CHARACTERISTICS OF CONNECTIVITY BETWEEN HARVESTED LANDSCAPES AND FIXED-WIDTH RIPARIAN BUFFERS

by

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ABSTRACT

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Fixed-width riparian buffers are a common best management policy enforced in forested landscapes on first and higher order streams. These buffer areas are delineated along stream banks in the field, based on the presence of flowing water. However the presence of ephemeral streams may affect the connectivity of harvested lands to riparian buffers. We sought to understand the influence of ephemeral streams, determined from terrain analysis, on fixed-width riparian buffers. The objectives were to: (1) use LiDAR data and spatially explicit analysis tools to establish the affect of ephemeral streams on buffer efficacy; (2) determine the effect of the location and size of cut-blocks in relation to the presence of a fixed-width riparian buffer; (3) demonstrate that fixed-width riparian buffers are an ineffective management practice for trapping sediments generated in harvested landscapes. The inclusion of high resolution terrain data in the evaluation of riparian buffers: decreased the estimates of the connectivity to harvested lands, the sensitivity of the distribution of cut-blocks on that connectivity and the overall efficacy of fixed-width buffers along first order streams. The inclusion of un-forested ephemeral streams: (i) reduced the area of harvested lands in which flow-paths were directly connected to a riparian buffer and (ii) identified areas within the fixed-width that were isolated from the majority of flow-paths from harvested lands. Finally, the flow-path analysis led to reduced estimates of riparian flow-path length, and the ratio of buffer area to upslope area. It also became evident that when all forested areas were included in the flow-path analysis, watersheds with a fixed-width riparian buffer or cut-to-shore were

indistinguishable. Because previous studies on the effectiveness of riparian buffers were based on 1st and higher order streams, the majority of the harvested lands were likely isolated in terms of surface runoff from the riparian buffer area studied. This thesis presents a case study of four watersheds to illustrate that the inclusion of high-resolution terrain data with a topographic flow-path analysis will provide valuable insight on use of fixed-width riparian buffers to mitigate non-point source pollutants from harvested lands.

Selective harvesting of riparian zones is becoming a common practice in forested landscapes adjacent to first and higher order streams. The types of selective harvesting include: single tree selection, group selection, and zoned harvest. Hydrological impacts of selective harvesting within different areas of the riparian zone may however not be uniform due to the presence of preferential flow-paths. High-resolution terrain data are required to accurately delineate preferential flow-paths. With the recent availability of light detection and ranging (LiDAR) data, terrain analysis can be performed to determine detailed flow-paths. The influence of preferential flow-paths on harvesting within riparian zones was investigated in the second portion of this thesis. The objectives of the second portion of the thesis were to: (4) evaluate the impact of preferential flow-paths from harvested areas on selective harvest within a fixed-width adjacent to 1st order streams; (5) examine the relationship between buffer characteristics based on flow-path and increasing the intensity of selective harvest within the riparian zone; and (6) explore the effect of selective harvesting of riparian zones on the percentage of non-riparian harvested area. The results of the study show that including preferential flow-paths in the evaluation of selective harvest within riparian zones increased: estimates of their importance in tree selection, the sensitivity of selective harvesting intensity on buffer

characteristics, and the effect on percentage of harvested land that was buffered. Application of preferential flow-paths analysis: (i) increased the harvestable area of riparian zones by indentifying areas in which flow-paths from cut-blocks were non-existent and (ii) identified areas within the riparian zone where the majority of flow-paths from harvested lands occurred and should be conserved. Finally flow-path analysis considering different harvest intensities of the riparian zone, led to reduced estimates of hydrologic sensitivity for the majority of the area adjacent to the stream. When all forested areas were included in the flow-path analysis, fixed-width riparian zones with varying degrees of harvest intensity were indistinguishable until almost the entire buffer area (95% of the buffer area in the four study streams) was harvested. Current guidelines for selective harvest within riparian zones do not include an analysis of preferential flow-paths. Therefore large portions of the harvested lands could become non-buffered as a result of preferential flow-paths being harvested. A case study of four watersheds on the Boreal Plain is presented to illustrate how preferential flow-path analysis can delineate the areas within fixed-width riparian zones that are most responsible for the isolation of aquatic eco-systems from harvested landscapes.

Keywords: Fixed-width riparian buffers _ Flow-path metrics_ Harvested landscapes_ LiDAR analysis_Natural disturbance emulation_Buffering landscape disturbances

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DEFINITIONS

Terms	Definition
Pixel	3-m by 3-m cell within a raster used in GIS calculations
Harvested Area	Area within the Cut-block shape file
Forested Area	Area with a vegetation height > 3.05m
Riparian Area	Area within 30 m perpendicular distance of a 1st order stream
Harvested Pixel	Pixel within the harvested area
Forested Pixel	Pixel within the forested area
Riparian Pixel	Pixel within the riparian area
Forested Flow-Path Length	Summed length of flow-path segments occurring through forested pixels (m)
Riparian Flow-Path Length	Summed Length of flow-path segments occurring through riparian pixels (m)
Buffer-Area Ratio	Ratio of the area of buffer to the upslope contributing area
Riparian Pixel Converted	Riparian pixel converted from a forested to a harvested pixel
Buffered	A summed length of flow-path segments occurring through at least 30-m of forested pixels

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Chapter 1

Introduction

Freshwater ecosystems are the foundation of economical resilience as well of great importance socially, culturally, and spiritually throughout the globe. Many of the world's river ecosystems are increasingly degraded because of the failure to predict anthropogenic impacts on complex biophysical system (Foley *et al.* 2005). A holistic approach to quantifying the hydrological process within a watershed that connects ecosystems to land-use changes is needed. Ecohydrologly is an emerging interdisciplinary field that focuses on the interactions between water and ecosystems and the impacts of land-use change (Zalewski *et al.* 1997). The intricate interactions between biota and water are crucial to discover, and can occur both within water bodies, such as rivers and lakes, or on land, in the case of forests and deserts. One goal of ecohydrology is to understand the influence of vegetation on streamflow and function, and the feedbacks between ecological processes and the hydrological cycle (Hayashi and Rosenberry 2002).

