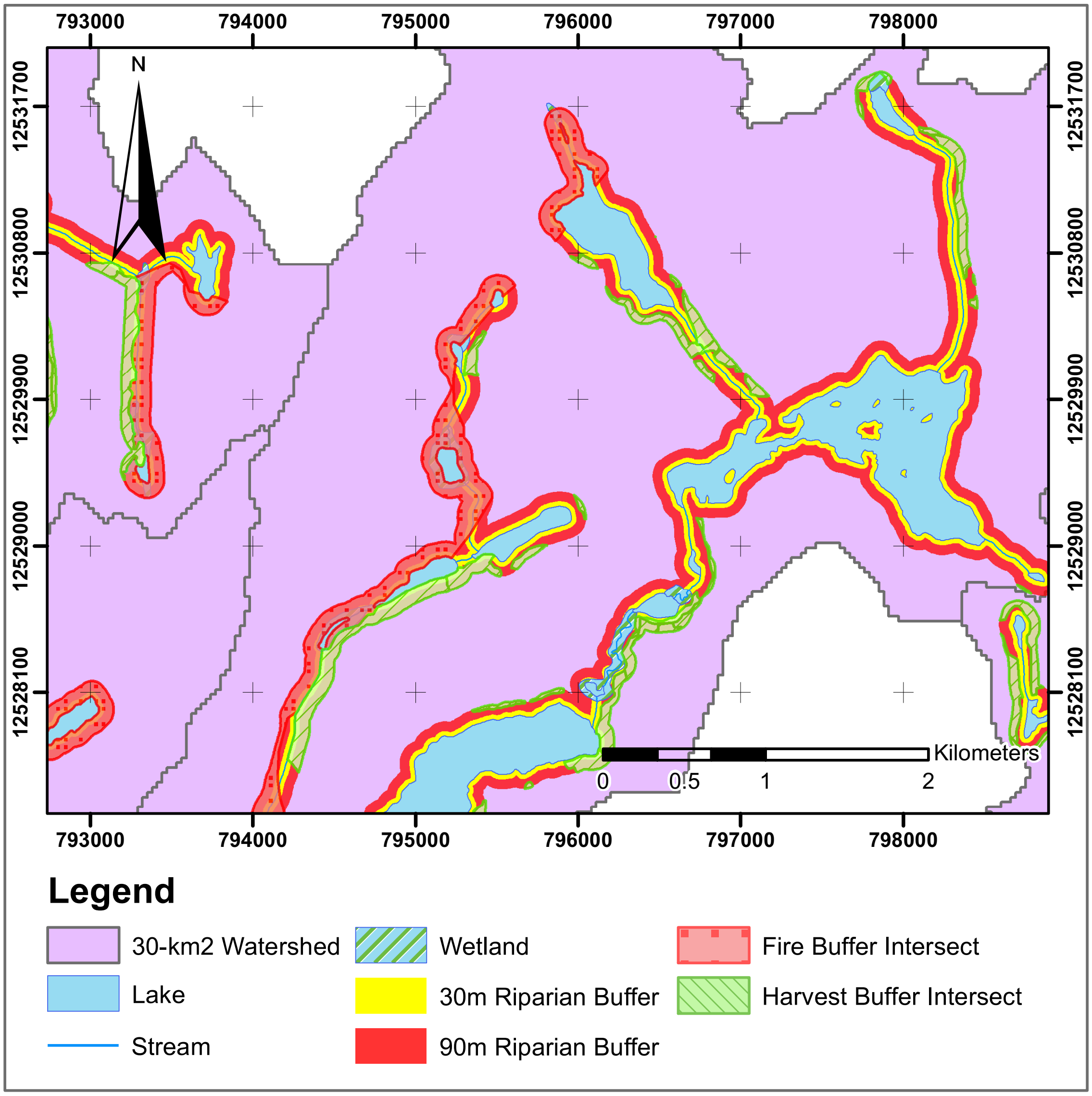

Figure 19: Sample fire and harvest disturbances intersected with study 90 m shoreline riparian buffers.

3.2.3 Shoreline Riparian Analysis

Fire and harvest disturbance within study buffers were compared during each time period using metrics describing their spatial pattern of disturbance. Collectively these metrics described: the prevalence of each disturbance type, the median level of disturbance and disturbance variability within the buffers, the landscape pattern of buffer disturbance, and the relationship between buffer and watershed disturbance. Metrics were assessed for normality using Shapiro-Wilk testing and visual inspection of their histograms to determine appropriate statistical procedures. In both the 30 and 90 m buffers all fields describing fire and harvest disturbance during each study time period were assessed as non-normal, respectively at $p < 0.05$ and $p < 0.01$. Fields included in the comparative table describing percent and $\log_{10}$ (percent) area disturbed values for the 30, 90, and outer 60 m buffers in addition to their containing watersheds were also assessed as non-normal $p < 0.01$. Employing non-normal data for statistical analyses required that non-parametric procedures be employed for all hypothesis testing (Lin & Wei 2008), although in some instances trends in the data were examined using parametric statistics.

The prevalence of disturbance within 30 m and 90 m shoreline riparian buffers was assessed in the same manner as in the watershed chapter. The percentage of buffers within each disturbance category, and the percentage of fire and harvest disturbed buffers with disturbance occurring in multiple years were calculated and compared during each study time period, within each buffer distance.

Median levels of disturbance within shoreline riparian areas were also compared in the same manner as in the watersheds. The same metrics compared in the watershed chapter were calculated and compared using Mann-Whitney U testing for each buffer distance, with the addition of the group median of buffer median disturbance patch sizes.

The landscape pattern of shoreline riparian disturbance was also compared in the same manner as in the watershed chapter. KS testing and cumulative frequency distributions were calculated for each buffer distance during each study time period. Additionally separate testing conducted the same comparisons within individual ecoregions in the study area.

The relationship between shoreline riparian and watershed disturbances was examined for fire and harvest disturbance during all study time periods. Analysis of covariance compared the disturbance types in terms of their relationships between 30 m, 90 m, and outer 60 m percentage of buffer area disturbed and the percentage of watershed land area disturbed. The outer 60 m buffer was included for these analyses to examine the difference in area between the 30 m and 90 m shoreline riparian buffers used for the other analyses employed in this chapter.

3.3 Results

3.3.1 Prevalence of Riparian Disturbance

Harvest disturbance affected a greater percentage of the study buffers than fire, at both the 30 and 90 m levels, during all study time periods (Tables 9 & 10). Most buffers were not disturbed, representing 71.09 to 79.04% of the 30 m, and 67.02 to 74.13% of the 90 m buffers (n=4866). Harvest disturbance prevalence varied between 19.24 and 23.65% of the 30 m, and 24.09 and 27.54% of the 90 m buffers among time periods. Conversely fire was less common, affecting about 1.5% of both the 30 and 90 m study buffers during most of the study time periods; the 1995-1999 period being the exception where 3.76 % of the 30 m and 3.66% of the 90 m buffers were disturbed. Buffers experiencing both disturbance types during a single time period were least common, representing between 0.16 to 0.37% of the 30 m and 0.18 to 0.45% of the 90 m buffers; excepting the 1995-1999 period where 1.5% of the 30 m and 1.71% of the 90 m buffers underwent both disturbance types.

Additional to being more prevalent, harvest disturbance within riparian buffers occurred more frequently than fire in both the 30 and 90 m buffers, during all time periods (Tables 9 & 10). During the periods covering 1990 to 2004 between 40.32 and 43.53% of harvested 30 m buffers, and 47.16 and 49.96% of harvested 90 m buffers underwent harvest during multiple years of the study time period. During the 2005-2009 period these values decrease to 34.19% of the 30 m and 41.13% of the 90 m buffers. Comparatively, percentages of fire disturbed buffers were far lower. At the 30 m level only 7.14 and 1.64% of fire disturbed buffers experienced additional fires during the 1990-1994 and 1995-1990 periods; no 30 m buffers underwent additional fires during the remaining periods. Similarly, 6.76, 1.69, and 1.43% of fire disturbed 90 m buffers experienced additional fires respectively during the 1990-1994, 1995-1999, and 2000-2004 periods, with none experiencing additional fires during the 2005-2009 period.

Table 9: Prevalence of 30 m shoreline riparian buffer disturbance by time period, and percentage of 30 m buffers with disturbance in multiple years.

Time Period	Disturbance Category	30 m Buffer Disturbance		Disturbance in Multiple Years	
		Count	Percentage of Total Buffers	Count	Percentage of Disturbed Buffers
1990-1994	None	3682	75.67	n/a	n/a
	Both	8	0.16	n/a	n/a
	Fire	70	1.44	5	7.14
	Harvest	1106	22.73	480	43.40
1995-1999	None	3459	71.09	n/a	n/a
	Both	73	1.50	n/a	n/a
	Fire	183	3.76	3	1.64
	Harvest	1151	23.65	501	43.53
2000-2004	None	3656	75.13	n/a	n/a
	Both	18	0.37	n/a	n/a
	Fire	71	1.46	0	0.00
	Harvest	1121	23.04	452	40.32
2005-2009	None	3846	79.04	n/a	n/a
	Both	11	0.23	n/a	n/a
	Fire	73	1.50	0	0.00
	Harvest	936	19.24	320	34.19

Table 10: Prevalence of 90 m shoreline riparian buffer disturbance by time period, and percentage of 90 m buffers with disturbance in multiple years.

Time Period	Disturbance Category	90 m Buffer Disturbance		Disturbance in Multiple Years	
		Count	Percentage of Total Buffers	Count	Percentage of Disturbed Buffers
1990-1994	None	3519	72.32	n/a	n/a
	Both	9	0.18	n/a	n/a
	Fire	74	1.52	5	6.76
	Harvest	1264	25.98	617	48.81
1995-1999	None	3270	67.20	n/a	n/a
	Both	83	1.71	n/a	n/a
	Fire	178	3.66	3	1.69
	Harvest	1335	27.44	667	49.96
2000-2004	None	3434	70.57	n/a	n/a
	Both	22	0.45	n/a	n/a
	Fire	70	1.44	1	1.43
	Harvest	1340	27.54	632	47.16
2005-2009	None	3607	74.13	n/a	n/a
	Both	16	0.33	n/a	n/a
	Fire	71	1.46	0	0.00
	Harvest	1172	24.09	482	41.13

3.3.2 Extent of Riparian Disturbance

Median levels of riparian buffer disturbance by fire and harvest, including the number of years of each period with disturbance, the number of disturbance patches, the group median of median buffer disturbance patch sizes, the percentage of buffer area disturbed, and the perimeter to area ratio of the disturbance were significantly different during all study time periods for both the 30 and 90 m buffers (Tables 11 & 12). Harvest disturbed buffers had significantly greater median numbers of disturbed years than fire at both buffer distances, despite resulting in the same median values during all time periods (Tables 11 & 12). The source of the statistical difference between the disturbance types is likely due to differences in their variability, while harvest maintains an IQR of 1 for both buffer widths during all period fire results in an IQR of 0 or none. The differences in the disturbance types are clearly evident when they are plotted together; both the range and outlying values in harvest disturbed buffers are clearly greater than those resulting from fire (Figures 20 & 21).

Table 11: Mann-Whitney U results and significance values comparing median 30 m shoreline riparian buffer disturbance by fire and harvest in each study time period.

Test Statistic	Disturbance Descriptor	Time Period	Fire		Harvest		Mann-Whitney U	p value
			Median	IQR	Median	IQR		
Mann-Whitney U	Years with disturbance during time period	1990-1994	1	0	1	1	53215	< 0.01
		1995-1999	1	0	1	1	149673	< 0.01
		2000-2004	1	n/a	1	1	55841.5	< 0.01
		2005-2009	1	n/a	1	1	45844	< 0.01
Mann-Whitney U	Number of disturbance patches during time period	1990-1994	5	8	6	12	45022.5	0.021
		1995-1999	4	5	6	11	131937	< 0.01
		2000-2004	3	4	7	13	56780	< 0.01
		2005-2009	5	7	7	14	40892.5	0.005
Mann-Whitney U	Median area of 30 m buffer median patch areas sqkm	1990-1994	0.017	0.062	0.0012	0.0031	6914	< 0.01
		1995-1999	0.015	0.042	0.0008	0.0019	21453	< 0.01
		2000-2004	0.018	0.073	0.0003	0.0010	4834	< 0.01
		2005-2009	0.009	0.033	0.0001	0.0004	2336	< 0.01
Mann-Whitney U	Percentage of 30 m buffer area disturbed during time period	1990-1994	27.73	50.80	1.04	2.92	6927	< 0.01
		1995-1999	14.44	48.42	0.80	2.10	26109	< 0.01
		2000-2004	16.03	29.11	0.33	1.22	9323	< 0.01
		2005-2009	8.68	28.54	0.08	0.38	2520	< 0.01
Mann-Whitney U	Disturbance perimeter to area ratio during time period	1990-1994	44.98	16.04	89.70	74.57	71741	< 0.01
		1995-1999	47.25	23.12	106.57	102.52	187742	< 0.01
		2000-2004	47.21	20.44	175.47	302.22	73729	< 0.01
		2005-2009	59.55	24.45	393.67	1747.64	66739	< 0.01

Table 12: Mann-Whitney U results and significance values comparing median 90 m shoreline riparian buffer disturbance by fire and harvest in each study time period.

Test Statistic	Disturbance Descriptor	Time Period	Fire		Harvest		Mann-Whitney U	p value
			Median	IQR	Median	IQR		
Mann-Whitney U	Years with disturbance during time period	1990-1994	1	0	1	1	67099.5	< 0.01
		1995-1999	1	0	1	1	176568.5	< 0.01
		2000-2004	1	0	1	1	68469.5	< 0.01
		2005-2009	1	n/a	1	1	58717	< 0.01
Mann-Whitney U	Number of disturbance patches during time period	1990-1994	3.5	6	7	15	60957.5	< 0.01
		1995-1999	4	5	8	15	165358.5	< 0.01
		2000-2004	3	4	10	20	74541.5	< 0.01
		2005-2009	4	6	10	16	58428	< 0.01
Mann-Whitney U	Median area of 90 m buffer median patch areas sqkm	1990-1994	0.064	0.156	0.0063	0.0105	15280	< 0.01
		1995-1999	0.049	0.128	0.0054	0.0080	45085	< 0.01
		2000-2004	0.080	0.261	0.0042	0.0060	13014	< 0.01
		2005-2009	0.032	0.105	0.0045	0.0055	16435	< 0.01
Mann-Whitney U	Percentage of 90 m buffer area disturbed during time period	1990-1994	24.63	48.43	1.70	4.30	14466	< 0.01
		1995-1999	15.10	49.49	1.65	3.67	37924	< 0.01
		2000-2004	13.08	27.22	1.73	3.37	20337	< 0.01
		2005-2009	8.58	29.44	1.35	2.60	13428	< 0.01
Mann-Whitney U	Disturbance perimeter to area ratio during time period	1990-1994	17.11	5.69	46.84	27.13	87039	< 0.01
		1995-1999	17.19	8.22	52.52	36.86	227400	< 0.01
		2000-2004	18.11	9.83	59.79	25.10	86165	< 0.01
		2005-2009	20.93	8.92	61.89	21.98	81745	< 0.01

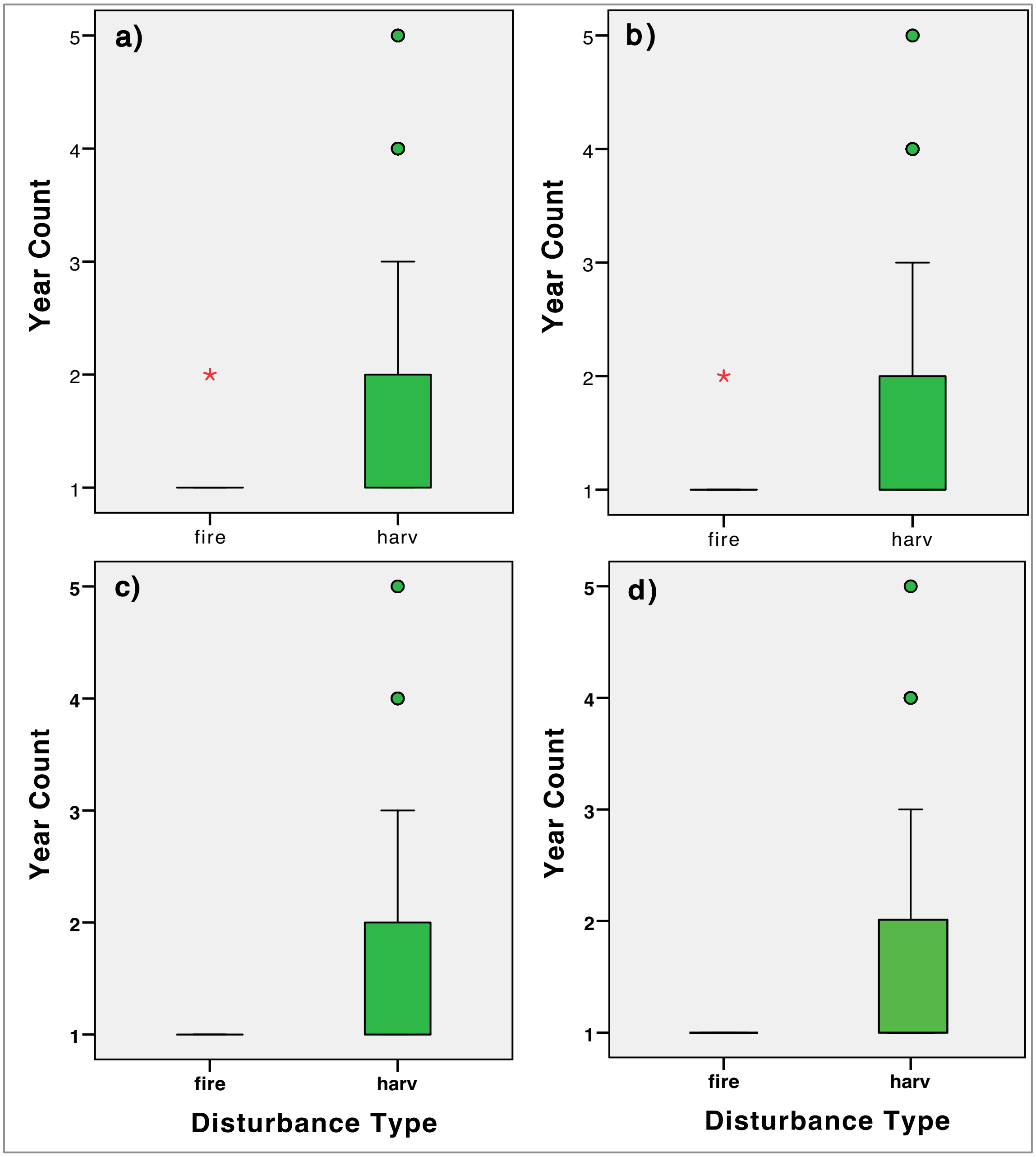

Figure 20: Boxplots depicting disturbed year counts for 30 m shoreline riparian buffers with a single disturbance type. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. The horizontal line represents median year count. Boxes represent the IQR; whiskers represent 1.5 times the IQR from the first and third quartile; hollow circles represent outlier data, and stars represent extreme outliers.

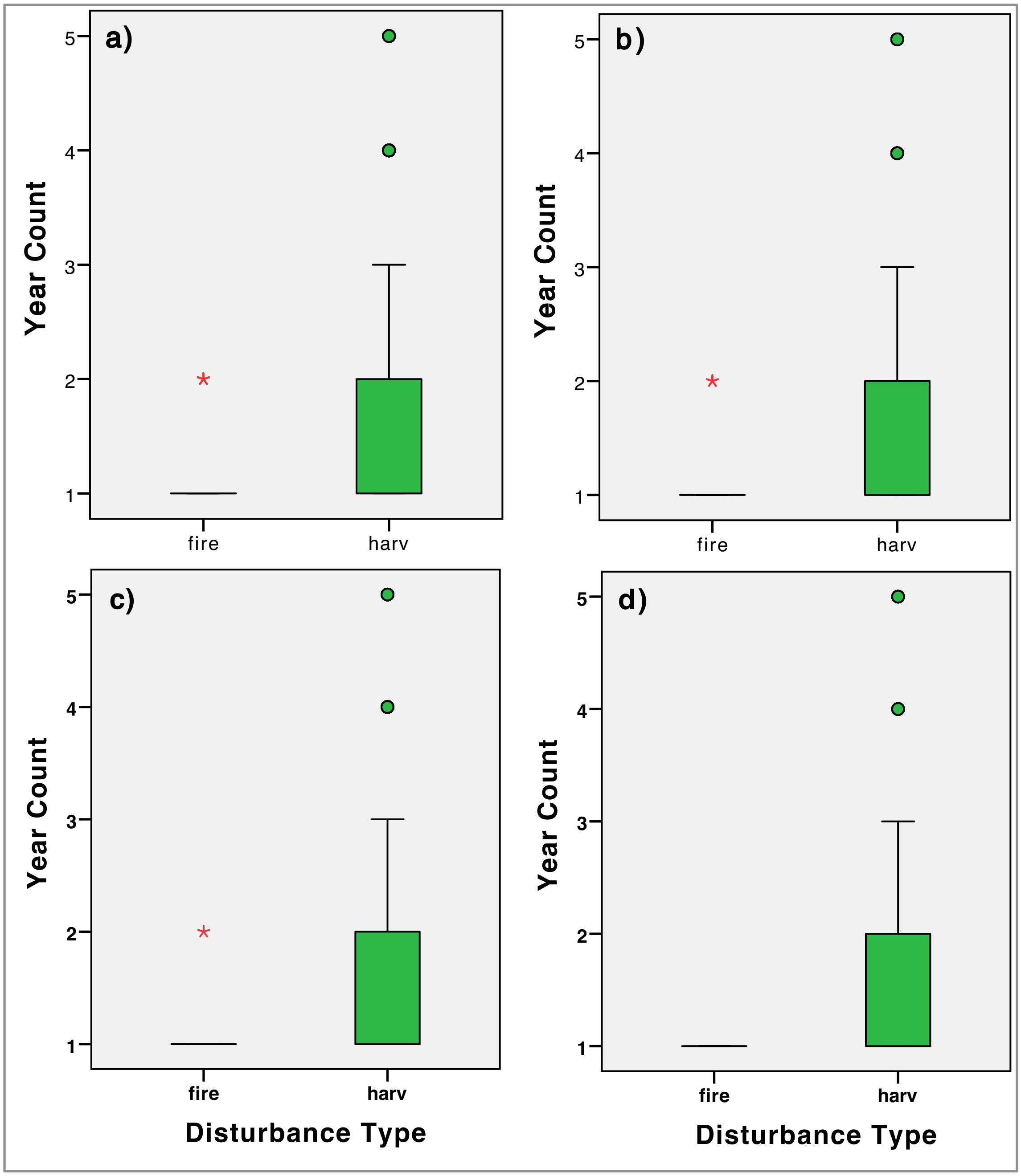

Figure 21: Boxplots depicting disturbed year counts for 90 m shoreline riparian buffers with a single disturbance type. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Boxplot elements are described in Figure 20.

Harvest disturbances in both the 30 and 90 m buffers resulted in significantly greater median numbers of disturbance patches than fire during all study time periods (Tables 11 & 12). During corresponding periods disturbance patch counts in harvested 30 m buffers were between 1.2 and 2.33 times greater than counts resulting from fire. At the 90 m level harvest patch counts increased to between 1.5 and 3.25 times greater than those resulting from fire. The range in disturbance patch counts was also greater in harvested over fire disturbed buffers, with IQRs between 1.5 and 3.25 times greater than fire in the 30 m buffers and 2.5 to 5 times greater in the 90 m. The differences between the disturbance type patch counts and the range in these values is clear when they are plotted together (Figures 22 & 23).

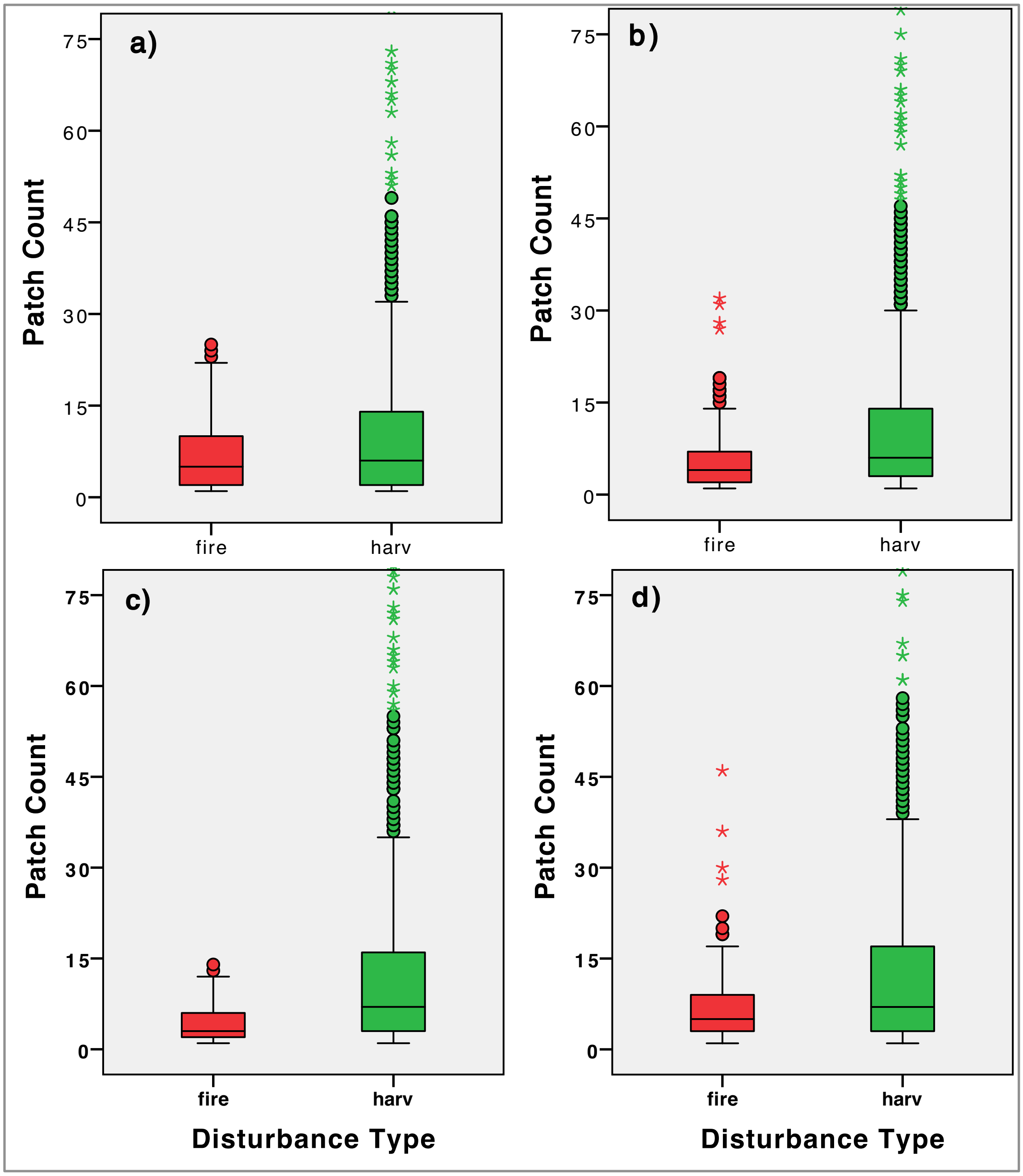

Figure 22: Boxplots depicting disturbance patch count for 30 m shoreline riparian buffers with a single disturbance type. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Patch count axis truncated to better view the disturbance IQR's, extreme outliers removed from the figure: a) 5 harvest, b) 4 harvest, c) 22 harvest, d) 15 harvest. Boxplot elements are described in Figure 20.

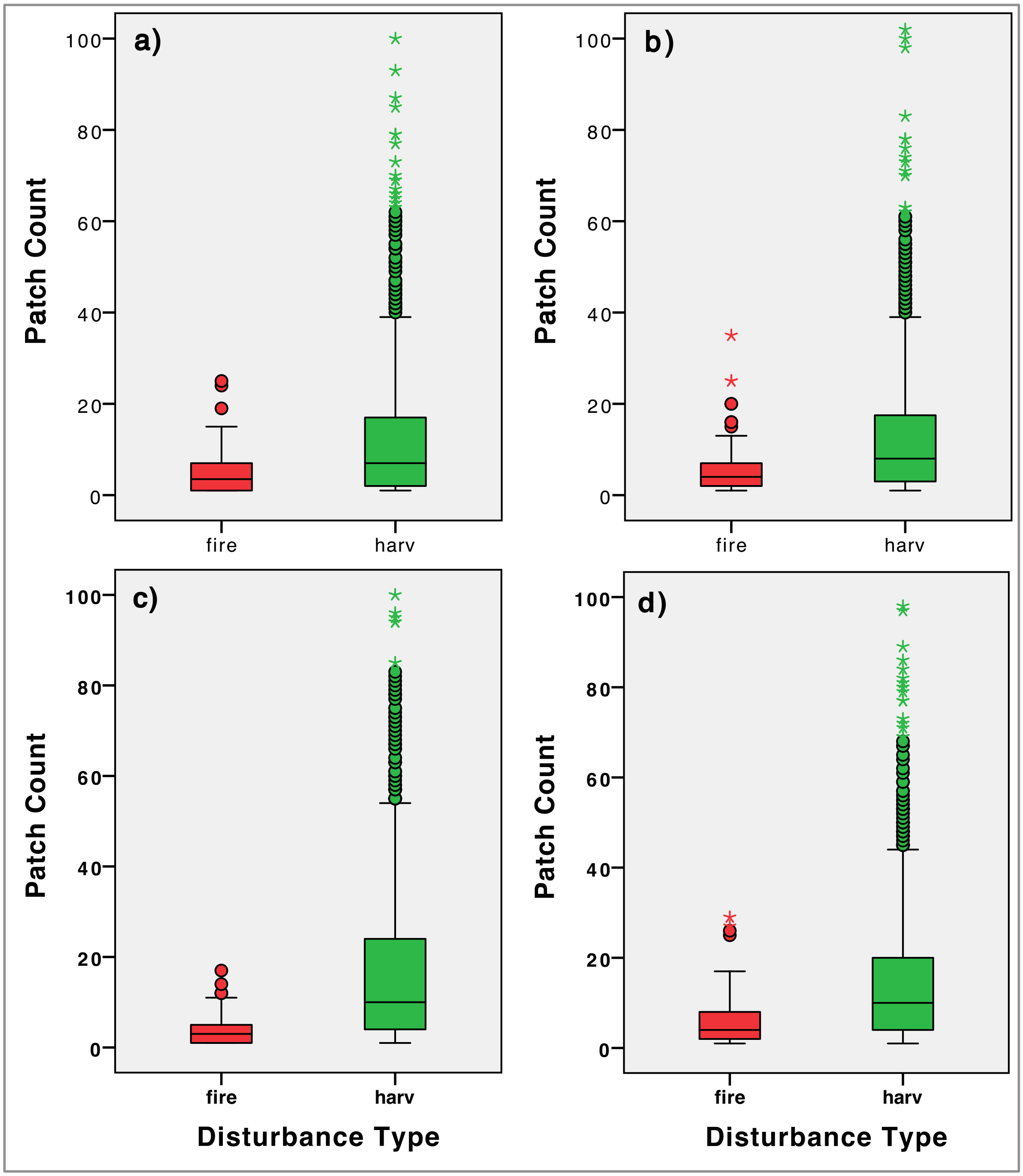

Figure 23: Boxplots depicting disturbance patch count for 90 m shoreline riparian buffers with a single disturbance type. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Patch count axis truncated in subsections b, c, and d to better view the disturbance IQR's, extreme outliers removed from figure: a) n/a, b) 5 harvest, c) 15 harvest, d) 2 harvest. Boxplot elements are described in Figure 20.

Fire disturbance in both the 30 and 90 m study buffers resulted in a significantly greater group median of median disturbance patch sizes than harvest during all study time periods (Tables 11 & 12). During corresponding time periods the group median disturbance patch size was between 14.2 and 90 times greater in fire over harvest disturbed 30 m buffers. Similarly the range of group median patch sizes was also larger in fire disturbed 30 m buffers with IQRs between 20 and 82.5 times greater than those resulting from harvest. In the 90 m buffer fire also resulted in larger group median patch sizes (7.1 to 19 times greater) and a greater range in these values (14.9 to 43.5 times greater) albeit to a lesser extent than in the 30 m buffers. The degree of difference between fire and harvest for this metric is clear both in terms of their medians and range of values when they are plotted together (Figures 24 & 25).

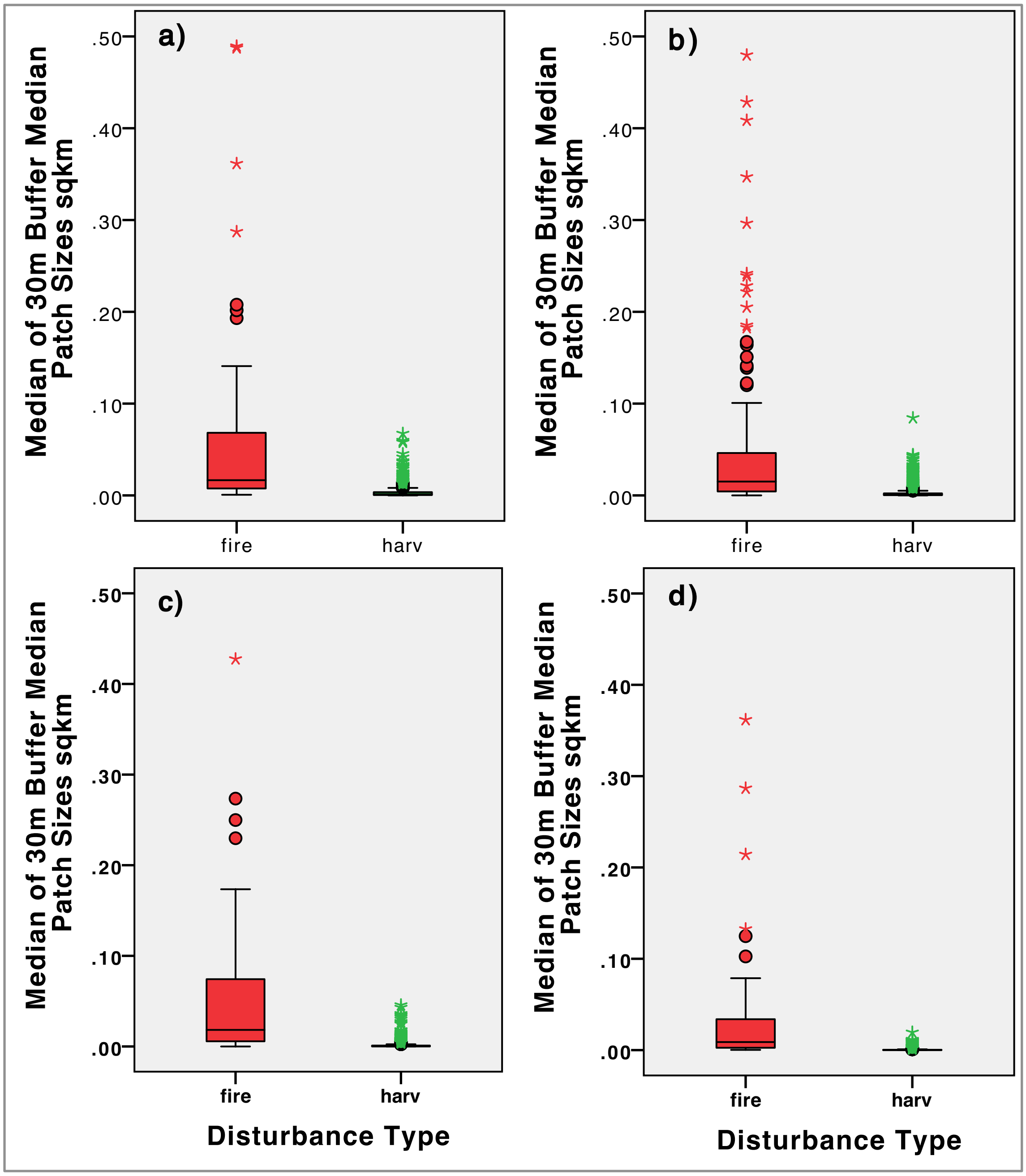

Figure 24: Boxplots depicting the median of 30 m shoreline riparian buffer median disturbance patch sizes. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Median of 30 m buffer patch sizes axis truncated to better view disturbance IQR's, extreme outliers removed from figure: a) 3 fire, b) 4 fire, c) 3 fire, d) 1 fire. Boxplot elements are described in Figure 20.