The hydrological cycle quantifies the flow and interaction of water on, above and below the surface of the earth. This flow can be altered by ecosystems in numerous ways in the atmosphere, on the surface and within the ground. Trees within the forest hydrologic cycle can influence the flow of water to the atmosphere by transpiration, while canopy interception and root uptake can have significant impacts on surface runoff and subsurface flow respectively (Fig. 1.1) (Hélie *et al.* 2005). The interaction between the hydrologic cycle and the landscape could also predict nutrient discharges and sediment loadings to streams in multiple watersheds throughout the Mid-Atlantic Region of United States (Jones *et al.* 2001). Even river morphology can be influenced by treed embankments and the prevention of soil erosion (Eaton and Giles 2005). Therefore an understanding of the forest hydrologic cycle is necessary to predict impacts on ecosystems from land-use changes.

Within forested ecosystems the interactions of vegetation and water within the riparian zone are important in determining how land-use changes will affect hydrology, and water chemistry (Dosskey *et al.* 2010). The linking of hydrology and vegetation should be applied to both our riparian management policies and strategies for buffering impacts from land-use changes (Dwire and Lowrance 2006). Currently the ability to link vegetation to water flow, or the study of ecohydrology, is the field of research required to resolve problems caused by current land and water management practices. In many countries excessive sediment and nutrient loadings from diffuse sources, are known to be a major freshwater environmental issue (Foley *et al.* 2005). An increase in nutrient loadings on receiving waters has numerous deleterious effects, including increased biomass of freshwater phytoplankton and periphyton, reduced water clarity, elevated pH and depletion of dissolved oxygen in the water column (Smith *et al.* 1999). Watershed disturbances (e.g., agriculture, deforestation) can alter nutrient loading and have substantial impacts on the hydrological process (Cooke and Prepas 1998). Physical links between vegetation and hydrology must be fully understood, to properly implement effective policies and practices to minimize the impacts of disturbed landscapes on receiving waters.

Within the Province of Alberta, and elsewhere in North America, the natural disturbance model is being increasingly adopted to minimize the anthropogenic impacts of the forestry industry (McRae *et al.* 2001; Long 2009). The natural disturbance model patterns forest harvesting strategies after forest fires, and prevents unnatural patterns of forest growth that are detrimental to the sustainability of forested ecosystems (Kreutzweiser *et al.* 2012; Moore and Richardson 2012). However with the implementation of the natural disturbance model, cut-block sizes can increase from 10's, to the 100's of hectares. With these increases in cut-block size, most harvestable trees, including those in riparian areas, are removed in small watersheds (<1000 ha) (McEachern *et al.* 2006). As the natural disturbance approach to forest management increases in acceptance, so does the practice of including riparian areas for harvesting (Lee *et al*. 2004). Therefore the efficacy of the current riparian management strategy of fixed-width riparian buffers for the purposes of buffering harvested landscapes should be evaluated before riparian harvesting is allowed.

Currently *Alberta Timber Harvest Planning and Operating Ground Rules Framework for Renewal,* states that no removal of timber shall be approved within 30 m of the high watermark for small permanent streams, while for intermittent streams, simply a buffer of brush and lesser vegetation is to be left undisturbed. The width of the buffer for intermittent streams is based according to soils, topographic breaks, water source areas and fisheries values. Thus by applying the less stringent buffer rules of intermittent streams, a treed buffer is only required at the request of a Forest Officer (Lee and Smyth 2003). Also in the United States the current administrative policy is being challenged on the premise that harvesting in the riparian buffers can be environmentally beneficial in capturing phosphorus over the long term (Kelly *et al.* 2007). It has been suggested that the thinning of remnant forests will encourage a greater growth of grasses which are responsible for trapping sediments (Knight *et al.* 2010). Therefore it becomes imperative that the hydrological processes within riparian buffers are fully understood, along with the effect of harvesting riparian buffers to emulate natural disturbances and the impacts of buffering disturbed landscapes.

An analysis of surface water flow-paths allows for the quantification of connectivity between disturbed landscapes and fixed-width riparian buffers. Surface water flow-paths are calculated along the steepest descent in the terrain (Baker *et al.* 2006). Within the four study watersheds investigated in this thesis the riparian zone was considered to be a 30-m fixed-width distance adjacent to 1^{st} order streams. Currently the Province of Alberta requires a treed buffer within the 30-m fixed-width riparian zone with discretionary regulations for treed buffers along ephemeral streams. The efficacy of fixed-width riparian buffers was the determination of the actual presence of the buffer along the flow-path from the harvested landscape to the stream network. Thus the efficacy of fixed-width riparian buffers was a determination of its ability to produce an effect on surface water quality and quantity and not a quantification of its efficiency to buffer surface runoff. Preferential flow-paths refer to the generation of channelized flow within the landscape in the form of rills and gullies.

In my thesis I delineated these preferential flow-paths for the four study watersheds within the Boreal Plain ecozone in the Province of Alberta, Canada to evaluate the efficacy of fixed-width riparian buffers. The goals of my thesis were to: (1) use LiDAR data and spatially explicit analysis tools to establish the affect of ephemeral streams on buffer efficacy; (2) determine the effect of the location and size of cut-blocks in relation to the presence of a fixed-width riparian buffer; (3) demonstrate that fixed-width riparian buffers are an ineffective management practice for trapping sediments generated in harvested landscapes; (4) evaluate the impact of preferential flow-paths from harvested areas on selective harvest within riparian zones; (5) examine the relationship between buffer characteristics based on flow-path and increasing the intensity of selective harvest within the riparian zone; and (6) explore the effect of selective harvesting of riparian zones on the percentage of non-buffered harvested area.

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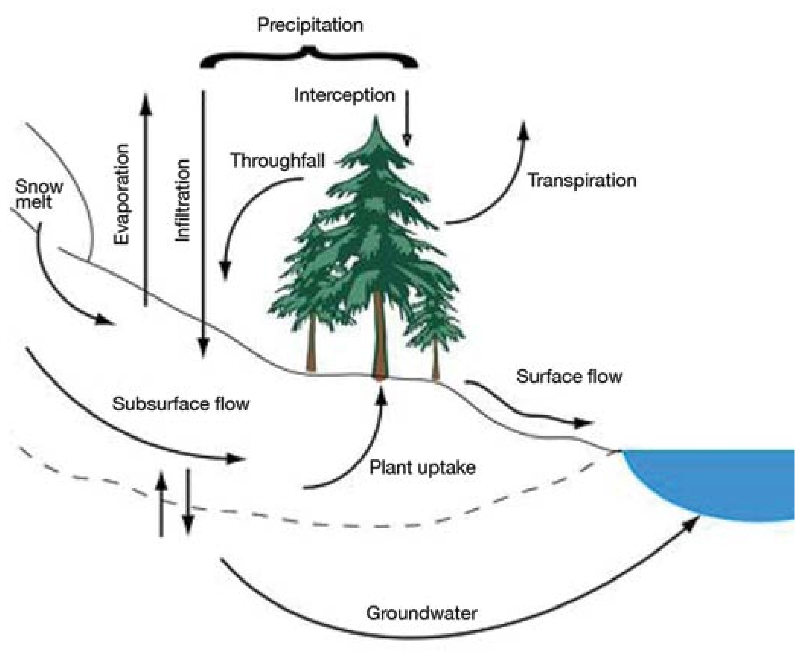