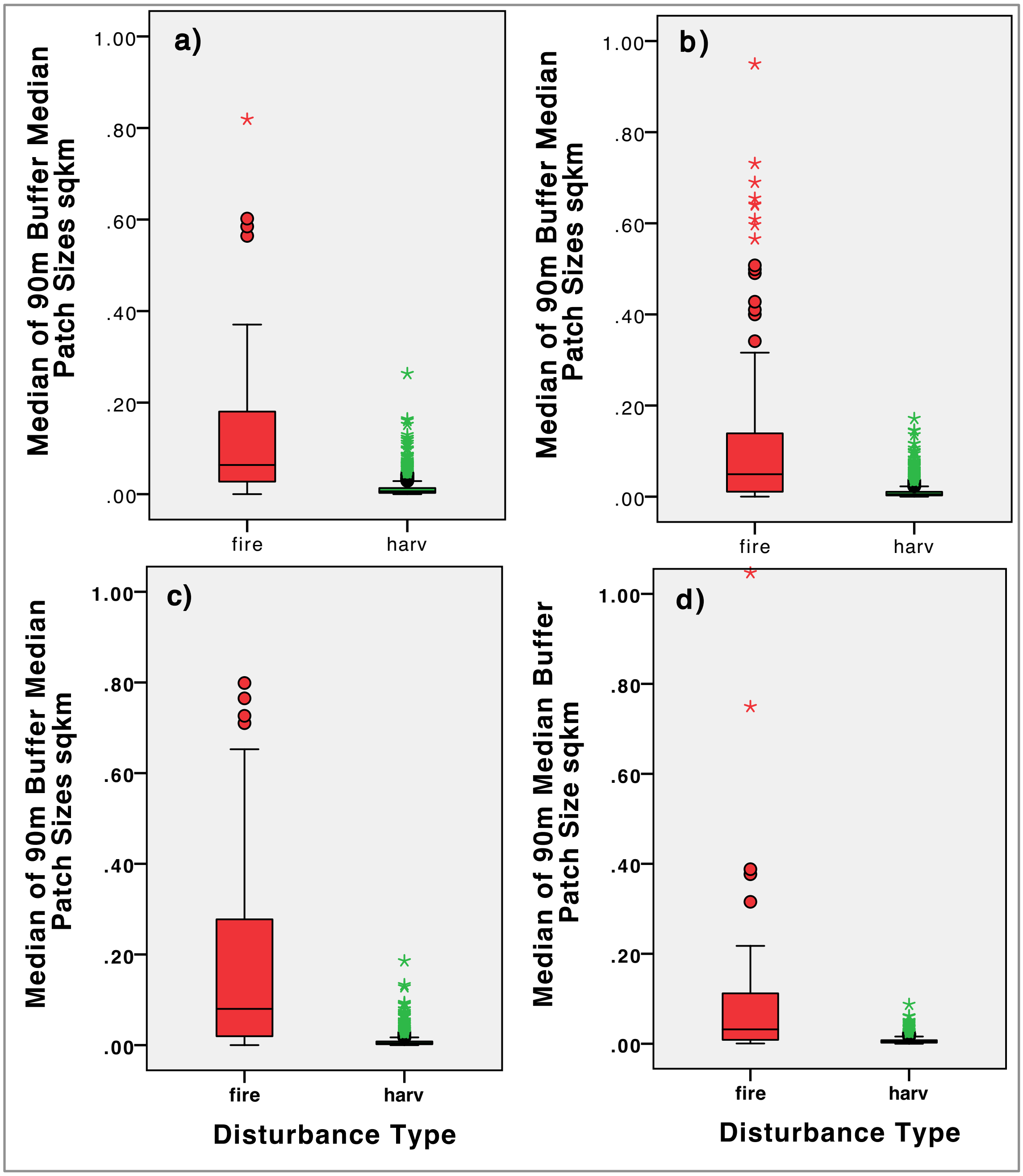

Figure 25: Boxplots depicting the median of 90 m shoreline riparian buffer median disturbance patch sizes. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Median of 90 m buffer median patch sizes axis truncated to better view disturbance IQR's, a) 6 fire, b) 5 fire, c) 5 fire, d) 4 fire. Boxplot elements are described in Figure 20.

Fire disturbance at both the 30 and 90 m buffer levels resulted in a significantly greater median percentage of buffer land area disturbed than harvest during all study time periods (Tables 11 & 12). During corresponding time periods fire disturbed a median percentage of the 30 m buffer area that was between 18 and 108 times greater than that resulting from harvest. Percentage disturbance values were also more variable in fire disturbed 30 m buffer than harvest with IQRs between 17 and 75 times greater than those of harvest disturbance. Results were similar albeit with slightly lessened differences in the 90 m buffer, where the median percent buffer areas disturbed by fire were between 17 and 75 times greater than harvest disturbance percentages, and IQRs between 8 and 13.5 times greater in fire disturbed 90 m buffers over harvest. For both buffer distances the differences between the disturbance types are clearly evident when they are plotted together, while harvest was concentrated well below 20% buffer area disturbance fire resulted in a wide range of disturbances percentages with several buffers disturbed in or near 100% of their area (Figures 26 & 27).

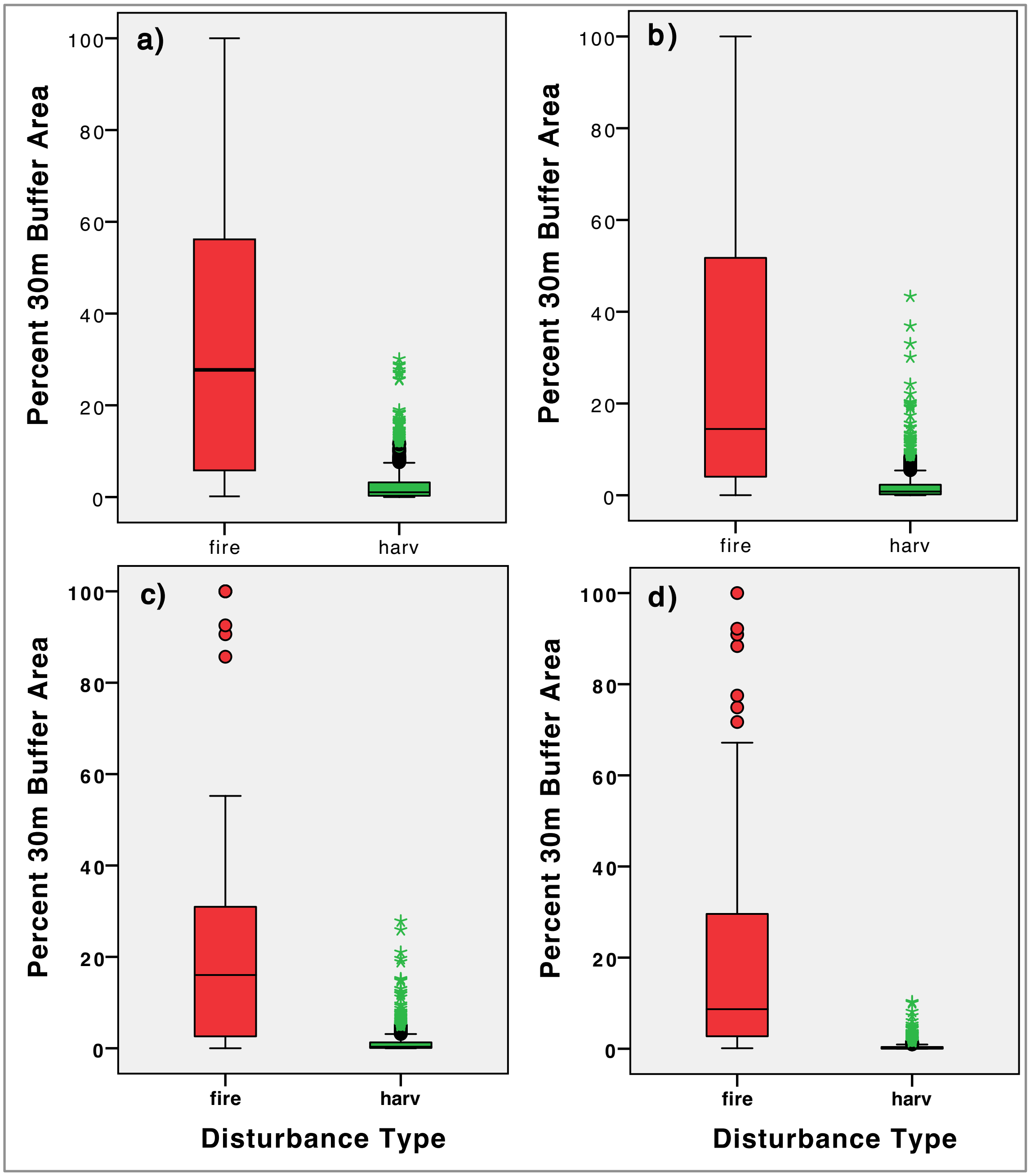

Figure 26: Boxplots depicting the percentage of 30 m shoreline riparian buffer area disturbed in single disturbance type watersheds. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Boxplot elements are described in Figure 20.

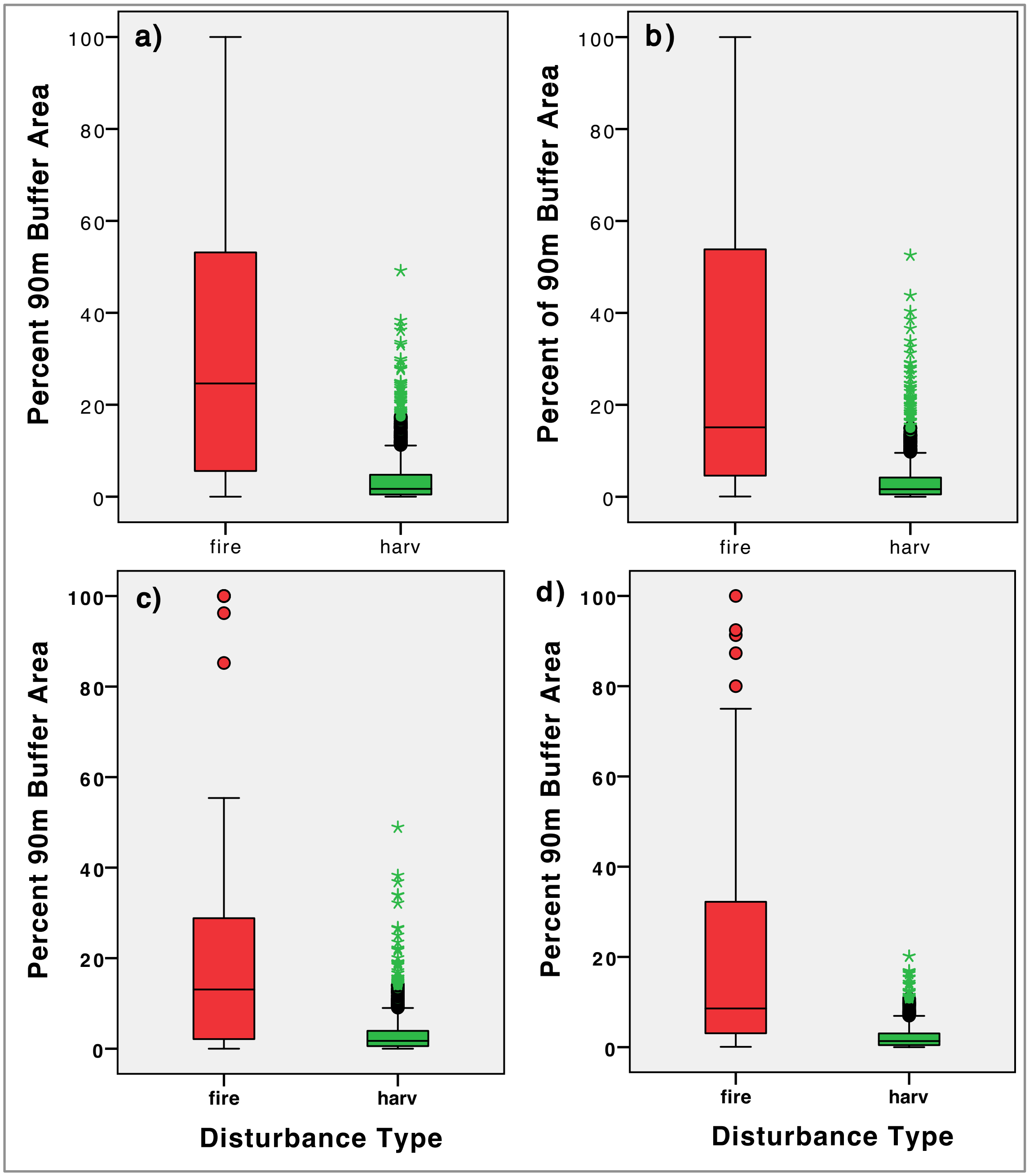

Figure 27: Boxplots depicting the percentage of 90 m shoreline riparian buffer area disturbed in single disturbance type watersheds. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Boxplot elements are described in Figure 20.

Harvest disturbance was significantly more complex in shape, with significantly greater median perimeter to area ratios than fire in both the 30 and 90 m buffers during all study time periods (Tables 11 & 12). In the 30 m buffer median perimeter to area ratios resulting from harvest were between 2 and 6.6 times greater than those resulting from fire during corresponding time periods. Harvest was also more variable in this metric with IQRs ranging between 4.4 and 71.5 times greater than those resulting from fire in the 30 m buffers. Similarly, harvest disturbances in the 90 m buffer had greater complexity than fire, with median perimeter to area ratios between 2.7 and 3.3 times greater than those resulting from fire. Harvest disturbance was also more variable and fire in terms of the perimeter to area ratios within the 90 m buffer although to a lesser degree than in the 30 m, with IQRs between 2.4 and 4.8 times greater than those resulting from fire. The degree of difference between the disturbance types in terms of their complexity is clear when they are plotted together, both the range and outlying values in perimeter to area ratios are far greater in harvested over fire disturbed riparian buffers (Figures 28 & 29).

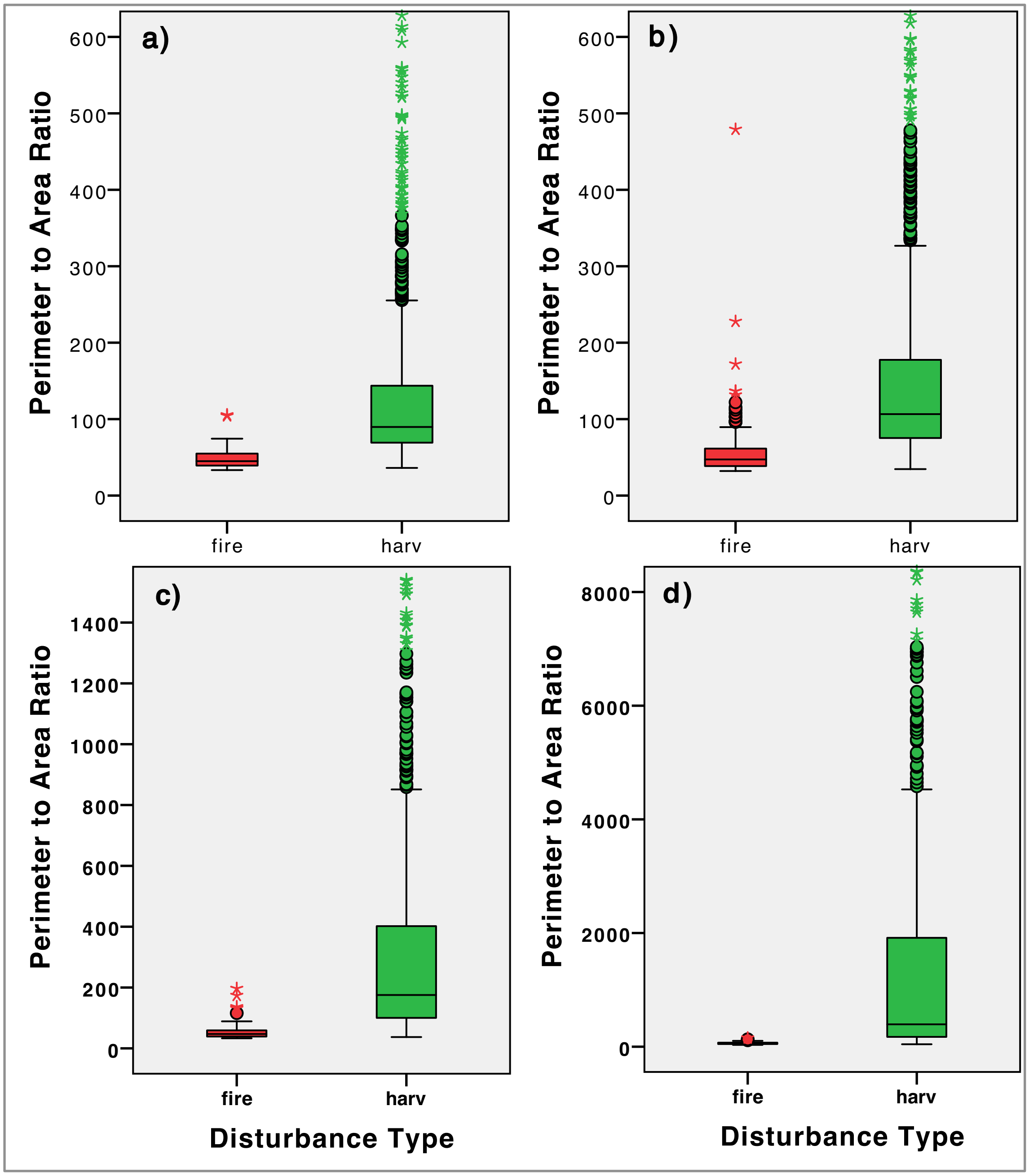

Figure 28: Boxplots depicting the perimeter to area ratio for 30 m shoreline riparian buffers with a single disturbance type. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Perimeter to area ratio axis truncated to better view disturbance IQR's, extreme outliers removed from the figure: a) 41 harvest, b) 56 harvest, c) 85 harvest, d) 124 harvest. Boxplot elements are described in Figure 20.