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Chapter 2
THE EFFICAY OF FIXED-WIDTH RIPARIAN BUFFERS IN FORESTED WATERSHEDS

Introduction

Riparian buffers are areas of vegetation located adjacent to a stream channel, that are left undisturbed as an effort to reduce the effects of landscape changes on water quality associated with anthropogenic disturbances. Within agricultural land management systems, riparian buffers have become a well established, best management practice, for reduction of surface and subsurface transport of sediments, nitrogen, and phosphorus to surface waters (Dwire *et al.* 2006; Dosskey *et al.* 2010; Hoffmann *et al.* 2009). In situations where surface runoff is uniformly distributed along the length of the buffer, non-point source pollutants can be reduced over the buffer width, dependent on regional and site specific factors (Schmitt *et al.* 1999; Lee *et al.* 2003, Newbold *et al.* 2010). These research findings have led to the requirement for fixed-width riparian buffers as a major component of regulatory policies on disturbed landscapes (Lee *at al.* 2004).

Despite the prominent role of fixed-width riparian buffers in land management policy, it is extremely difficult to quantify the attenuation of nutrient and sediment loading to streams that can be attributed to these buffers and there is a large disparity between reported mass removal rates (Mayer *et al.* 2005). Further, there is no guarantee that mass removal rates reported for fixed-width riparian buffers subjected to uniform surface runoff conditions can be achieved on a regional landscape scale (Vidon *et al.* 2008). The continual occurrence of increased phytoplankton, reduced water clarity, elevated pH and the depletion of dissolved oxygen due to increased nutrient loadings despite the application of generalized land management policies, demonstrates that the site-specific comprehension of natural processes within fixed-width riparian buffers is incomplete (Cooke and Prepas 1998; Smith *et al.* 1999). Therefore new methods for visualizing and quantifying the hydrological processes within riparian buffers and management practices based upon these methods are needed to mitigate the unwanted or unintended effects of landscape disturbance.

The application of spatially-explicit tools is becoming increasingly important for a more detailed evaluation of the effectiveness of fixed-width riparian buffers and allows for site-specific management recommendations. In particular, the application of high resolution data and spatially-explicit tools are extremely important in quantifying the effectiveness of best management practices in landscape settings, such as forested areas, in which surface runoff is non-uniform (Berry *et al.* 2003, Weller *et al.* 2011). In disturbed areas, the effectiveness of riparian buffers is diminished by the occurrence of preferential flow-paths through the buffer to the stream channel (Weller *et al.* 1998; Blanco-Canqui *et al.* 2006; Baker *et al.* 2006; Knight *et al.* 2010).

Investigations have also shown that non-uniform upslope contributing areas to a fixed-width riparian buffer are a major factor in explaining the spatial variability detected in mass removal rates (Dosskey *et al.* 2002; McGlynn and Seibert 2003; Polyakov *et al.* 2005). Variable-width riparian buffer designs have been proposed for increased effectiveness maintaining a fixed-loading parameter expressed as a ratio of buffer area to upslope contributing area (Bren 1998; Tomer *et al.* 2003; Dosskey *et al.* 2005). The ineffectiveness of fixed-width riparian buffers in the reduction of mass loading to streams has also been hypothesized to be the result of preferential flow-paths (Belt and

O'Loughlin 1994; Rivenbark and Jackson 2004; Gomi *et al*. 2005; May 2007). However within forested landscapes only the variability in upslope contributing area has been considered in the evaluation of fixed-width riparian buffers, and not preferential flow-paths (Bren 2000).

An obstacle for the implementation of an updated buffer location strategy is the availability and capability to utilize high resolution digital elevation data to determine the occurrence of preferential surface flow-paths. The occurrence and location of ephemeral streams can further influence the connectivity of disturbed lands to stream networks (Gomi *et al.* 2002), yet most field studies of riparian buffers are based on first and second order streams (Lee *et al.* 2004). Thus to accurately quantify site-specific effectiveness of a riparian buffer, preferential surface flow-paths and ephemeral streams must be included. Many investigations have highlighted the issues of surface runoff being mistakenly represented as a uniform hillslope process rather than a preferential-path surface flow due to limited map resolution (Montgomery and Dietrich 1988; Hancock and Evans 2006; Baker *et al.* 2007; van Schaik *et al.* 2008).

Seasonal and event-driven precipitation may cause the periodic expansion and contraction of the stream network within a watershed, which will drastically alter the stream connectivity to the disturbed landscape (Wondzell and Swanson 1996; Stanley *et al*. 1997; Fisher and Welter 2005). Even the smallest ephemeral streams can have a profound impact on surface runoff flow-paths. Hence the application of precise and spatially explicit methods for establishment of riparian areas becomes critically important (Baker *et al.* 2006). Studies also have shown that the implementation of fixed-width riparian buffers based upon field observations or land cover information derived from 30-

m resolution satellite imagery could have very little merit (Hollenhorst *et al.* 2006; Jones *et al.* 2001). In some instances the acquisition and utilization of higher resolution data can completely alter the evaluation of a disturbed watershed from being well buffered to being largely un-buffered (Baker *et al.* 2007). Even the generation of roads and skid trails can drastically alter the hydrologic connectivity between harvested landscapes and the stream network rending riparian buffers ineffective (Wemple *et al.* 1996; Gomi *et al.* 2006b).

In this study the concept of flow-path analysis was applied to evaluate four commercially viable forested watersheds that were winter clear-cut harvested in 2004 (details in Prepas *et al.* 2008). A 30-m fixed-width riparian buffer adjacent to 1st order streams was retained in two of the four harvested watersheds. The remaining two watersheds were cut-to-shore wherever possible. Post-harvest high resolution light detection and ranging (LiDAR) topographical data were available for all four watersheds after harvesting. The LiDAR data were used to determine the landscape flow-paths, including the ephemeral stream network, and to assess the efficacy of fixed-width riparian buffers. The objectives were that: (1) LiDAR data and spatially explicit analysis tools can be used to establish the affect of ephemeral streams on buffer efficacy; (2) the location and size of cut-blocks have a greater effect in buffering a watershed than the presence of a fixed-width riparian buffer; and (3) the establishment of fixed-width riparian buffers are an ineffective management practice for trapping sediments generated in harvested landscapes.