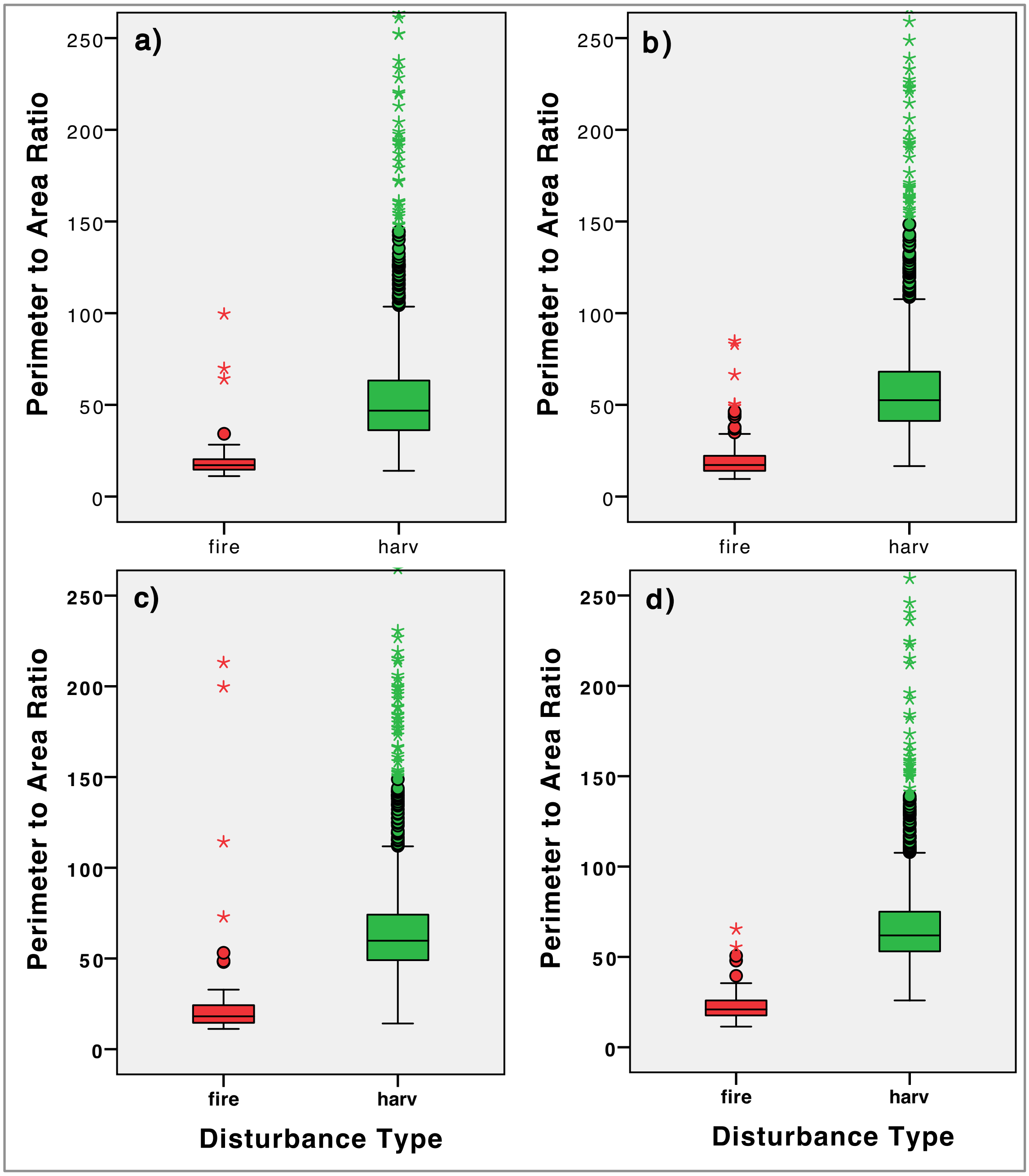

Figure 29: Boxplots depicting the perimeter to area ratio for 90 m shoreline riparian buffers with a single disturbance type. Subfigures represent the study time periods a) 1990-1994, b) 1995-1999, c) 2000-2004, and d) 2005-2009. Perimeter to area ratio axis truncated to better view disturbance IQR's, extreme outliers removed from figure: a) 2 fire 36 harvest, b) 25 harvest, c) 22 harvest, d) 17 harvest. Boxplot elements are described in Figure 20.

3.3.3 Landscape Pattern of Shoreline Riparian Disturbance

At a landscape scale, the spatial pattern of disturbance within both the 30 and 90 m buffers differed significantly between fire and harvest disturbance (Tables 13 & 14). At the 30 m level, fire disturbance was less frequent but resulted in wide a range of buffer disturbances from <10% to >90% of the buffer area. Conversely, harvest disturbance within the 30 m buffer was concentrated below the 10% disturbance level (Figures 30-33 a). The cumulative percentage frequency distributions show fire gradually increasing through the range of disturbance bins whereas harvest rapidly approaches its maximum in the first bin of <10% area disturbed (>1000 buffers), during each study time period (Figures 30-33a). Results were similar when examining the frequency distributions of 90 m buffer disturbance. Fire resulted in a range of buffer disturbance percentages from <10% to >90%, with a gradual increase in cumulative percent frequency distribution of disturbance percentage (Figures 30-33 b). Harvest within the 90 m buffers generally disturbed <10% of buffer area and the cumulative percent frequency distribution approached its maximum in the first bin during each study period (Figures 30-33 b). KS test comparisons of 30 and 90 m buffer disturbance by fire and harvested were also conducted within each ecoregion in the study area, the results of these comparisons can be found in Appendix B.

Frequency distributions of the extent of disturbance by fire within 30 and 90 m buffers were similar and consistent across the study time periods. Contrasting this, distributions for harvest disturbance differed between the two buffer distances, and this difference was not consistent over the study time periods (Figures 30-33). During each time period, 90 m buffers had more examples of higher levels of disturbance than the 30 m buffers. As example, the maximum disturbance in 30 m buffers was in the 30-40%, 40-50%, 20-30%, and 10-20% bins respectively during the 1990-1994, 1995-1999, 2000-2004, and 2005-2009 periods, over the same periods maximum disturbance in 90 m buffers was in the 40-50%, 50-60%, 40-50%, and 20-30% bins (Figures 30-33). There was also a downward trend in the highest levels of disturbance in both 30 and 90 m buffers over time. Harvest within the 30 m buffers had maximum levels in the 30-40% and 40-50% range during the 1990-1994 and 1995-1999 periods, which then declined to the 20-30% and 10-20% range respectively during the 2000-2004 and 2005-2009 periods (Figures 30-33 a). Similarly, the maximum harvest level within 90 m buffers was in the 50-60% range during the 1995-1999 period, and dropped to a maximum in the 20-30% range during the 2005-2009 period (Figures 30-33 b). For both of the buffer widths examined fewer appear to be harvested in >10% of their respective areas over time.

Table 13: KS test statistics for comparisons of frequency distributions of percent 30 m buffer area disturbed by fire and harvest within the full study area, during each study time period.

Disturbance Descriptor	Time Period	Num. Fire	Num. Harvest	Abs. Difference	Test Statistic	p value
Percentage of 30m buffer area disturbed	1990-1994	70	1106	0.655	5.317	**< 0.001**
Percentage of 30m buffer area disturbed	1995-1999	183	1151	0.626	7.864	**< 0.001**
Percentage of 30m buffer area disturbed	2000-2004	71	1121	0.663	5.416	**< 0.001**
Percentage of 30m buffer area disturbed	2005-2009	73	936	0.792	6.514	**< 0.001**

Table 14: KS test statistics for comparisons of frequency distributions of percent 90 m buffer area disturbed by fire and harvest within the full study area, during each study time period.

Disturbance Descriptor	Time Period	Num. Fire	Num. Harvest	Abs. Difference	Test Statistic	p value
Percentage of 90m buffer area disturbed	1990-1994	74	1264	0.587	4.909	**< 0.001**
Percentage of 90m buffer area disturbed	1995-1999	178	1335	0.569	7.134	**< 0.001**
Percentage of 90m buffer area disturbed	2000-2004	70	1340	0.537	4.378	**< 0.001**
Percentage of 90m buffer area disturbed	2005-2009	71	1172	0.543	4.446	**< 0.001**

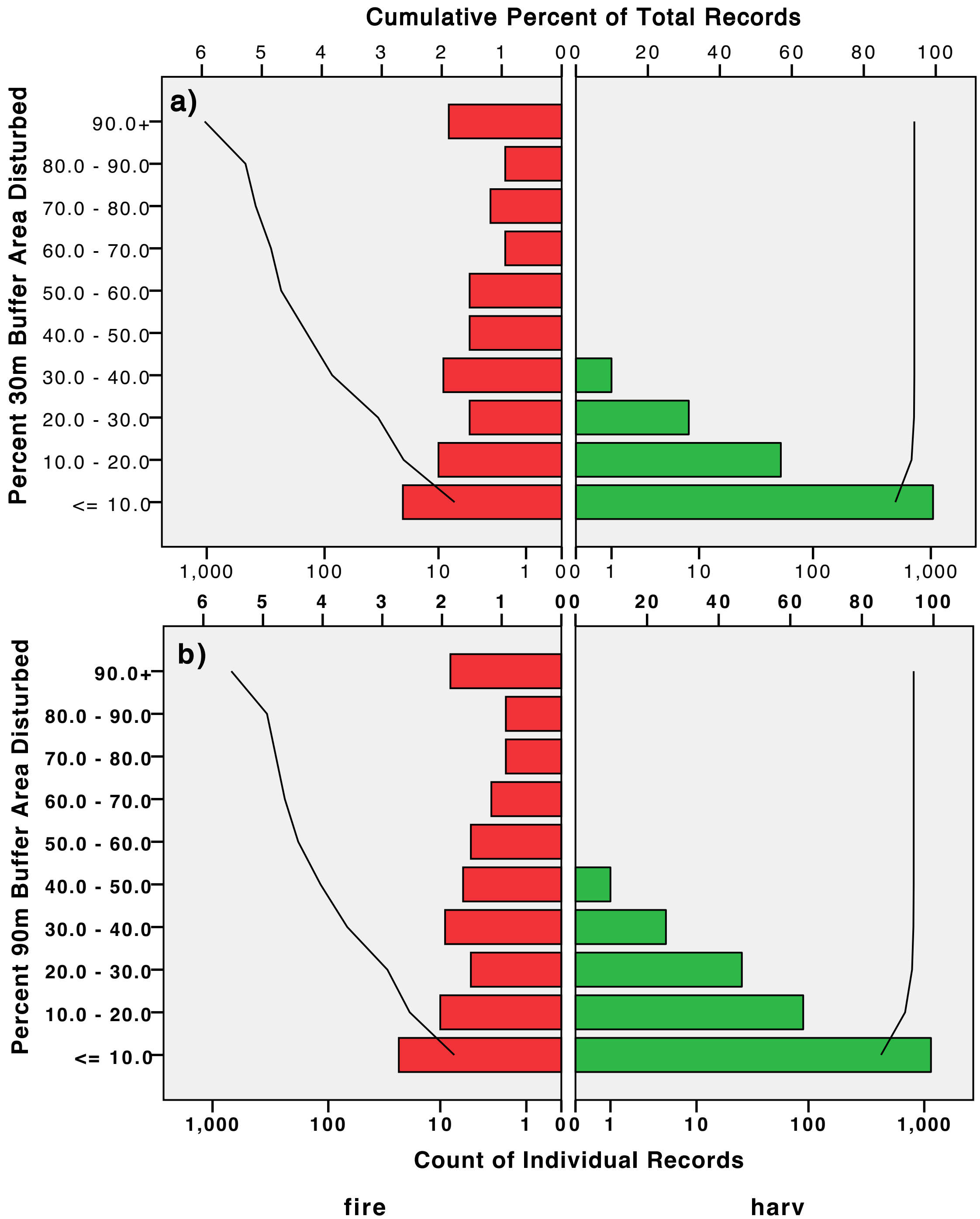

Figure 30: Frequency distributions and cumulative percent frequency distributions percent area disturbed by fire and harvest within a) 30 m study buffers, and b) 90 m study buffers during the 1990-1994 time period.

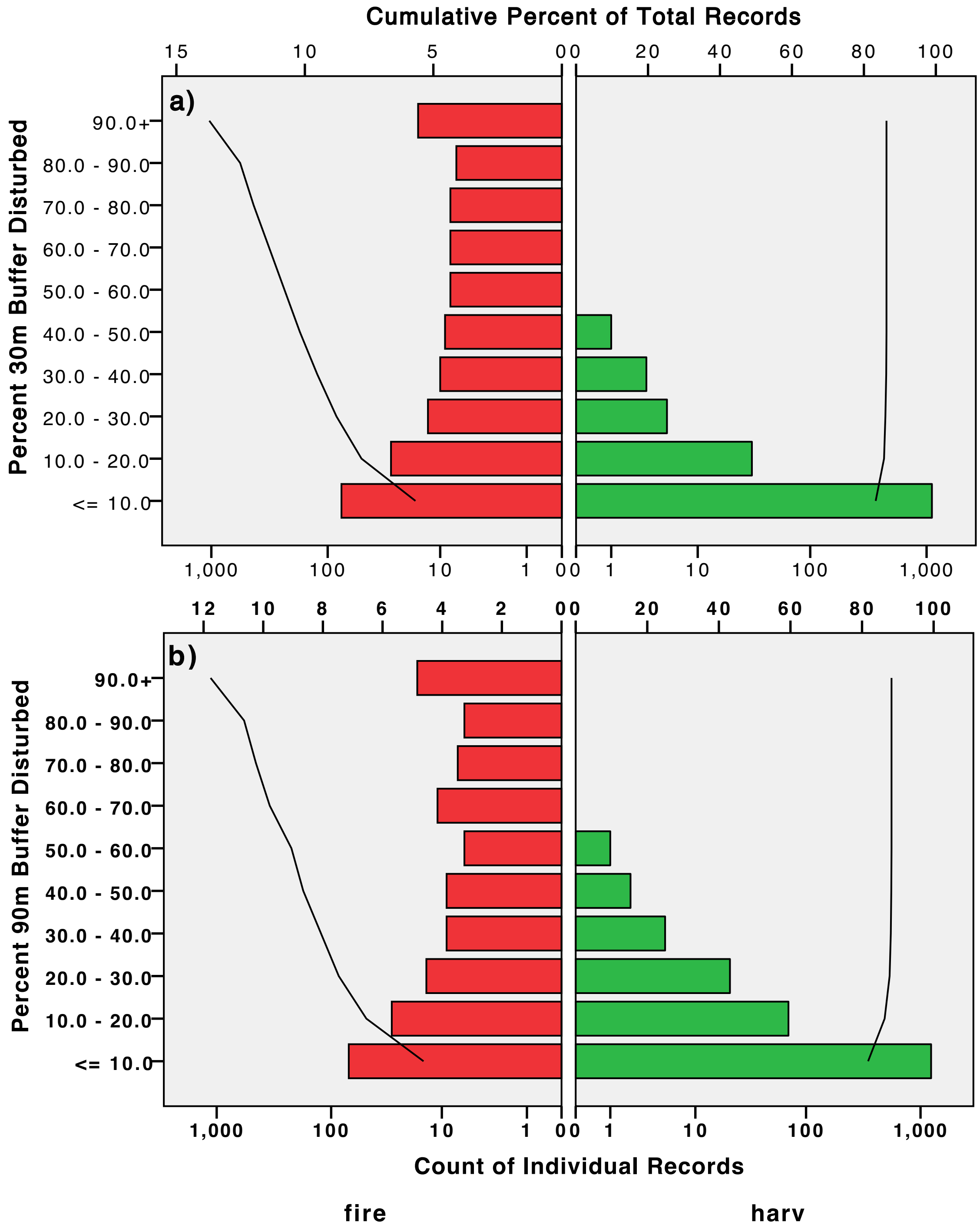

Figure 31: Frequency distributions and cumulative percent frequency distributions percent area disturbed by fire and harvest within a) 30 m study buffers, and b) 90 m study buffers during the 1995-1999 time period.

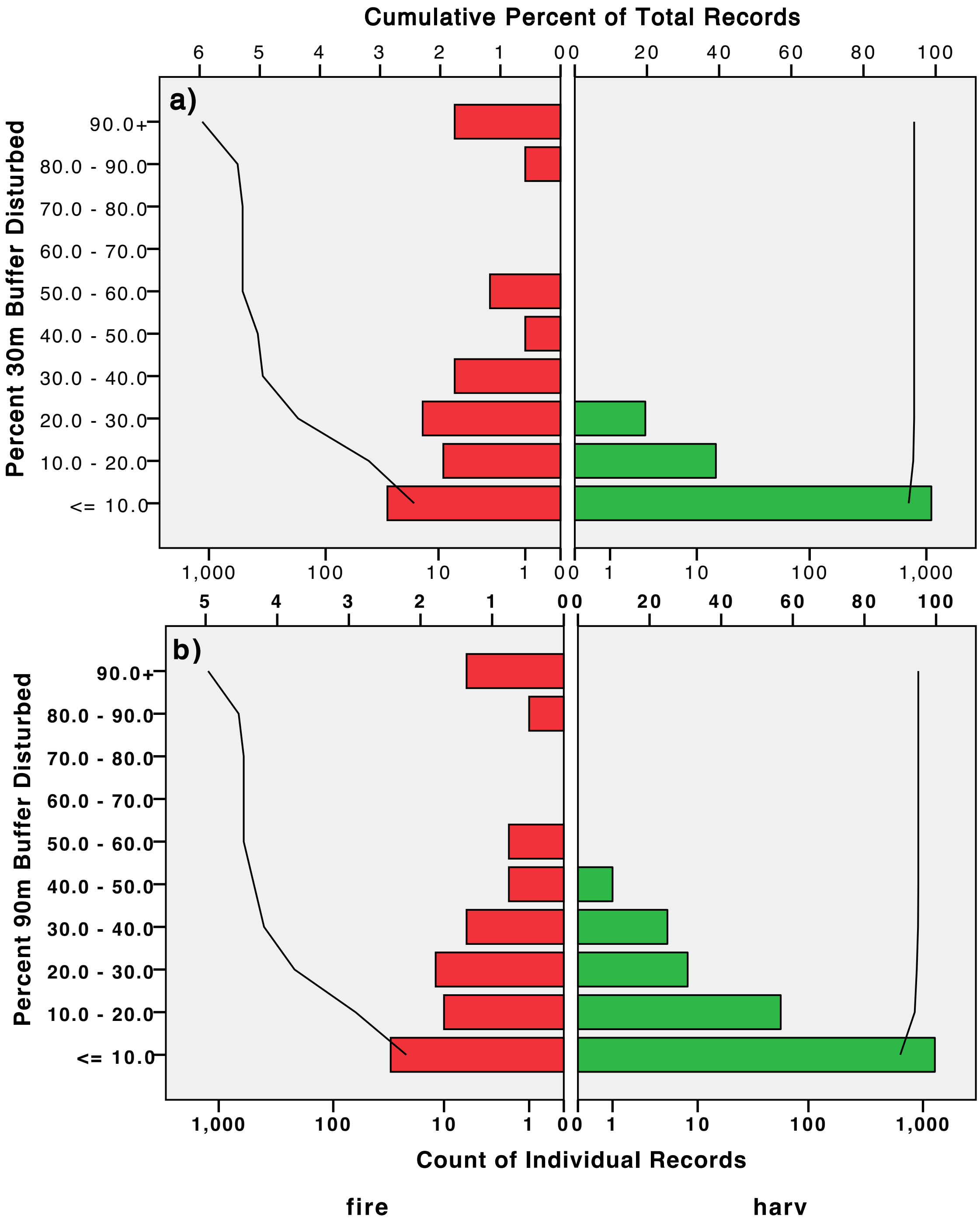

Figure 32: Frequency distributions and cumulative percent frequency distributions percent area disturbed by fire and harvest within a) 30 m study buffers, and b) 90 m study buffers during the 2000-2004 time period.

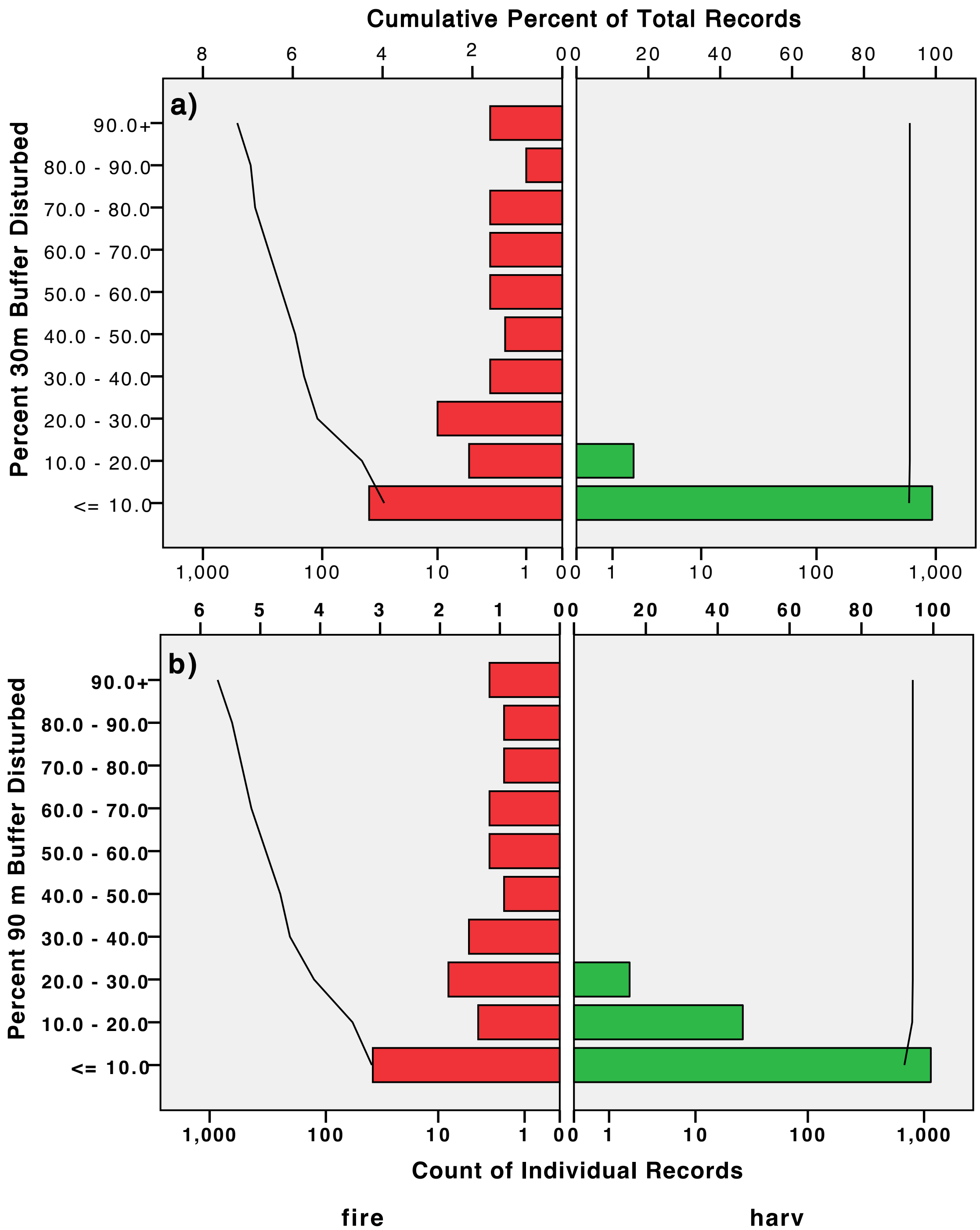

Figure 33: Frequency distributions and cumulative percent frequency distributions percent area disturbed by fire and harvest within a) 30 m study buffers, and b) 90 m study buffers during the 2005-2009 time period.

3.3.4 Relationship Between Shoreline Riparian and Watershed Disturbance

During all study time periods the percentage of buffer area disturbed was positively associated with the percentage of watershed land area disturbed for both disturbance types. This was true for each of the 30, 90, and outer 60 m buffer types (Figures 34-37). However the relationship between watershed and buffer disturbance area differed between the disturbance types. Fire disturbance showed an almost directly proportional relationship between watershed area and buffer area disturbed (i.e. 1:1 regression slope) for all buffer widths in all time periods, whereas harvest disturbance within the buffers did not increase in direct proportion to watershed disturbance. The significance of this difference between the disturbance types was assessed by the interaction between disturbance type and watershed area disturbed in the ANCOVA model (Table 15). The difference was highest in 30 m harvested buffers where percent buffer area disturbed increased by approximately 0.5% or less for every 1% increase in watershed disturbance area (i.e. regression slope of 0.5). The difference was less pronounced in the 90 m and outer 60 m harvested buffers, which were more similar to fire but not directly proportional (Figures 34-37). Abbreviated ANCOVA tables describing the relationship between buffer and watershed disturbance during each study time period are available in Appendix D.

Table 15: ANCOVA interaction terms describing the relationship between disturbance in the 30, 90, and outer 60 m buffers and watershed disturbance during each study time period.

Time Period	Dependent Variable (Log10 of percent area disturbed)	Interaction Term	Type III Sum of Squares	df	Mean Square	F	p value
1990-1994	30 m Buffer	Disturbance Type * log10(percent watershed area disturbed)	8.393	1	8.393	151.448	< 0.001
	90 m Buffer		3.519	1	3.519	83.641	< 0.001
	Outer 60 m Buffer		2.266	1	2.266	53.164	< 0.001
1995-1999	30 m Buffer	Disturbance Type * log10(percent watershed area disturbed)	19.568	1	19.568	370.025	< 0.001
	90 m Buffer		5.635	1	5.635	142.448	< 0.001
	Outer 60 m Buffer		2.988	1	2.988	73.628	< 0.001
2000-2004	30 m Buffer	Disturbance Type * log10(percent watershed area disturbed)	10.514	1	10.514	233.593	< 0.001
	90 m Buffer		1.232	1	1.232	34.401	< 0.001
	Outer 60 m Buffer		0.27	1	0.27	6.705	0.01
2005-2009	30 m Buffer	Disturbance Type * log10(percent watershed area disturbed)	19.711	1	19.711	1142.365	< 0.001
	90 m Buffer		2.936	1	2.936	114.658	< 0.001
	Outer 60 m Buffer		1.149	1	1.149	35.236	< 0.001

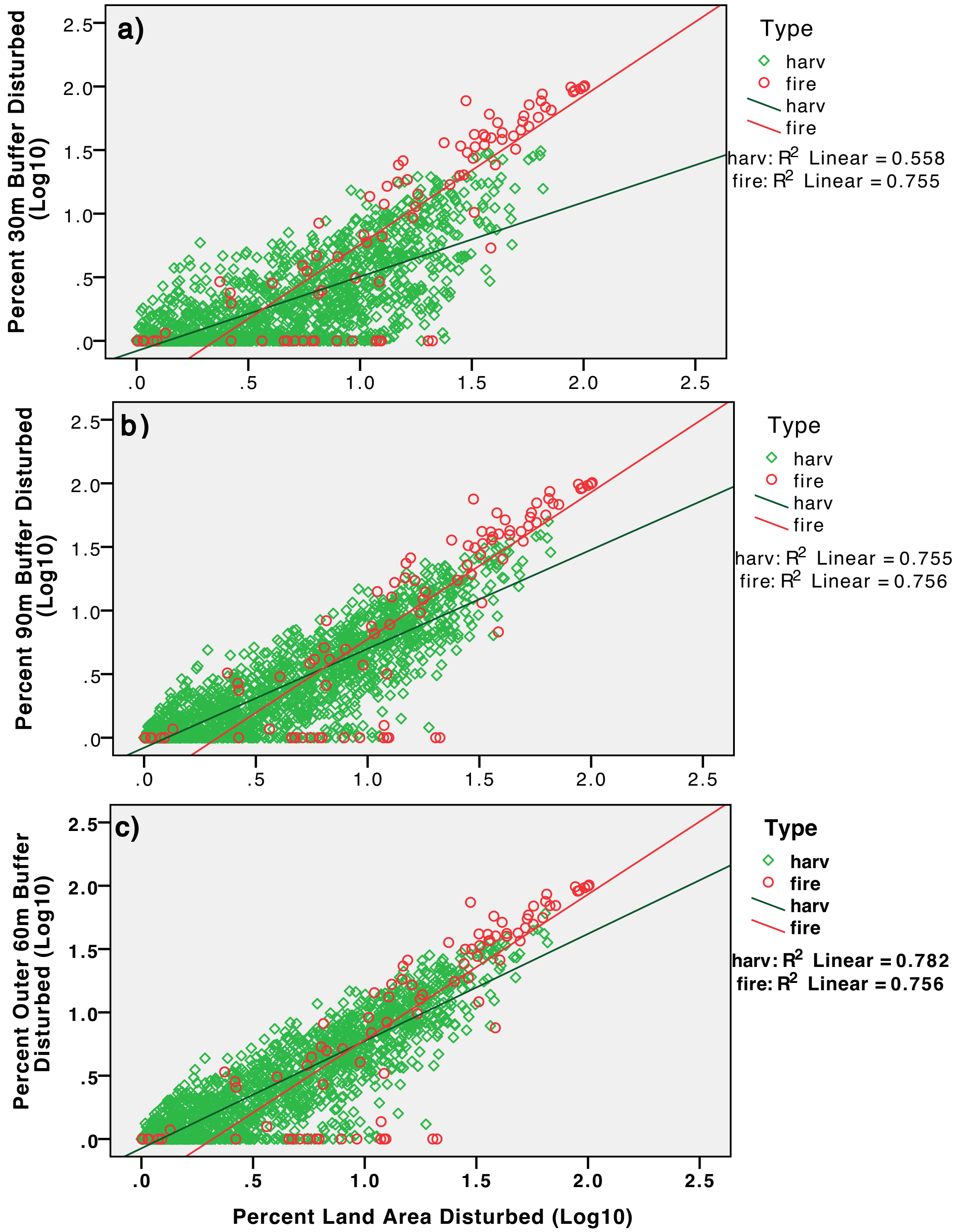

Figure 34: Scatterplots depicting the relationship between percent buffer area disturbed and percent watershed land area disturbed by fire and harvest during the 1990-1994 time period, with best fit lines for the disturbance types. Subfigures represent the different buffer distances employed in this study a) 30 m, b) 90 m, c) outer 60 m.

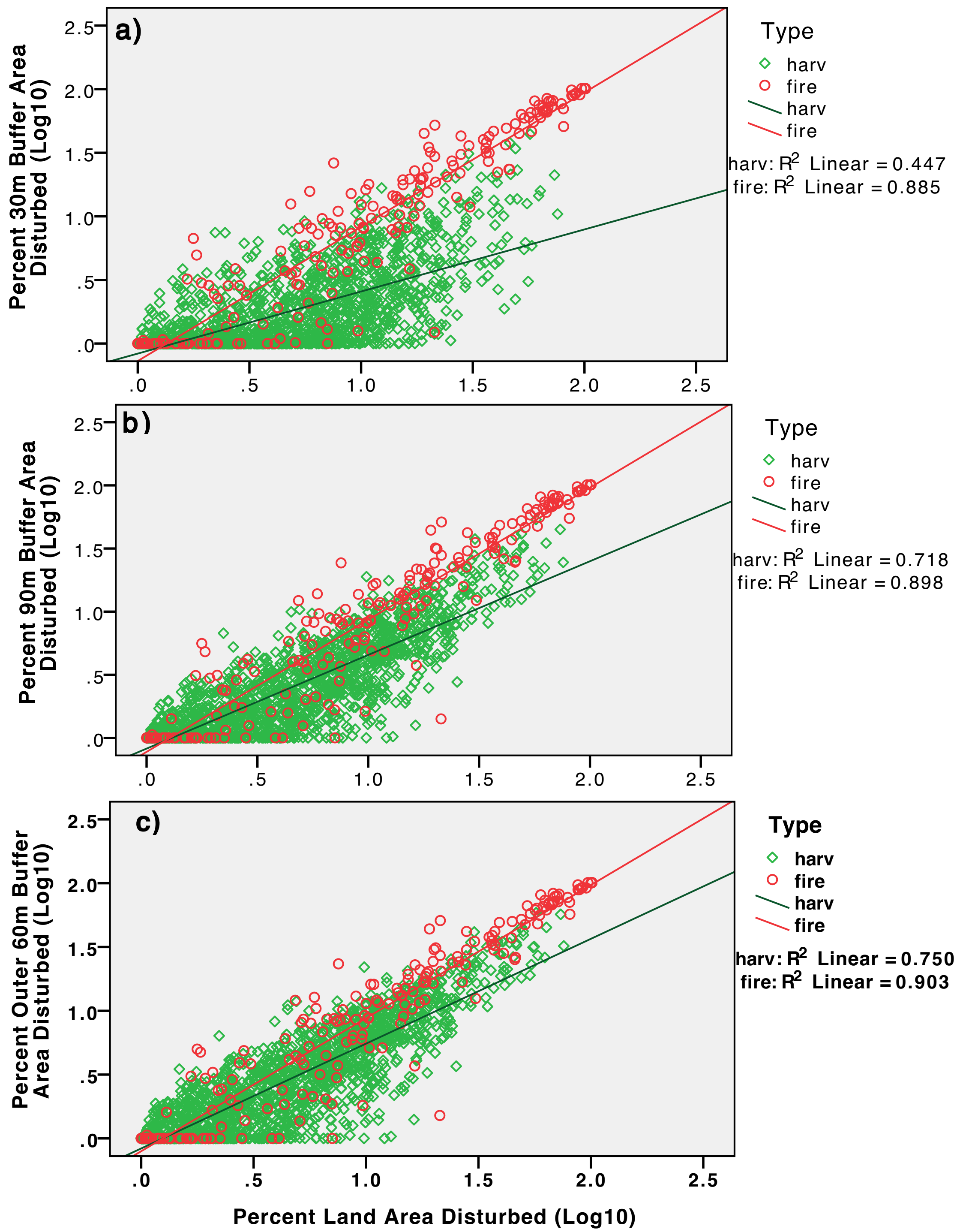

Figure 35: Scatterplots depicting the relationship between percent buffer area disturbed and percent watershed land area disturbed by fire and harvest during the 1995-1999 time period, with best fit lines for the disturbance types. Subfigures represent the different buffer distances employed in this study a) 30 m, b) 90 m, c) outer 60 m.

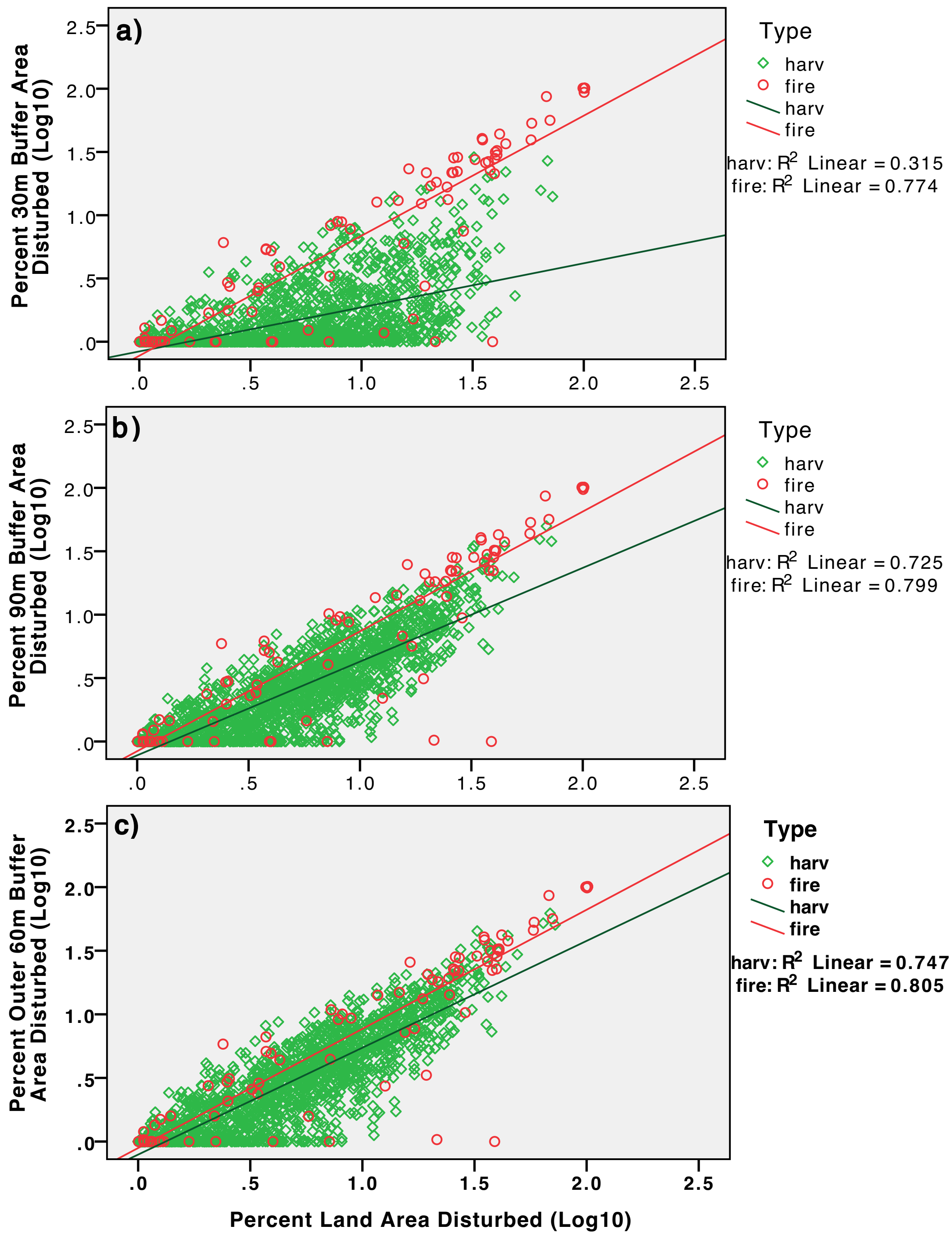

Figure 36: Scatterplots depicting the relationship between percent buffer area disturbed and percent watershed land area disturbed by fire and harvest during the 2000-2004 time period, with best fit lines for the disturbance types. Subfigures represent the different buffer distances employed in this study a) 30 m, b) 90 m, c) outer 60 m.