Methods

Study Watersheds

The landscape flow-path analysis was performed on four commercially harvested watersheds (Table 2.1) located in the Alberta, Canada section of the Boreal Plain ecozone. Over the past decade the Boreal Plain has experienced an increased intensity of forest disturbance, due to both harvesting for timber and pulp production, and clearing for oil and gas extraction (Alberta Economic Development 2008). These four watersheds are part of the Forest Watershed and Riparian Disturbance (FORWARD) research program located in the Swan Hills, 240 km northwest of Edmonton, Alberta, Canada (Fig.2.1). A reference watershed could not be implemented in the flow-path analysis study because all pixels were forested within reference watersheds and a harvested pixel was required for the initiation of a flow-path.

The study watersheds are forested with trembling aspen (*Populustremuloides*-Michx.), balsam poplar (*P. balsamifera* L.), white spruce (*Piceaglauca* (Moench) Voss), black spruce (*P. mariana* (Mill.) BSP), lodgepole pine (*Pinuscontorta* Dougl. Ex Loud. var. *latifolia* Engelm.), and tamarack (*Larixlaricina* (Du Roi) K. Koch). The dominant soil class is deep, fine, Orthic Gray Luvisols (Whitson *et al.* 2003), but Organics and Brunisols are also present (Ecological Stratification Working Group 1996).The Boreal Plain is a semi-arid to sub-humid region (Zoltai *et al.* 1998), subject to substantial inter-annual variation in precipitation (total annual precipitation at Whitecourt, Alberta, 50 km to the southeast of the study sites ranged from 364 to 786 mm between 1980 and 2004).

The area of the four harvested watersheds ranged from 268 to 420 ha (Table 2.1). Harvest intensity of the watershed area for the 2004 winter clear-cut varied from 47 to 77 per cent (%) and was organized into large cut-blocks (Fig. 2.2). A 30-m fixed-width riparian buffer (measured perpendicular to the 1st order stream channel) was retained in two of the four watersheds (RB1 and RB2), while the remaining two watersheds (CS1 and CS2) were harvested to the stream channel (cut-to-shore) whenever possible. The fixed-width buffer was in accordance with Alberta's provincial guidelines regulating a 30-m wide buffer strip along permanent watercourses, and is intended in part to limit nutrient and sediment loading to surface waters after harvest (Alberta Sustainable Resource Development 2006). In addition the four harvested watersheds were treated with post-harvest mechanical site preparation along with the application of glyphosate to limit the colonization by grasses and shrubs. The outlet location of each watershed was monitored for streamflow rate, and nutrient concentration before and after harvest.

Geographic Data Sources

LiDAR and geographical data provided by industrial partner Millar Western Forest Products Ltd. were analyzed to determine elevation, and delineate stream channels and land cover with GIS. A digital elevation model (DEM) of a 3m resolution was created for each watershed from the LiDAR xyz data. From the DEM, the number of upslope pixels, each having an area of 9 m^2, contributing to each downslope pixel was estimated based on the standard flow accumulation technique available in Arc/Info (ESRI, Inc) geographic information system (GIS) (O'Callaghan and Mark 1984; Jenson and Domingue 1988). Stream channels for all four watersheds were formed using the flow accumulation results, with a contributing area threshold defined for the heads of the stream network. A contributing area threshold of 50 ha was estimated to define the heads of 1st order streams. A 50 ha threshold corresponds to the initiation of the fixed-width riparian buffer in watershed RB1 and RB2. A threshold of 5 ha was estimated for ephemeral streams from the visual detection of gullies in the hill shaded DEM. The stream network for all four watersheds was then formed from these contributing area thresholds and the flow accumulation results. All of the ephemeral streams defined with a flow accumulation of at least 5 ha had a minimum of 12 ha of accumulated flow, prior to entering the riparian zone. Thus only the length of the ephemeral stream network was sensitive to the flow accumulation threshold with the threshold being inconsequential to the harvested area draining into the ephemeral stream network. The locations of the streamflow and water quality monitoring stations were then used to represent the watershed outlets in GIS. The watershed catchments were then delineated from the flow accumulation results using the upslope contributing area to the watershed outlet pixel.

Vegetation height was derived by subtracting the LiDAR ground surface DEM from the LiDAR top of canopy DEM. The industrial partner also provided cut-block areas that were imported as GIS shape files. The area stipulated by current provincial regulations to maintain a fixed width riparian buffer (buffer area), was delineated in all four watersheds at a constant distance of 30 m perpendicular to the 1st order streams. The buffer area in RB1 and RB2 represented an actual forested area, while in CS1 and CS2 the buffer area was harvested wherever possible.

<u>Pixel Categories</u>

Three categorical descriptors, namely harvested, forested, and riparian, were used in the summation of flow-path lengths for a particular category of pixel along a flow-path. For each pixel within the watershed, it was determined if any of the three possible categorical descriptors should be applied (Table 2.2, Fig. 2.3). A pixel was deemed harvested if it was located within a cut-block shape file. If the vegetation height of a pixel was greater than 3.05 m, the pixel was considered forested. Finally if the pixel was within the 30-m fixed distance of the 1^{st} order stream, regardless if it was forested, it was labeled as riparian. A pixel could have all three categorical descriptors or any combination of two descriptors; within the cut-block areas, LiDAR still detected the presence of very small isolated patches of trees resulting in a few pixels being labeled both harvested and forested. In the cases of CS1 and CS2 the cut-block areas extended into the riparian zones, and pixels were labeled harvested and riparian, or if a tree was present labeled as forested, harvested, and riparian.

Flow-Path Metric calculation

To quantify flow-path length within a harvested watershed, we used the LiDAR DEM to identify the surface transport pathway (flow-path) following the steepest descent from each harvested pixel. The flow-paths from the harvested pixels to the stream network were produced based on topographic analysis techniques that are available within GIS software applications (Jenson and Domingue 1988). A single pixel flow-path model was selected instead of a flow-path model which partitions flow to multiple cells because of the fine resolution of the DEM. Partition flow-path models are required in coarse resolution DEMs in which multiple rills and gullies can be present within a single pixel and drain to alternate pixels. However with a 3-m by 3-m DEM the number of rills and gullies draining from a pixel will never be greater than one. Therefore a single pixel flow-path model which directs all of the flow to a single pixel is appropriate since there is only a single rill or gully draining from a particular pixel.