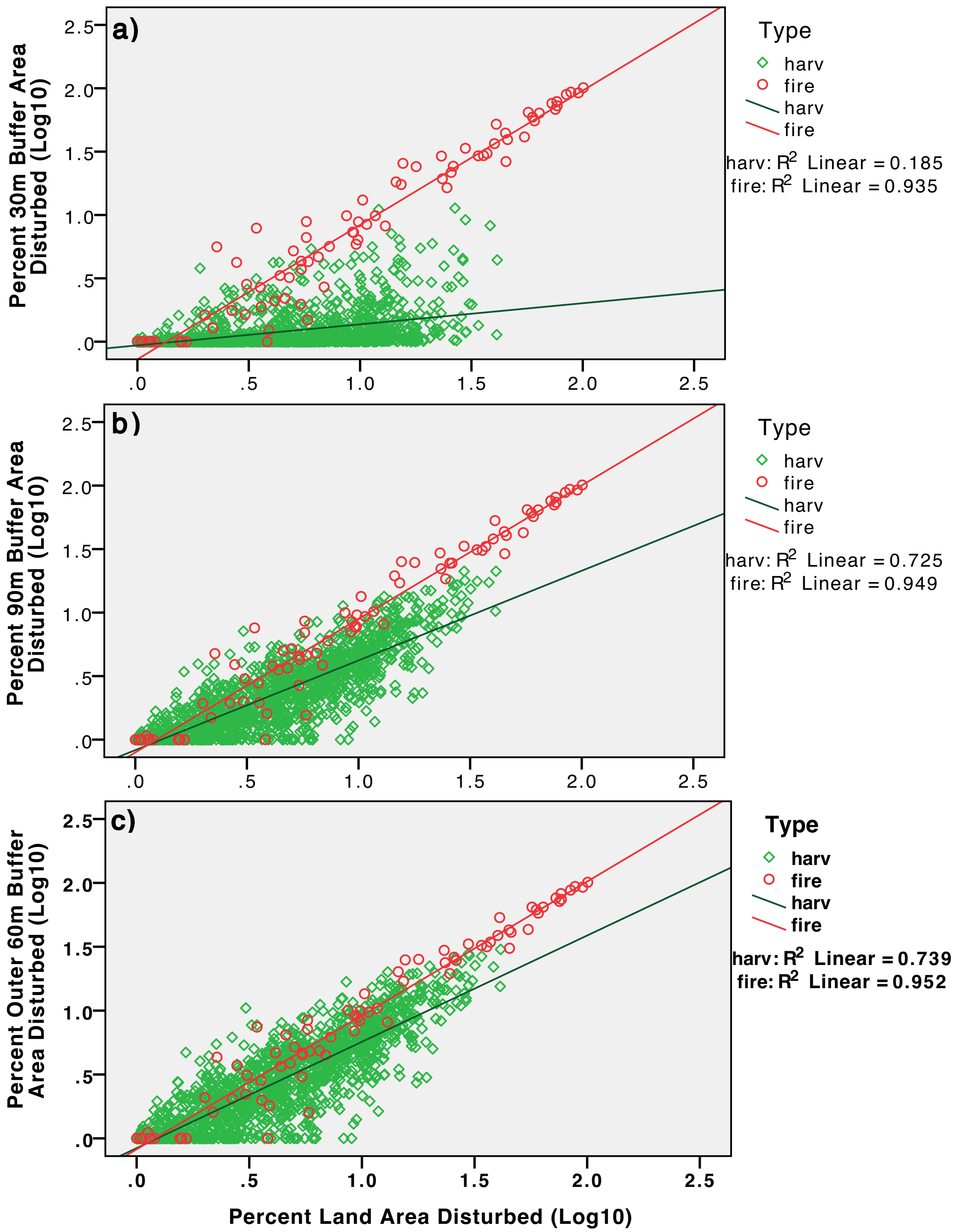

Figure 37: Scatterplots depicting the relationship between percent buffer area disturbed and percent watershed land area disturbed by fire and harvest during the 2005-2009 time period, with best fit lines for the disturbance types. Subfigures represent the different buffer distances employed in this study a) 30 m, b) 90 m, c) outer 60 m.

3.4 Discussion

Current forest management practices in Ontario employ a reserve forested area that restricts most shoreline harvest activity (Lamb *et al.,* 2003; OMNR 2010). These practices prevent harvest activity within riparian forests that would naturally be affected by fire (Buttle 2002; Lamb *et al.,* 2003; Sibley *et al.,* 2012), and accordingly are expected to be a major source of difference between the disturbance types. Additionally, disturbance influence on streamflow may increase with decreasing distance to the stream channel (Abdelnour *et al.,* 2011). It is clear from the analyses conducted that forest harvest activities in Ontario's boreal forest do not result in similar patterns of disturbance as fire within riparian forests, although the differences are lessened the greater the riparian buffer width considered. This is true in terms of the prevalence of the disturbance types, the extent of their disturbance, and the landscape pattern of disturbance across the landscape. The differences observed have important implications in both terms of successional patterns in riparian forests, and boreal stream environments.

Harvest disturbance, while more frequent than fire resulted in a far lower extent of disturbance within riparian forests. Harvest at both buffer widths disturbed a lower percentage of shoreline buffer area, typically less than 10%, and generally resulted in more numerous disturbance patches, which were smaller, more complex in shape, and often spread out over a number of years in each study time period. Fire disturbance within shoreline riparian buffers was far less common, and resulted in a far greater extent and range of disturbances within riparian forests. At both buffer widths fire disturbed a greater percentage of shoreline buffer area, up to and including 100% disturbance, generally in fewer but larger disturbance patches that were less complex in their shape, usually occurring during a single year of a study period. The measured differences between the disturbance types were largely consistent regardless of the buffer width examined, although differences were somewhat diminished when comparing the 90 m buffer to the 30 m.

Differences observed between the disturbance types are largely in agreement with other studies that describe the disturbance regimes of fire and harvest, and their spatial pattern of disturbance, although in many cases these studies were not conducted specifically within riparian forests. Patch densities have been shown to be greater in harvested versus fire disturbed landscapes (Schroeder & Perera 2002). This is consistent with the greater median patch numbers and variability in patch numbers observed in my study. Patch sizes have been shown to be greater for fire disturbances versus harvest in Ontario's boreal forest (Schroeder & Perera 2002), which is consistent with my observation of significantly larger group median values of median disturbance patch sizes within fire disturbed shoreline riparian buffers at both distances. Fire disturbances have been described as having a general ellipse pattern compared with straight edged block like shapes of harvest disturbance (McRae *et al.,* 2001). In this study I observed higher perimeter to area ratios in harvest disturbed shoreline riparian buffers of both widths due to straight edged block like shapes in harvests having higher perimeter to area ratios than rounded ellipse shapes. Finally, the range of fire disturbance sizes has been described as covering a few, to hundreds or thousands of hectares (Bouchard *et al.,* 2008; McRae *et al.,* 2001), and in Ontario's boreal forest fire regularly burns to the stream edge (Buttle 2002; Lamb *et al.,* 2003; Sibley *et al.,* 2012). Conversely, the range in harvest disturbance sizes has been described as covering only a small subset of the potential range of fire (McRae *et al.,* 2001), and harvest is regularly restricted from nearly all harvest activity near mapped water features, particularly within 30 m from shore (Lamb *et al.,* 2003; OMNR 2010). Differences in disturbance area within shoreline riparian buffers was one of the major differences between fire and harvest observed in this study, with frequency and cumulative frequency distributions of harvest disturbed buffers severely clustered towards the lowest levels of disturbance (10% buffer area) at both buffer widths, whereas fire resulted in a wide range of disturbances up to and including 100% of the buffer area.

Interestingly, in terms of shared disturbance metrics that were examined at both the riparian and watershed scale, differences measured between the disturbance types were largely consistent. When a disturbance type resulted in a significantly greater median value for a disturbance metric at the watershed scale it also resulted in a significantly greater median values in the buffer widths examined at the riparian scale. In terms of the extent and landscape pattern of disturbance in watersheds and their riparian forests, fire was particularly consistent, resulting in a wide range of disturbances up to and including 100% area disturbed in watersheds and both buffer widths. Harvest disturbance was far less consistent; although in both watersheds and riparian forests harvest disturbance was concentrated toward low levels of disturbance this concentration was not constant between watersheds and riparian forests, or even between the 30 and 90 m buffer widths. Examining the relationship between percent watershed and percent buffer area disturbed further clarifies this difference between the disturbance types. Fire disturbance showed an almost directly proportional relationship between watershed and buffer area disturbed (i.e. 1:1 regression slope), regardless of the buffer width examined (30, 90, and outer 60 m) during all study time periods. This proportional relationship between upland and riparian disturbance is consistent with descriptions of fire disturbed landscapes in the literature (Arkle & Pilliod 2010). Harvest disturbance most greatly differed from this proportional relationship within the 30 m buffer width, where the percentage of buffer area disturbed increased by only 0.5% for every 1 % increase in watershed disturbance area. Differences became less pronounced when more upland area was included with the buffer width at 90 m, even more so when the 30 metres closest to shore was excluded from analysis using the outer 60 m buffer width. The relationship between watershed and riparian disturbance was more similar to fire within these buffer widths, but did not reach direct proportionality. Differences observed in the watershed and buffer disturbance relationships likely reflect the widespread application of a 30 m shoreline riparian no-cut reserve during forest management, as opposed to 60 and 90 m reserves which are less commonly applied (Lamb *et al.,* 2003; OMNR 2010).

Factors contributing to the observed differences in shoreline riparian disturbance by fire and harvest include the practice of using 30 m no-cut reserves, limitations on harvest size distributions, and spatial data quality. The most significant cause of difference in riparian forest disturbance between fire and harvest is likely because forestry operations commonly leave a 30 m no-cut reserve (Lamb *et al.,* 2003; OMNR 2010). Usage of these protective forested buffer strips may create an unnatural landscape of mature forest strips surrounding boreal water features (Buttle 2002), and this pattern is reflected in my results. The presence of harvest activity within the 30 m buffer width ordinarily restricted to harvest activity may reflect data errors in spatial harvest records, or inconsistencies between the spatial records of aquatic features employed in this study and those originally used in harvest planning. The reduction in frequency of harvest within the 30 m buffer above 10% of their area over this study's time period may reflect improvements in GPS methods, resulting in more accurate digitization of harvest blocks.

Management direction limiting the size of the majority of clearcuts to below 260 ha (Perera & Cui 2010) likely has resulted in a legacy of smaller disturbance patches and few large harvest disturbances. Conversely, spatial data quality in available fire data may under represent smaller disturbance patches and may not adequately represent the spatial complexity of fire disturbances. Only fires larger than 40 ha were represented in available spatial data, and while large fires do compose the majority of disturbed area (Cumming 2001; Girardin *et al.,* 2006) small fires represent the vast majority of fires that occur. The digitization of some fires below that 40 ha threshold would likely reduce some of the observed differences in fire and harvest disturbance patch counts, patch sizes, and frequency of disturbances affecting <10% of riparian buffer areas. Additionally, the inclusion of smaller fires and improvements to the digitization of older fires would potentially reduce the observed differences in perimeter to area ratios between the disturbance types. For example, improving the reduced accuracy of older fires, as described by Bridge and others (2005), and accurately representing ragged edges and unburnt islands of fire disturbances (McRae *et al.,* 2001).

The observed differences in the spatial extent and landscape pattern of disturbance within riparian forests have a number of consequences both for succession in boreal riparian forests and for boreal stream environments. Disturbances in forest environments directly influence the age, species composition, structure and arrangement of forest types in the landscape (Bergeron *et al.,* 2001; Bouchard *et al.,* 2008; Cui & Perera 2008). For riparian forests in Ontario's boreal region that have naturally evolved with fire disturbance (Sibley *et al.,* 2012) differences in the landscape pattern of disturbance between harvest and fire will also affect successional regimes. Results from this study indicate that while fire results in a range of disturbance percentages within riparian shoreline buffers, harvest does not, and instead results in a large number of buffers disturbed in low percentage of their area. Based on these differences it is likely that fire and harvest will not result in similar successional patterns within shoreline areas in the boreal forest. Differences between fire and harvest were particularly stark within 30 m from the shoreline, likely reflecting the widespread protection these areas receive in the form of no-cut reserves (Lamb *et al.,* 2003; OMNR 2010). Additionally, temporal differences between the disturbance types, along with differences in disturbance patch numbers and sizes, indicate that while fire will typically result in even aged regrowth in a few larger disturbance patches, harvest will result in regrowth in a larger number of small disturbance patches, often with a variety of ages within a single riparian buffer. Furthermore, while fire disturbance resulted in a similar level of disturbance within both watersheds and shoreline riparian buffers (i.e. 1:1); harvest does not, and is likely providing different disturbance regimes, and as a result providing a different disturbance and successional regimes in both upland and shoreline riparian areas in boreal watersheds.

In consideration of the relationship between flow path distance and changes in streamflow described by Abdelnour and others (2011), and between riparian disturbance and increases in stream temperatures (Kreutzweiser *et al.,* 2012; Moore *et al.,* 2005; Pettit & Naiman 2007), differences in the spatial extent and landscape pattern of riparian forest disturbance will have a number of implications for boreal streams. In this study fire disturbance resulted in a range of disturbance levels within each buffer width examined, disturbances occurring closer to streams may result in larger increases in flow compared with a similar disturbance occurring near the ridge of a watershed (Abdelnour *et al.,* 2011). It is likely then that fire disturbance in these areas will result in a range of increases in streamflow, including some large increases in flow caused by some of the higher level fire disturbances (>50% riparian buffer disturbed). Conversely, harvest resulted in far lower levels of disturbance within the study's riparian shoreline buffers, and as a result may only provide small increases in flow, if any at all within a large number of affected streams across the landscape.

Disturbances that remove riparian canopy cover allow for increased solar radiation reaching streams, leading to increases in stream temperatures (Kreutzweiser *et al.,* 2012; Moore *et al.,* 2005; Pettit & Naiman 2007). Fire disturbance resulted in a wide range of shoreline riparian buffer disturbance, and accordingly a range of canopy removal over affected streams. This range in disturbances will result in a range of potential stream temperature increases, due to increased solar radiation reaching the stream in fire disturbed riparian areas. Harvest disturbance on the other hand is unlikely to provide for a similar range in temperature increases, and may not provide for any significant increases in stream temperatures at all. This is due to the extremely low levels of riparian buffer disturbance we observed in this study; particularly within the 30 m shoreline buffer width, which experienced the lowest levels of harvest disturbance. Changes to stream flow regimes and temperatures will affect boreal aquatic ecosystems and their biota (Burn *et al.,* 2008; Heicher 1993, as cited in Smakhtin 2001), although these changes may not necessarily be negative. Boreal riparian forests and by association their streams have naturally developed with fire (Silbey *et al.,* 2012), and this regular disturbance may contribute to habitat heterogeneity and natural patterns of diversity in aquatic ecosystems (Kreutzweiser *et al.,* 2012).

The potential differences in riparian forest succession and natural changes in boreal stream environments are of particular concern if fire suppression efforts are believed to be largely successful within the AOU. Significant reductions in the spread and incidence of large fires in the intensive zone (Bridge *et al.,* 2005), means that harvest will exert the most significant influence on successional regimes in the boreal forests of the AOU. In consideration of the differences observed harvest is not likely to provide a regime of succession in boreal riparian forests that would have naturally been provided in the region by fire disturbance (Arkle & Pilliod 2010; Flannigan *et al.,* 2005), and is instead continuing to create an unnatural landscape of forested ribbons surrounding aquatic features as described by Buttle (2002). Furthermore, the observed differences indicate that additional to successional changes, forest management in Ontario's boreal riparian forest is unlikely to provide the same range of stream flow and temperature changes resulting from fire.

The results of the study show that the landscape pattern of stand replacing disturbances within boreal riparian forests differs between natural disturbance and forest management. The potential changes in stream flow and temperature resulting from riparian harvesting are likely less than those of fire, due to the low levels of disturbances and the widespread usage of a 30 m no-cut reserves. However the lack of harvest activity close to shore may have other implications for both forest succession and boreal stream environments. Because fire regularly disturbs riparian forests, the resulting changes to both stream flow regimes and temperatures may play an important role in the natural renewal of boreal stream ecosystems. In order for forest management to result in more similar spatial patterns of disturbance within riparian forests, considerations should be made for harvest within these areas, particularly within 30 m from, and for associated changes in stream flow regimes and temperatures.

4.0 GENERAL DISCUSSION AND CONCLUSION

In this study I evaluated and compared the spatial and landscape patterns of disturbance resulting from fire and harvest in Ontario's boreal forest. For both watersheds and their riparian areas the disturbance types resulted in significantly different disturbance regimes Generally fire disturbed a greater percentage area and was more variable in its disturbances; fire disturbance typically resulted in fewer total patches that were more complex in their shape and occurred during a single year of a time period. Conversely harvest disturbed a far lower percentage area and was less variable in terms of percentage area disturbed, only resulting in a small subset of the range resulting from fire. Harvest disturbance generally occurred in numerous disturbed patches that were more complex in their shape and occurred during multiple years of the time period. The observed differences between fire and harvest were largely consistent between the watershed level and analyses conducted within the 30 and 90 m buffer widths; an additional metric describing the group median of median disturbance patch sizes was evaluated in the riparian chapter with fire resulting in larger disturbance patch sizes within the buffers. Interestingly extent of disturbance resulting from fire were extremely consistent between watersheds and the buffer widths examined, in particular the percentage area disturbed, as well as the frequency and cumulative frequency distributions of that metric. Harvest disturbance was not consistent between the watershed and buffers, resulting in far lower disturbance percentages within the buffers, particularly within the 30 m buffer width. So, not only does harvest not result in similar landscape patterns of disturbance as fire within boreal watersheds and riparian forests, harvest results in different disturbance regimes between watersheds and their riparian areas, whereas fire disturbance was consistent at both levels.

The differences observed between fire and harvest in this study were consistent with descriptions of their spatial characteristics of disturbance found in the literature.

Differences in the landscape patterns of disturbance generated by fire and harvest have a number of implications both for forest succession and stream environments in Ontario's boreal forest. This is especially true considering the success of fire suppression efforts throughout the AOU, success which is apparent by the north-south geographic separation observed between fire and harvest disturbed watersheds in this study. Differences in the percent area disturbed clearly indicate that harvest will result in different successional regimes within both boreal watersheds and their riparian forests. Additionally, harvest disturbance resulting in numerous small patches occurring over multiple years suggest that it will not result in the even aged regrowth within large disturbed areas that naturally results from fire.

The relationship between the percentage of watershed area disturbed and stream flow changes, as well as the relationships between flow path distances and flow changes, and riparian disturbance and stream temperature changes, suggest that differences between fire and harvest in the extent of disturbance within watersheds and riparian forests may affect boreal stream environments. Flow changes potentially occurring after large scale (i.e. high percentage) disturbances resulting from fire may serve important roles in creating habitat heterogeneity in boreal streams; harvest disturbance is unlikely to result in similar flow changes, and may result in little change at all if disturbance thresholds are not exceeded. Specifically within riparian forests, which are generally protected from harvest by use of a no-cut reserve, fire can result in far greater levels of disturbance closer to the stream. These disturbances have the potential to cause flow changes due to their close proximity to the stream, and may result in stream temperature increases if sufficient canopy is removed. Changes to the boreal stream environment may negatively affect some biota, but these changes would result naturally from fire in an unsuppressed landscape; harvest disturbance is unlikely to provide for these changes, particularly due to widespread application of a 30 m no-cut reserve around water features in management planning.

Research employing spatial data for fire or harvest in Ontario in the future should attempt to improve the quality of available data. Increases in digitization accuracy and digitization of some fires below 40 ha in area would improve the comparison between the types and in the case of some metrics reduce degree of the observed differences. A large number of errors also appear to be included in provincial harvest records, partially caused by a multi-year overlap between collected datasets. Efforts were made to correct these errors in this study but were concentrated on the most significantly affected forest management units.

Future research on this topic could expand the range of watershed sizes examined, or examine watersheds in multiple size classes. The potential exists given the nature of watersheds to employ a nested study area design, examining both large watersheds and the smaller watersheds that compose them. The types of data analyzed within watersheds in this study could be expanded to include factors like ecology or pedology, which may provide additional detail relevant to predicting both successional changes and changes in stream flow. For example, both the infiltration capacity of the dominant soil type, and the average ET generated by the dominant tree species in a watershed prior to disturbance would be relevant to the potential for increases in streamflow. Employing a higher resolution DEM to delineate watersheds, identifying significant hydrologic features such as flow paths, and calculating upland contributing areas within disturbed sites would also improve the capacity to predict significant flow changes following disturbance.

Considering the results of this study, forest management should attempt to take watersheds into consideration in planning future harvests in an effort to result in more natural spatial patterns of disturbance and potential hydrologic changes as result from fire. The widespread usage of a 30 m no-cut reserve may prove unnecessary, and potentially detrimental to riparian forest succession considering the natural range of fire disturbance extents in these areas, and the proportional relationship between watershed and riparian disturbance by fire observed in this study. Efforts should be made to consider and provide for riparian disturbance more similar to fire at a landscape scale in management planning. Greater flexibility around, or an increase in the upper size limits of clearcuts may also be necessary in order for harvest to provide a landscape pattern of disturbance within watersheds that is more similar to fire; in particular larger scale disturbances that affected a high percentage of watershed land area were not well represented in harvest disturbance. Finally, the practice of conducting numerous harvest passes spread over multiple years within a single area could be modified; contrasting harvest, fire rarely affected a study watershed during multiple years of any of our study periods, so efforts should be made to spatially and temporally concentrate harvest cuts.

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6.0 APPENDIX

Appendix A – Harvest Disturbance Data Error Corrections

Harvest records used for analysis in this study were a result of the combination of two datasets maintained by the MNRF, which individually covered 1990-2003 and 2002-2012. The two datasets were sourced from annual reporting by Ontario FMUs, although the earlier dataset (1990-2003) included some cuts that were estimated from free to grow reporting. There is a clear temporal overlap in the two datasets as both include harvests occurring in 2002 and 2003. The combination of the two datasets revealed a large number of errors with most occurring in the overlapped years (2002-2003) and those occurring immediately before and after (2001 & 2004). In order to reduce the influence of the observed errors on the final results a concerted effort was made to identify and correct the greatest number of these as possible. However, due to time constraints and the large number of errors included in the data efforts were concentrated within the most affected FMUs. To identify target FMUs for correction efforts the two harvest datasets were combined using the Intersect tool, and additional fields were calculated describing the percentage of overlap and the year difference between the cuts. Cuts exhibiting a high percentage of overlap and low difference in years (0-5 years gap) were flagged as potentially in need of correction. The FMUs with the largest numbers of these cuts were selected for focused correction efforts. During these efforts all harvests occurring within the focus FMUs were examined with reference to 2005-2009 forest cover satellite imagery for the region. A wide variety of error types were identified during this process, and cuts were edited, shifted, combined, or removed to correct these errors and better reflect cuts evident in the imagery.

Types of error included in these harvest records included: missing records, cuts that were clearly evident in the imagery but not present in any of the harvest datasets (Figure A1); outline blips, seemingly the result of the combination of various records these errors appear as a number of small blips around the outside of a cut (Figure A2); missing cuts, harvest records included in the datasets that are not evident in the imagery (Figure A3); polygon combination, different result of an attempt to correct for duplicated records, these errors seem to be a combination of two versions of the same cut, which end up not reflecting cuts in the imagery (Figure A4); duplicated and shifted cuts, the same harvest polygon duplicated in both datasets and/or shifted from the actual harvest location evident in the imagery (Figure A5).

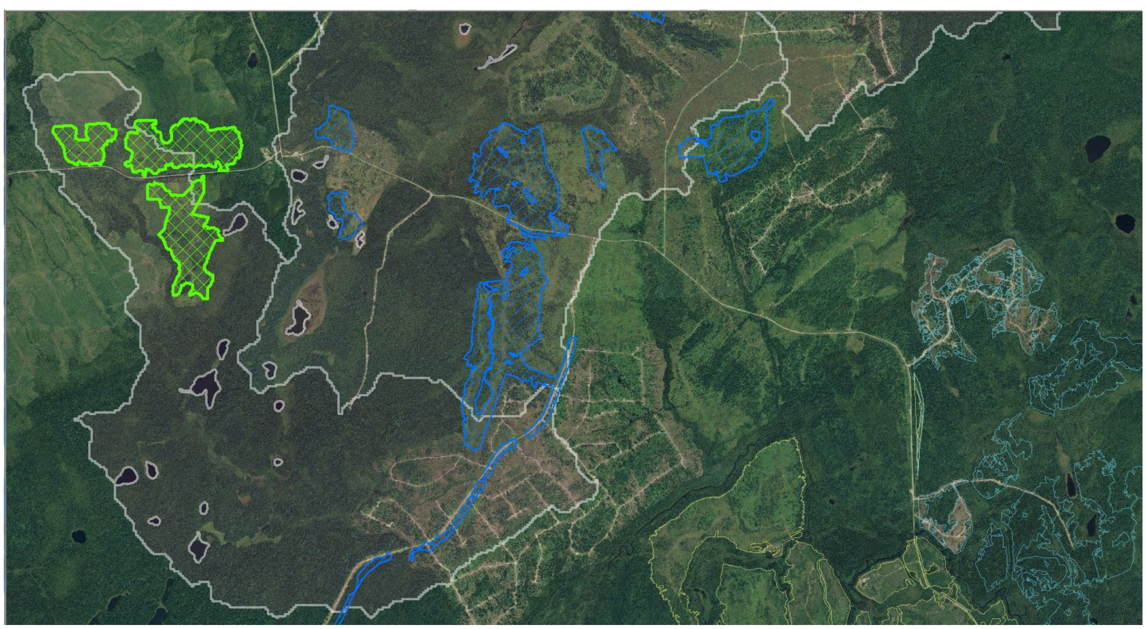

Figure A1: Harvests clearly evident in the imagery that are not included in either set of harvest data.

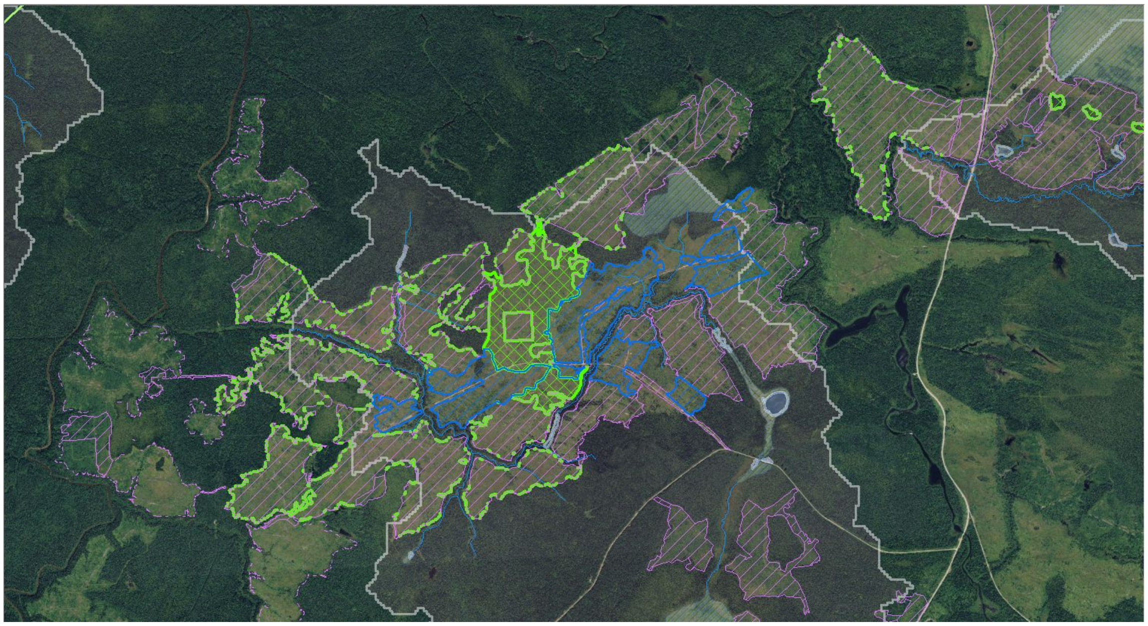

Figure A2: Outline blips around the outside of harvests that are clearly reflected in imagery but not truly included in the harvest datasets, note the purple spots surrounding cuts to the left side of the image.

Figure A3: Cuts included in the datasets, which clearly did not occur given the imagery, note the uncut 'CC_1996' harvest in the centre of the image in comparison with other 1996 cuts throughout the image.

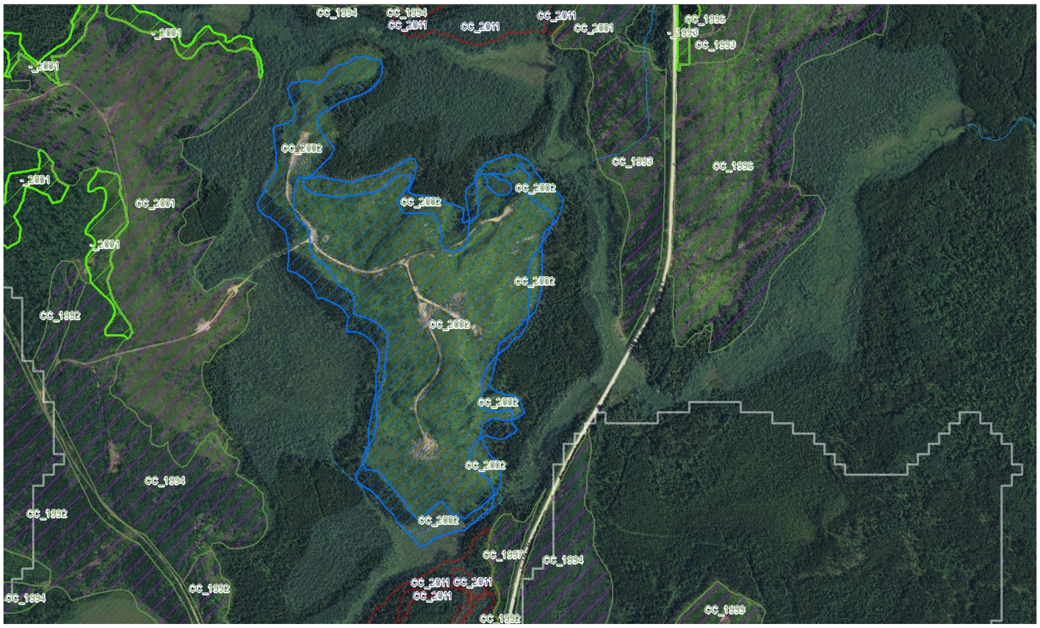

Figure A4: Harvest polygon combination error, note the seemingly overlapped blue harvests in the centre of the image. The two outlines appear to represent the same cut but are combined and do not accurately reflect the imagery.

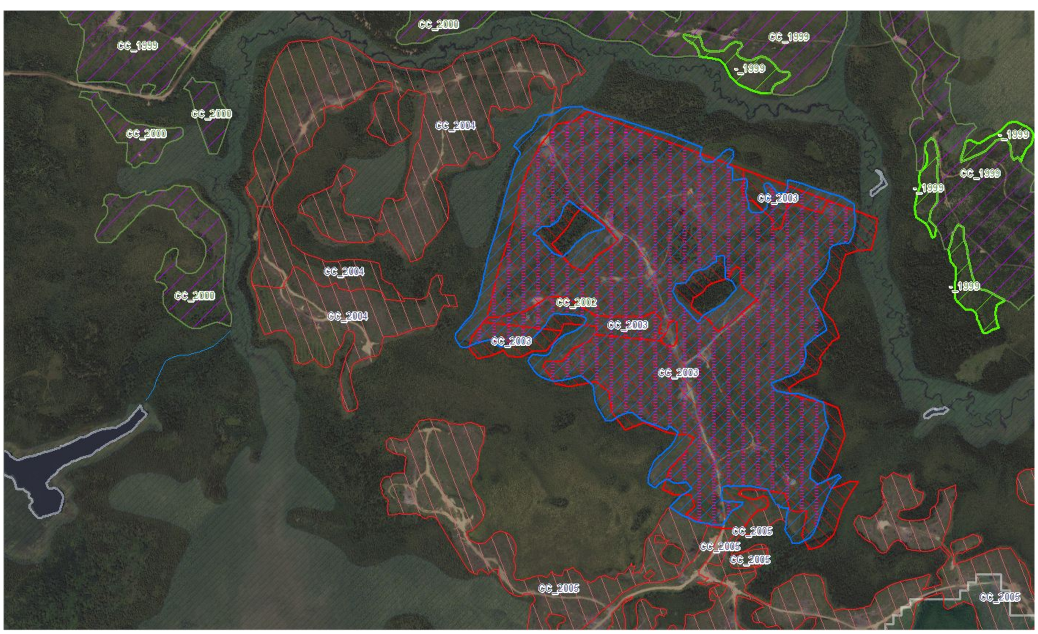

Figure A5: Overlapped red and blue cuts in the centre of this image are reflective of the duplicate cut errors. Both represent the same cut and occur in 2002 and 2003 according to the records, but only one matches the imagery. Other cuts in red can be seen shifted from where they actually occurred according to the imagery.

Appendix B – Landscape Pattern of Disturbance By Ecoregion

Table B1: KS test statistics for comparisons of frequency distributions of percent watershed area disturbed by fire and harvest within each ecoregion comprising the study area, during each study time period.

Ecoregion	Disturbance Descriptor	Time Period	Num. Fire	Num. Harvest	Abs. Difference	Test Statistic	p value
2E	Percentage of watershed land area disturbed	1990-1994	12	**0**	**unable to compute**		**n/a**
		1995-1999	4	1	1	0.894	0.400
		2000-2004	3	2	0.5	0.548	0.925
		2005-2009	2	1	1	0.816	0.518
2W	Percentage of watershed land area disturbed	1990-1994	43	29	0.582	2.423	**< 0.001**
		1995-1999	69	15	0.571	2.004	**0.001**
		2000-2004	27	31	0.523	1.988	**0.001**
		2005-2009	13	31	0.211	0.638	0.810
3E	Percentage of watershed land area disturbed	1990-1994	5	636	0.567	1.263	0.082
		1995-1999	28	597	0.366	1.893	**0.002**
		2000-2004	4	565	0.598	1.192	0.116
		2005-2009	5	493	0.211	0.468	0.981
3S	Percentage of watershed land area disturbed	1990-1994	27	28	0.705	2.614	**< 0.001**
		1995-1999	38	28	0.331	1.328	0.059
		2000-2004	32	44	0.548	2.36	**< 0.001**
		2005-2009	21	44	0.385	1.453	**0.029**
3W	Percentage of watershed land area disturbed	1990-1994	1	298	0.973	0.972	0.302
		1995-1999	52	344	0.18	1.207	0.109
		2000-2004	6	343	0.486	1.181	0.123

		2005-2009	29	287	0.368	1.891	**0.002**
4E	Percentage of watershed land area disturbed	1990-1994	2	160	0.638	0.896	0.398
		1995-1999	0	155	unable to compute		n/a
		2000-2004	0	151	unable to compute		n/a
		2005-2009	1	152	0.934	0.931	0.351
4S	Percentage of watershed land area disturbed	1990-1994	1	169	0.787	0.785	0.569
		1995-1999	5	207	0.455	1.006	0.264
		2000-2004	3	212	0.332	0.571	0.901
		2005-2009	2	179	0.483	0.68	0.745
4W	Percentage of watershed land area disturbed	1990-1994	0	69	unable to compute		n/a
		1995-1999	4	81	0.531	1.036	0.233
		2000-2004	1	89	1	0.994	0.276
		2005-2009	6	74	0.486	1.146	0.145
5E	Percentage of watershed land area disturbed	1990-1994	0	106	unable to compute		n/a
		1995-1999	1	120	0.842	0.838	0.483
		2000-2004	4	117	0.28	0.55	0.922
		2005-2009	1	112	1	0.996	0.275
5S	Percentage of watershed land area disturbed	1990-1994	0	12	unable to compute		n/a
		1995-1999	1	17	1	0.972	0.301
		2000-2004	2	14	0.857	1.134	0.153
		2005-2009	0	18	unable to compute		n/a

Table B2: KS test statistics for comparisons of frequency distributions of percent 30 m buffer area disturbed by fire and harvest within each ecoregion comprising the study area, during each study time period.