We then determined the summed length of flow-path segments that occurred through forested and riparian pixels along the flow-path from each harvested pixel to the stream (Baker *et al.* 2006, example in Fig. 2.4). For example, consider the flow-path from a harvested pixel that transverses straight through three harvested pixels, then diagonally through four forested pixels, then through seven harvested pixels and finally straight through ten riparian pixels, of which only five are forested, before entering a stream. Based on the flow-path metrics established above, the forested flow-path length would be 32 m [4 x (3√2, four diagonal forested) + 5 x (3, straight forested)= 32 m], while the riparian flow-path length would be 30 m [10 x (3, straight buffer) = 30 m]. In addition to the flow-path metrics, a buffer-area ratio was calculated for each harvested pixel. The buffer-area ratio is defined as the riparian flow-path length for a harvested pixel multiplied by the pixel width divided by the upslope contributing area to the first riparian pixel encountered along the flow-path. Buffer-area ratios are a quantitative predictor for sediment trapping efficiency in riparian buffers (Dosskey *et al*. 2002).

The flow-path lengths for two pixel categories, forested and riparian, were determined for each watershed. The forested flow-path length was utilized to compare the variance between the fixed-width riparian buffer and the cut-to-shore treatment. The forested flow-path length included all forested pixels that occurred outside and within the riparian zone, regardless of connectivity or distance from the stream network.

The length of flow-path that occurred through the riparian pixels was also determined along the total flow-path length from positions within the cut-block to the stream network. All designated riparian pixels with, or without, the presence of trees contributed to the riparian flow-path length. This procedure allowed the efficacy of fixed-width riparian buffers in trapping sediments to be assessed in watersheds where a forested buffer was left and also in the cut-to-shore watersheds. For the fixed-width riparian buffer the efficacy was a determination of whether or not the harvested area drained through the riparian zone or through the non-forested ephemeral stream network.

Results

Forested Flow-Path Length

Forested flow-path length was determined for each harvested pixel in all four watersheds (Fig. 2.5). The forested flow-path lengths ranged from 0 to 492 m, with the watershed means ranging from 28 m in CS2 to 58 m in CS1 (Table 2.3). No effect due to the presence of a fixed-width riparian buffer could be detected on forested flow-path length, or on percentage of harvested pixels with a forested flow-path length of zero. In watershed RB1 percentage of harvested pixels with forested flow-path length of zero was 15%, whereas the percentage in watersheds CS1 and CS2 ranged from 10% and 27%, respectively (from smaller to greater than RB1). Percentage of harvested pixels with forested flow-path length of zero increased from 10% in CS1 to 27% in CS2. The increase can be attributed to the difference in harvest intensity that occurred in CS1 and CS2 (47%, 77%, respectfully), because both were cut-to-shore watersheds.

Percentage of harvested pixels with forested flow-path of zero in RB2 (11%) and CS1 (10%) was similar even though RB2 had a fixed-width riparian buffer. Both RB2 and CS1 had very similar harvest intensities (50%, 47%, respectively) and wetland areas

(16%, 18%, respectively). The presence of wetlands could restrict commercial harvesting in areas in which flow-paths converge; hence undisturbed treed wetlands result in a decrease in the percentage of harvested pixels with forested flow-path length of zero. The two watersheds with fixed-width riparian buffers had a greater percentage of harvested pixels with forested flow-path lengths of zero (i.e., RB1 15%, RB2 11%) than the cut-to-shore watershed with an equivalent harvest intensity (i.e., CS1 10%). The greater percentage of harvested pixels with forested flow-path length of zero in fixed-width riparian buffer watersheds suggests that the parameter is dependent on the size and spatial distribution of the cut-blocks, and not on the presence of a fixed-width riparian buffer.

Riparian Flow-Path Length

Riparian flow-path length was determined for each harvested pixel as the summation of riparian pixels along the flow-path, regardless if the riparian pixel was forested or not (Fig. 2.6). On average 99% of the riparian flow-path lengths were either 0 m or greater than 30 m. A riparian flow-path length greater than 30 m is possible due to the flow-paths not being perpendicular to the stream network. The mean riparian flow-path length for the harvested pixels ranged from 6.0 m in CS2 to 14.8 m in RB2 (Table 4). Mean percentage of harvested pixels with a riparian flow-path length of 0 m was 77% for the four watersheds. The spatial distribution of the riparian flow-path pixels within each watershed often took on series triangular shapes with their bases oriented along the stream network (Fig. 2.7).

In addition, the buffer-area ratios were calculated for all harvested pixels which had a riparian flow-path length greater than 0 m. Buffer-area ratios ranged from 1 to less than 0.001, with the majority of the ratios being less than 0.01 (Fig. 8). The majority of the buffer-area ratios in watershed RB1 were between 0.02 and 0.001, while the buffer-area ratios in CS2 were either greater than 0.1 or less than 0.001. Over 50% of the buffer-area ratios for watersheds RB2 and CS1 were within an order of magnitude of 0.001. The variability of buffer-area ratios between watersheds was seemingly due to landscape and spatial distribution of the cut-blocks rather than harvest intensity. Any increase in harvest intensity outside the upslope contributing area to the riparian pixels would result in creating non-riparian harvested pixels. Since the upslope contributing areas to the riparian pixels are typically easily accessible there is a high probability that these upslope areas would be harvested regardless of watershed harvest intensity. An increase in watershed harvest intensity then typically results in more remote areas of the watershed being harvested. These remote areas typically discharge to ephemeral streams and not through the riparian zone. Therefore an increase in harvest intensity would have no impact on buffer-area ratios because non-riparian harvested pixels are excluded from the calculation.

Discussion

Forested flow-path lengths provide valuable insight for understanding the hydrology of fixed-width riparian buffers within harvested watersheds. Previous statistical analysis of data from the four watersheds concluded that a fixed-width riparian buffer had no detectable effect on outlet flows or on the export of total dissolved phosphorus (TDP) and particular phosphorus (PP) (Prepas *et al.* 2008). The lack of detectable difference between streams with or without a fixed-width buffer is expected since the forested flow-path lengths are similar in the fixed-width riparian buffer and cut-to-shore watersheds. Mean forested flow-path length was at least 28 m and the cut-to-shore watersheds had both the minimum and maximum mean forested flow-path lengths (Table 2.3). RB1 and CS1 had similar harvest intensities (Table 2.1) yet RB1 and CS1 differed in the percentage of pixels with a non-forested flow-path. Even though RB1 had a fixed-width riparian buffer, the percentage of pixels with a non-forested flow-path at 15% was greater than the number of pixels with a non-forested flow-path in CS1 at 10% (Fig. 2.5).