Ecoregion	Disturbance Descriptor	Time Period	Num. Fire	Num. Harvest	Abs. Difference	Test Statistic	p value
2E	Percentage of 30m buffer area disturbed	1990-1994	8	0	unable to compute		n/a
		1995-1999	2	1	1	0.816	0.518
		2000-2004	2	1	1	0.816	0.518
		2005-2009	0	1	unable to compute		n/a
2W	Percentage of 30m buffer area disturbed	1990-1994	29	24	0.759	2.749	**< 0.001**
		1995-1999	54	9	0.981	2.726	**< 0.001**
		2000-2004	19	24	0.947	3.085	**< 0.001**
		2005-2009	9	25	0.8	2.058	**< 0.001**
3E	Percentage of 30m buffer area disturbed	1990-1994	5	452	0.634	1.41	**0.038**
		1995-1999	31	425	0.621	3.339	**< 0.001**
		2000-2004	4	377	0.637	1.267	**0.081**
		2005-2009	5	296	0.885	1.963	**0.001**
3S	Percentage of 30m buffer area disturbed	1990-1994	26	20	0.785	2.638	**< 0.001**
		1995-1999	31	21	0.63	2.228	**< 0.001**
		2000-2004	30	34	0.649	2.591	**< 0.001**
		2005-2009	20	34	0.832	2.954	**< 0.001**
3W	Percentage of 30m buffer area disturbed	1990-1994	1	202	0.985	0.983	0.289
		1995-1999	55	263	0.471	3.175	**< 0.001**
		2000-2004	7	251	0.682	1.779	**0.004**
		2005-2009	30	193	0.856	4.363	**< 0.001**
4E	Percentage of 30m buffer area disturbed	1990-1994	1	126	0.937	0.933	0.349
		1995-1999	1	118	0.746	0.743	0.640

		2000-2004	0	106	unable to compute		n/a
		2005-2009	1	111	1	0.996	0.275
4S	Percentage of 30m buffer area disturbed	1990-1994	0	133	unable to compute		n/a
		1995-1999	4	158	0.744	1.469	**0.027**
		2000-2004	3	164	0.447	0.768	0.598
		2005-2009	2	131	0.74	1.039	0.230
4W	Percentage of 30m buffer area disturbed	1990-1994	0	59	unable to compute		n/a
		1995-1999	3	64	0.969	1.64	**0.009**
		2000-2004	1	70	1	0.993	0.278
		2005-2009	6	57	0.842	1.962	**0.001**
5E	Percentage of 30m buffer area disturbed	1990-1994	0	79	unable to compute		n/a
		1995-1999	1	81	0.975	0.969	0.304
		2000-2004	3	86	0.523	0.891	0.405
		2005-2009	0	76	unable to compute		n/a
5S	Percentage of 30m buffer area disturbed	1990-1994	0	11	unable to compute		n/a
		1995-1999	1	11	1	0.957	0.318
		2000-2004	2	8	1	1.265	0.082
		2005-2009	0	12	unable to compute		n/a

Table B3: KS test statistics for comparisons of frequency distributions of percent 90 m buffer area disturbed by fire and harvest within each ecoregion comprising the study area, during each study time period.

Ecoregion	Disturbance Descriptor	Time Period	Num. Fire	Num. Harvest	Abs. Difference	Test Statistic	p value
2E	Percentage of 90m buffer area disturbed	1990-1994	8	0	unable to compute		n/a
		1995-1999	2	1	1	0.816	0.518
		2000-2004	3	1	1	0.866	0.441
		2005-2009	0	1	unable to compute		n/a
2W	Percentage of 90m buffer area disturbed	1990-1994	32	26	0.611	2.313	**< 0.001**
		1995-1999	55	10	0.855	2.486	**< 0.001**
		2000-2004	19	26	0.737	2.441	**< 0.001**
		2005-2009	9	28	0.528	1.377	**0.045**
3E	Percentage of 90m buffer area disturbed	1990-1994	5	523	0.598	1.331	0.058
		1995-1999	29	497	0.521	2.728	**< 0.001**
		2000-2004	4	475	0.404	0.805	0.536
		2005-2009	4	391	0.563	1.121	0.162
3S	Percentage of 90m buffer area disturbed	1990-1994	26	23	0.798	2.787	**< 0.001**
		1995-1999	32	25	0.505	1.892	**0.002**
		2000-2004	30	38	0.6	2.457	**< 0.001**
		2005-2009	20	40	0.7	2.556	**< 0.001**
3W	Percentage of 90m buffer area disturbed	1990-1994	1	237	0.979	0.977	0.296
		1995-1999	51	304	0.437	2.886	**< 0.001**
		2000-2004	5	295	0.359	0.797	0.549
		2005-2009	29	241	0.507	2.581	**< 0.001**
4E	Percentage of 90m buffer area disturbed	1990-1994	1	139	0.871	0.867	0.439
		1995-1999	0	138	unable to compute		n/a

		2000-2004	0	131	unable to compute		n/a
		2005-2009	1	131	1	0.996	0.274
4S	Percentage of 90m buffer area disturbed	1990-1994	1	148	0.851	0.848	0.468
		1995-1999	4	178	0.739	1.461	**0.028**
		2000-2004	3	185	0.328	0.563	0.909
		2005-2009	2	158	0.5	0.703	0.707
4W	Percentage of 90m buffer area disturbed	1990-1994	0	64	unable to compute		n/a
		1995-1999	3	72	0.792	1.344	0.054
		2000-2004	1	79	1	0.994	0.277
		2005-2009	6	69	0.565	1.328	0.059
5E	Percentage of 90m buffer area disturbed	1990-1994	0	92	unable to compute		n/a
		1995-1999	1	97	0.938	0.933	0.348
		2000-2004	3	102	0.304	0.519	0.951
		2005-2009	0	99	unable to compute		n/a
5S	Percentage of 90m buffer area disturbed	1990-1994	0	12	unable to compute		n/a
		1995-1999	1	13	1	0.964	0.311
		2000-2004	2	8	1	1.265	0.082
		2005-2009	0	14	unable to compute		n/a

APPENDIX C – STATISTICAL OUTPUTS FOR PCA AND DFA OF DISTURBED WATERSHED CHARACTERISTICS

Table C1: Eigenvalues and percent of variance explained by PCA components during each study time period.

Component Num.	1990-1994			1995-1999			2000-2004			2005-2009		
	Initial Eigenvalues			Initial Eigenvalues			Initial Eigenvalues			Initial Eigenvalues		
	Total	% of Var.	Cum. %	Total	% of Var.	Cum. %	Total	% of Var.	Cum. %	Total	% of Var.	Cum. %
1	2.511	31.392	31.392	2.588	32.345	32.345	2.628	32.850	32.850	2.756	34.454	34.454
2	2.061	25.764	57.156	2.060	25.749	58.094	1.955	24.442	57.292	1.900	23.756	58.210
3	1.187	14.835	71.991	1.087	13.588	71.682	1.132	14.151	71.443	1.087	13.584	71.794
4	0.876	10.954	82.945	0.882	11.021	82.703	0.919	11.489	82.932	0.927	11.592	83.386
5	0.639	7.986	90.931	0.648	8.097	90.801	0.632	7.906	90.838	0.607	7.582	90.968
6	0.498	6.219	97.150	0.508	6.354	97.155	0.502	6.275	97.113	0.490	6.126	97.093
7	0.156	1.946	99.097	0.153	1.908	99.063	0.156	1.949	99.061	0.162	2.025	99.119
8	0.072	0.903	100.000	0.075	0.937	100.000	0.075	0.939	100.000	0.070	0.881	100.000

Table C2: Complete component scores generated by PCA during each study time period.

Time Period		1990-1994			1995-1999			2000-2004			2005-2009		
Component Num.		1	2	3	1	2	3	1	2	3	1	2	3
Watershed Centroid	Easting	0.496	-0.622	-0.545	0.624	-0.539	-0.496	0.642	-0.522	-0.491	0.667	-0.474	-0.498
	Northing	-0.704	0.020	0.652	-0.721	-0.076	0.624	-0.711	-0.003	0.615	-0.713	-0.011	0.627
Watershed Elevation	Average (masl)	0.082	0.790	-0.111	-0.114	0.787	-0.124	-0.165	0.745	-0.113	-0.180	0.708	-0.168
	Range (m)	0.834	0.348	0.273	0.759	0.498	0.377	0.760	0.507	0.177	0.756	0.528	0.166
	Roughness	0.792	0.044	0.395	0.787	0.175	0.252	0.793	0.228	0.260	0.784	0.272	0.285
Watershed Density	Lake Area (total area)	-0.224	0.641	-0.307	-0.358	0.557	-0.219	-0.397	0.526	-0.382	-0.464	0.511	-0.349
	Stream Length (land area)	0.565	-0.191	0.311	0.566	-0.091	0.370	0.547	-0.007	0.480	0.603	0.012	0.411
	Wetland Area (Land Area)	-0.267	-0.692	0.174	-0.143	-0.739	0.215	-0.138	-0.736	0.156	-0.070	-0.749	0.136

Table C3: DFA Standardized Canonical Discriminant Function Coefficients (SCDFC) and corresponding structure matrix values during each study time period.

Time Period		1990-1994		1995-1999		2000-2004		2005-2009	
Function Num.		1		1		1		1	
Output		SCDFC	Structure Matrix	SCDFC	Structure Matrix	SCDFC	Structure Matrix	SCDFC	Structure Matrix
Watershed Centroid	Easting	0.452	-0.229	0.644	-0.237	0.202	-0.352	0.392	-0.463
	Northing	**1.075**	**0.750**	**1.255**	**0.809**	**0.990**	**0.818**	**1.215**	**0.841**
Watershed Elevation	Average (masl)	0.328	-0.251	0.316	-0.269	0.071	-0.272	0.135	-0.161
	Range (m)	-0.072	-0.273	-0.214	-0.299	0.050	-0.316	0.161	-0.126
	Roughness	0.368	-0.125	0.516	-0.114	0.224	-0.176	0.401	-0.017
Watershed Density	Lake Area (total area)	-0.048	-0.109	0.091	0.017	-0.063	-0.058	0.199	0.233
	Stream Length (land area)	**-0.344**	**-0.263**	**-0.251**	**-0.252**	**-0.253**	**-0.261**	**-0.333**	**-0.385**
	Wetland Area (Land Area)	**0.564**	**0.550**	**0.342**	**0.445**	**0.510**	**0.522**	**0.225**	**0.149**

Table C4: Original and cross-validated watershed classification results using DFA function calculated during each study time period.

Time Period	Classification	Disturbance Type	Predicted Group		Percent Correctly Classified
			Fire	Harvest	
1990-1994	Original	Fire	96.7	3.3	94.4
		Harvest	5.7	94.3	
	Cross-Validated	Fire	96.7	3.3	94.4
		Harvest	5.8	94.2	
1995-1999	Original	Fire	83.2	16.8	88.1
		Harvest	11.3	88.7	
	Cross-Validated	Fire	81.2	18.8	87.8
		Harvest	11.3	88.7	
2000-2004	Original	Fire	79.3	20.7	90.5
		Harvest	8.9	91.1	
	Cross-Validated	Fire	79.3	20.7	90.5
		Harvest	8.9	91.1	
2005-2009	Original	Fire	62.5	37.5	82.4
		Harvest	16.5	83.5	
	Cross-Validated	Fire	61.3	38.8	82.1
		Harvest	16.8	83.2	

APPENDIX D – ANCOVA TABLES COMPARING THE RELATIONSHIP BETWEEN WATERSHED AND BUFFER DISTURBANCE DURING EACH STUDY TIME PERIOD

Table D1: Abbreviated ANCOVA tables describing the relationship between each study buffer distance (30 m, 90 m, outer 60 m) and watershed disturbance during the 1990-1994 time period.

Time Period	Dependent Variable	Source	Type III Sum of Squares	df	Mean Square	F	p value
1990-1994	Log10 (Percent 30 m Buffer Disturbed)	Disturbance type	1.631	1	1.631	29.426	< 0.001
		Log10 (percent watershed disturbed)	75.868	1	75.868	1368.937	< 0.001
		Disturbance type * log(percent watershed disturbed)	**8.393**	**1**	**8.393**	**151.448**	**< 0.001**
		Error	88.341	1594	0.055		
		Total	438.162	1598			
1990-1994	Log10 (Percent 90 m Buffer Disturbed)	Disturbance type	1.367	1	1.367	32.482	< 0.001
		Log10 (percent watershed disturbed)	92.369	1	92.369	2195.354	< 0.001
		Disturbance type * log(percent watershed disturbed)	**3.519**	**1**	**3.519**	**83.641**	**< 0.001**
		Error	67.067	1594	0.042		
		Total	622.83	1598			
1990-1994	Log10 (Percent outer 60 m Buffer Disturbed)	Disturbance type	1.287	1	1.287	30.198	< 0.001
		Log10 (percent watershed disturbed)	98.487	1	98.487	2310.931	< 0.001
		Disturbance type * log(percent watershed disturbed)	**2.266**	**1**	**2.266**	**53.164**	**< 0.001**
		Error	67.933	1594	0.043		
		Total	719.562	1598			

Table D2: Abbreviated ANCOVA tables describing the relationship between each study buffer distance (30 m, 90 m, outer 60 m) and watershed disturbance during the 1995-1999 time period.

Time Period	Dependent Variable	Source	Type III Sum of Squares	df	Mean Square	F	p value
1995-1999	Log10 (Percent 30 m Buffer Disturbed)	Disturbance type	0.16	1	0.16	3.022	0.082
		Log10 (percent watershed disturbed)	144.85	1	144.85	2739.051	< 0.001
		Disturbance type * log(percent watershed disturbed)	**19.568**	**1**	**19.568**	**370.025**	**< 0.001**
		Error	93.233	1763	0.053		
		Total	529.232	1767			
1995-1999	Log10 (Percent 90 m Buffer Disturbed)	Disturbance type	0.032	1	0.032	0.805	0.37
		Log10 (percent watershed disturbed)	194.478	1	194.478	4915.959	< 0.001
		Disturbance type * log(percent watershed disturbed)	**5.635**	**1**	**5.635**	**142.448**	**< 0.001**
		Error	69.745	1763	0.04		
		Total	764.3	1767			
1995-1999	Log10 (Percent outer 60 m Buffer Disturbed)	Disturbance type	0.022	1	0.022	0.549	0.459
		Log10 (percent watershed disturbed)	211.37	1	211.37	5208.5	< 0.001
		Disturbance type * log(percent watershed disturbed)	**2.988**	**1**	**2.988**	**73.628**	**< 0.001**
		Error	71.545	1763	0.041		
		Total	883.533	1767			

Table D3: Abbreviated ANCOVA tables describing the relationship between each study buffer distance (30 m, 90 m, outer 60 m) and watershed disturbance during the 2000-2004 time period.

Time Period	Dependent Variable	Source	Type III Sum of Squares	df	Mean Square	F	p value
2000-2004	Log10 (Percent 30 m Buffer Disturbed)	Disturbance type	0.026	1	0.026	0.574	0.449
		Log10 (percent watershed disturbed)	49.068	1	49.068	1090.166	< 0.001
		Disturbance type * log(percent watershed disturbed)	**10.514**	**1**	**10.514**	**233.593**	**< 0.001**
		Error	74.086	1646	0.045		
		Total	234.249	1650			
2000-2004	Log10 (Percent 90 m Buffer Disturbed)	Disturbance type	0.024	1	0.024	0.668	0.414
		Log10 (percent watershed disturbed)	82.672	1	82.672	2308.787	< 0.001
		Disturbance type * log(percent watershed disturbed)	**1.232**	**1**	**1.232**	**34.401**	**< 0.001**
		Error	58.939	1646	0.036		
		Total	538.268	1650			
2000-2004	Log10 (Percent outer 60 m Buffer Disturbed)	Disturbance type	0.058	1	0.058	1.446	0.229
		Log10 (percent watershed disturbed)	91.6	1	91.6	2271.17	< 0.001
		Disturbance type * log(percent watershed disturbed)	**0.27**	**1**	**0.27**	**6.705**	**0.01**
		Error	66.345	1645	0.04		
		Total	691.934	1649			

Table D4: Abbreviated ANCOVA tables describing the relationship between each study buffer distance (30 m, 90 m, outer 60 m) and watershed disturbance during the 2005-2009 time period.

Time Period	Dependent Variable	Source	Type III Sum of Squares	df	Mean Square	F	p value
2005-2009	Log10 (Percent 30 m Buffer Disturbed)	Disturbance type	0.246	1	0.246	14.285	< 0.001
		Log10 (percent watershed disturbed)	37.121	1	37.121	2151.315	< 0.001
		Disturbance type * log(percent watershed disturbed)	**19.711**	**1**	**19.711**	**1142.365**	**< 0.001**
		Error	25.313	1467	0.017		
		Total	133.948	1471			
2005-2009	Log10 (Percent 90 m Buffer Disturbed)	Disturbance type	0.007	1	0.007	0.274	0.601
		Log10 (percent watershed disturbed)	76.129	1	76.129	2972.6	< 0.001
		Disturbance type * log(percent watershed disturbed)	**2.936**	**1**	**2.936**	**114.658**	**< 0.001**
		Error	37.57	1467	0.026		
		Total	396.398	1471			
2005-2009	Log10 (Percent outer 60 m Buffer Disturbed)	Disturbance type	0.002	1	0.002	0.055	0.815
		Log10 (percent watershed disturbed)	87.187	1	87.187	2672.923	< 0.001
		Disturbance type * log(percent watershed disturbed)	**1.149**	**1**	**1.149**	**35.236**	**< 0.001**
		Error	47.852	1467	0.033		
		Total	533.451	1471			