No relationship between the presence of a fixed-width riparian buffer and both forested flow-path length and percentage of pixels with a non-forested flow-path was identifiable. This could explain why previous studies within the Boreal Plain found that the retention of a fixed-width riparian buffer of up to 800 m did not influence the change in TP concentration in lakes (Prepas *et al.* 2001). In the Southern Appalachian region, no difference was found in total suspended solids on the no-buffer site between pre- and post-harvest periods (Clinton 2011). Also from the Pacific Northwest to Boreal Shield, Canada to the Southeastern Piedmont, USA it has been observed that a fixed-width riparian buffer had no impact on sediment loading occurring due to harvesting, yet the studies did not conduct a flow-path analysis (Moring 1982, Belt and O'Loughlin 1994, Kreutzweiser and Capell 2001; Rivenbark and Jackson 2004; Gomi *et al.* 2006b). However the ephemeral stream network and the flow-paths from harvested areas were identified as a research need to better understand the hydrology-related changes in sediment yield (Gomi *et al.* 2006a). Cut-block designs in experimentally observed harvested watersheds should include a flow-path analysis *a priori* before attempting to discern if there is a quantifiable variation in water quantity and quality as a result of the watershed treatment. In the province of British Columbia invertebrate sampling was conducted to evaluate the impacts of harvesting directly adjacent to a 1st order stream, yet the cut-bock had an ephemeral stream that drained into a different and un-monitored 1st order stream (Kiffney *et al.* 2003). Therefore the direction of flow-paths from cut-blocks to ephemeral streams should be included in harvest impact studies.

A relationship between harvest intensity and forested flow-path length was seen in the two cut-to-shore watersheds, CS1 and CS2. The difference in harvest intensity between CS1 and CS2 (47% and 77%, respectively, Table 2.1), explains the difference in the percentage of pixels with non-forested flow-path between CS1 at 10%, and CS2 at 27% (Fig. 2.5). The percentage of pixels with non-forested flow-path were observed to be the closest in CS1 and RB2 at 10 and 11% respectively, and also had similar percentages of wetlands (16%, 18%) and harvest intensities (47% , 50%). Wetlands are often not commercially viable to harvest and can affect the spatial distribution of cut-blocks. The presences of wetlands have also been predicted by various forms of the wetness index, which is a function of upslope contributing area and the slope (Grabs *et al.* 2009). Thus in this study landscape low relief areas with converging flow-paths would remain undisturbed since they are likely to be wetlands. In CS1 and RB2 the spatial distribution of cut-blocks avoided the wetlands, which resulted in areas of converging, non-harvested, flow-paths. Watershed RB1 with only 4% wetlands had 15% pixels with a non-forested flow-path, which was greater than watershed CS1 and RB2 (10%, 11% of pixels, respectively). Areas of converging flow-paths were more likely to be harvested in RB1 since the slope of the terrain prevented the formation of wetlands. Therefore percentage of pixels with non-forested flow-path was related to the magnitude and spatial distribution of the cut-blocks with respect to converging flow-paths, and not with the presence of a fixed-width riparian buffer. In future incorporating a consideration of areas of converging flow-paths into regulatory processes may have a greater impact on the mitigation of non-point source pollutants than the requirement of a fixed-width riparian buffer.

Riparian flow-path lengths provide a metric to evaluate the efficacy of fixed-width riparian buffers on the harvested landscape or the presence of a riparian buffer between the cut-block and the stream. Since harvesting 100% of the watershed is usually impossible due to the presence of wetlands and mechanical limitations, a flow-path analysis was conducted with riparian pixels ignoring the presence of forested pixels within the watershed. Prior to the flow-path analysis, it was believed that the majority of the surface runoff generated from the harvested landscapes would discharge through the fixed-width riparian buffer to the stream network. However the calculated riparian flow-path length demonstrated that, on average, 77% of the harvested pixels are non-riparian. Therefore the presence of ephemeral streams compromises the integrity of the fixed-width riparian buffer and reduces its efficacy, since the areas adjacent to the ephemeral streams were not considered riparian zones.

Mean riparian flow-path length varied between watersheds from 6.0 m in CS2 to 14.8 m in RB2; with CS2 resembling the shape of a fan while RB2 was cigar-shaped (Fig. 2.7). The variation in mean riparian flow-path length seemed dependent upon watershed shape or the perpendicular distance from the stream to the catchment edge. Increased distance from stream to catchment edge resulted in decreased mean riparian flow-path length. In fan-shaped watershed CS2, the distance from stream to catchment edge would exceed 1km with a corresponding mean riparian flow-path length of 6.0 m. In comparison to CS2 the distance from stream to catchment edge was less than 300 m for approximately a third of RB2 watershed resulting in a mean riparian flow-path length of 14.8 m. Percentage of non-riparian flow-path pixels was also greater in CS2 at 85% than in RB2 at 64%, which were also the maximum and minimum percentage of non-riparian flow-pixels calculated in all four watersheds. In the portions of RB2 watershed with a distance of stream to catchment edge less than 300 m the entire cut-block area drained through the riparian zone and not into an ephemeral stream. When the stream to catchment edge was greater than 300 m, which was always the case for RB1, CS1, and CS2 watershed, only triangular portions of the harvested pixels would flow through the riparian zone (Fig. 2.7). The high proportion of harvested pixels flowing through the riparian zone is expected in short flow-path lengths from the catchment edge since rill, gully and ephemeral stream formation is directly related to flow-path length (Desmet *et al.* 1999). Therefore with increased flow-path length from catchment edge to the stream network the efficacy of fixed-width riparian buffers decreases, due to the formation of ephemeral streams.

Riparian flow-path length alone does not provide a complete quantification of the efficacy of the fixed-width riparian buffer. Buffer-area ratio is another quantifiable parameter which is used to predict sediment trapping efficiency in fixed-width riparian buffers (Dosskey *et al.* 2002). Buffer-area ratios were only calculated for pixels with a buffered flow-path, since pixels with an un-buffered flow-path do not flow through the fixed-width riparian buffer. Buffer-area ratios for the harvested watersheds clearly demonstrate that the majority of the flow is through a small portion of the buffer (Fig.

2.8). A large percentage of the harvested pixels with a buffered flow-path had buffer-area ratios less than 0.01. Buffer-area ratios less than 0.01, typically result in the buffer becoming inundated with a contributing area at least two orders of magnitude greater than the riparian buffer area. It is nearly impossible for a buffer to have a sediment trapping efficiency greater than 20%, with a buffer-area ratio less than 0.01. For a sediment trapping efficiency of at least 50%, a buffer-area ratio of 0.05 is required and 80% efficiency achievable with a buffer-area ratio of 0.15 (Dosskey *et al.* 2005). To reduce sediment export due to harvesting the buffer-area ratios must be increased from the 0.01 that fixed-width riparian buffers currently provide. On average 75% of the surface runoff from harvested pixels did not flow through a riparian pixel, while the majority of the harvested pixels that did flow through a riparian pixel had ineffective buffer-area ratios. . Therefore due to the percentage of non-riparian harvested pixels and the buffer-area ratios, fixed-width riparian buffers within the harvested landscapes of the Boreal Plain have no efficacy for prevention of export of sediment and particulate nutrients.

We were able to use LiDAR data and spatially explicit analytical tools to establish the effect of ephemeral streams on buffer efficacy. We demonstrated that the presence of ephemeral streams resulted, on average, in 75% of the generated surface runoff from harvested landscapes not flowing through a fixed-width riparian buffer. It has been argued that extending riparian buffers to ephemeral streams would help maintain the natural hydrogeomorphic processes in a harvested watershed (Bren and Turner 1980). However the simple application of a fixed-width riparian buffer to ephemeral streams is neither effective nor commercially viable. We established using buffer-area ratio calculations that fixed-width riparian buffers are an ineffective management practice for trapping sediments generated from harvested landscapes. Buffer-area ratios along the 1st order stream were often less than 0.01 resulting in sediment trapping efficiencies of less than 20%. Similar buffer-area ratios are expected if a fixed-width riparian buffer was applied to the ephemeral streams. Therefore fixed-width riparian buffers are an ineffective spatial distribution of conserved lands for mitigation of non-point source pollutants from harvested landscapes.

Past models have predicted that fixed-width riparian buffers can effectively control sedimentation under certain circumstances. These predictive models have led to the establishment of fixed-width riparian buffers throughout North America that vary with environmental factors (Lee *et al.* 2004). However the predicted reduction in sediment only incorporated the effects of substrate characteristics, uniform slope, vegetation roughness, and overland flow patterns to determine the required fixed-width (Wong and McCuen 1982; Cook College Department of Environmental Resources 1989). Predictive models for sediment trapping efficacy in fixed-width riparian buffers in forested landscapes to date have failed to incorporate a flow-path analysis. Attempts have been made to establish a variable-width riparian buffer dependent on maintaining a constant and effective buffer-area ratio (Bren 2000). However Bren's (2000) study utilized a 30-m DEM in the determination of buffer-area ratios, and not high resolution LiDAR data. Upon visualization of natural forested landscapes through the implementation of LiDAR it becomes evident that cut-blocks are not a hill-slope process but a dendrite flow-path system. Thus any perpendicular increase in buffer width from the stream network to normalize buffer-area ratios would be ineffective because the buffer width is not increased along the actual flow-path. Therefore a new methodology for designing buffers in harvested landscapes is required in order to decrease sediment export to streams. Future regulations must adopt an integrated watershed approach (i.e., dividing the landscape into units based on the direction of water flow) by linking forest management planning processes to surface waters flow-paths and begin to move away from fixed-width riparian buffers, which create linear strips with little-to-no hydrological impact on the landscape.

A new methodology for designing buffers in harvested landscapes however may not be one that prescribes a particular spatial buffer design constantly applied to all harvested watersheds. Instead a quantitative flow-path analysis should be performed upon the proposed cut-block locations to determine the forested flow-path lengths. A prescribed buffer design fails to account for non-harvested (forested) areas along the flow-paths from the cut-blocks. Criteria should be established specifying a maximum percentage of non-forested flow-path pixels and a minimum mean forested flow-path length. A proposed cut-block should only be accepted if these criteria are met instead of requiring a prescribed geometric buffer design in hopes it will be effective. In this study both of the fixed-width riparian buffer watersheds were less effective in terms of flow-path metrics than the cut-to-shore watersheds with similar harvest intensities. However it should be noted that fixed-width riparian buffers may still be required for other ecological reasons, but there is no little support to prescribe a fixed-width for a desired reduction in nutrient and sediment loadings to streams via surface flow.

Tables

Table 2.1: Characteristics of the study watersheds in the Swan Hills, Alberta.

Watershed (name)	Previous Study[1]	Area (ha)	Wetland (% area)	Harvest (% area)	Buffer width (m)
RB1	H4	420	4.0	51.8	30
RB2	H2	308	15.5	50.0	30
CS1	H3	366	18.2	46.9	0
CS2	H1	268	13.7	76.7	0

1* Watershed numbering in Prepas et al. 2008

Table 2.2: The number of 3-m by 3-m pixels (1000's) for the harvested, forested, and riparian categorical descriptor in each of the four watersheds.

Watershed (name)	Total (# of pixels)	Harvested (# of pixels)	Forested (# of pixels)	Riparian (# of pixels)	Unclassified (# of pixels)
RB1	466.7	241.7	192.1	32.3	51.9
RB2	341.7	170.7	147.2	15.3	30.2
CS1	407.0	190.8	194.7	17.6	34.2
CS2	297.3	228.1	66.4	11.6	18.0

Table 2.3: Descriptive statistics for forested flow-path length for harvested pixels in the study watersheds of Riparian Buffer 1 (RB1, *n*=241,734), Riparian Buffer 2 (RB2, *n*=170,657), Cut-to-Shore 1 (CS1, *n*=190,801), and Cut-to-Shore 2 (CS2, *n*=228,073).

	RB1	RB2	CS1	CS2
Mean	56	44	57	28
Standard Error	0.15	0.13	0.15	0.09
Median	29	26	34	12
Sample Variance	5679	2753	4527	1931
Kurtosis	4.3	19.2	2.6	7.9
Skewness	2.1	3.4	1.8	2.6
Maximum	419	492	328	268
% Pixels Non-Forested	14.5	10.7	9.9	26.8

Table 2.4: Descriptive statistics for riparian flow-path length for harvested pixels in the study watersheds of Riparian Buffer 1 (RB1, *n*=241,734), Riparian Buffer 2 (RB2, *n*=170,657), Cut-to-Shore 1 (CS1, *n*=190,801), and Cut-to-Shore 2 (CS2, *n*=228,073).

	RB1	RB2	CS1	CS2
Mean	8.6	14.8	13.3	6.0
Standard Error	0.04	0.05	0.06	0.04
Median	0	0	0	0
Sample Variance	419	460	639	325
Kurtosis	6.0	-0.4	4.5	21.0
Skewness	2.4	1.0	2.2	4.2
% Pixels Non-Riparian	82.8	64.5	69.3	84.9

Figures

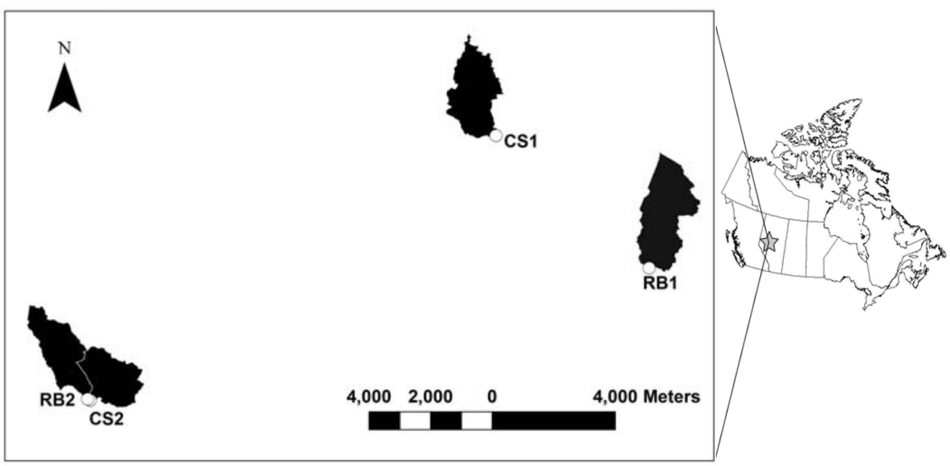

Figure 2.1: Forest Study watersheds in the Swan Hills on the Boreal Plain of Alberta, Canada. Fixed-width Riparian Buffer (RB1, RB2) and Cut-to-Shore (CS1, CS2) watershed characteristics are listed in Table 2.1.

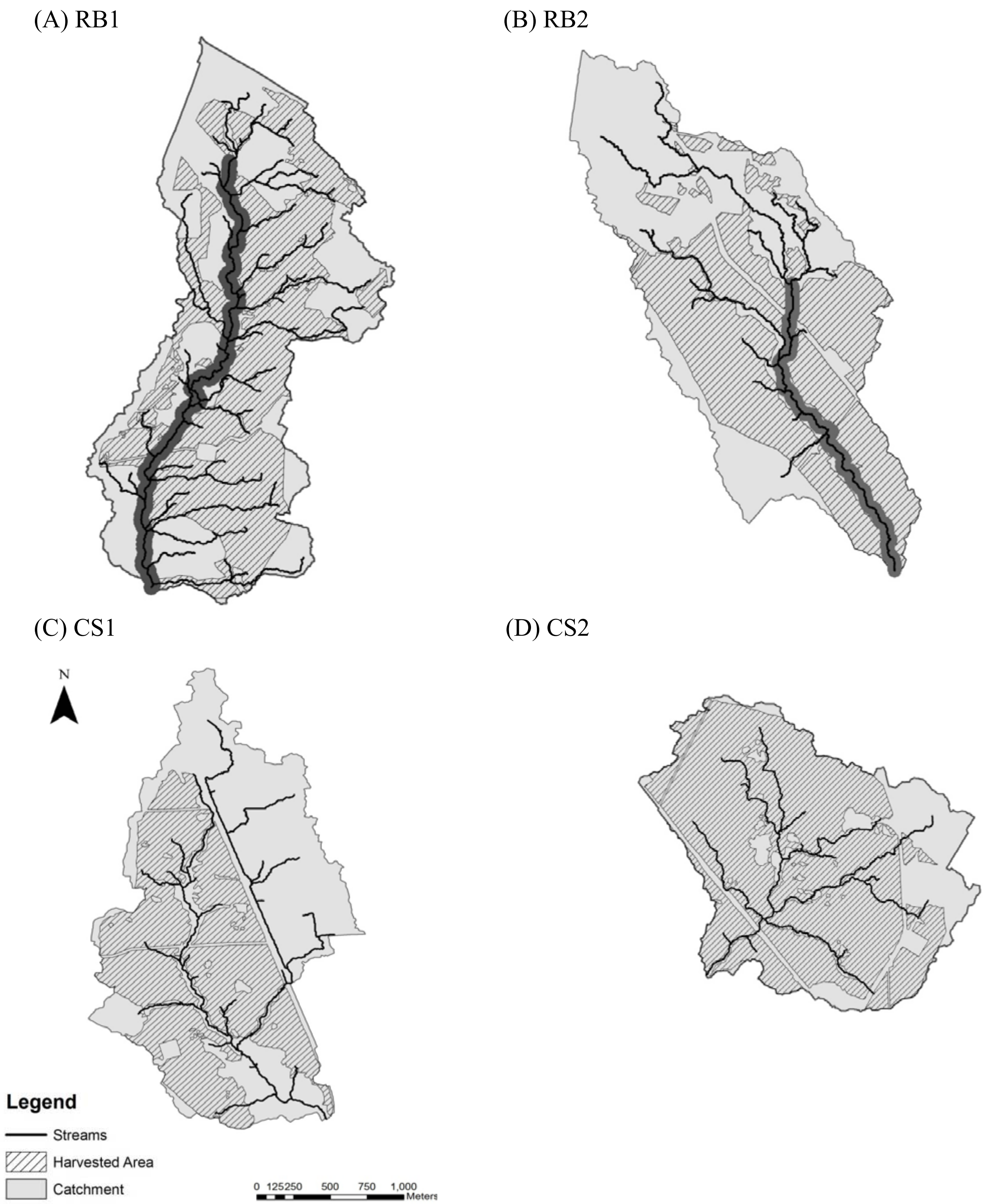

Figure 2.2: Harvested watersheds in the current study (light gray), with locations and sizes of cut-blocks (harvested areas, lined) relative to the stream channels (black) shown and fixed-width riparian buffer (dark gray); (A) Riparian Buffer 1 (RB1), (B) Riparian Buffer 2 (RB2), (C) Cut-to-Shore 1 (CS1), (D) Cut-to-Shore 2 (CS2).

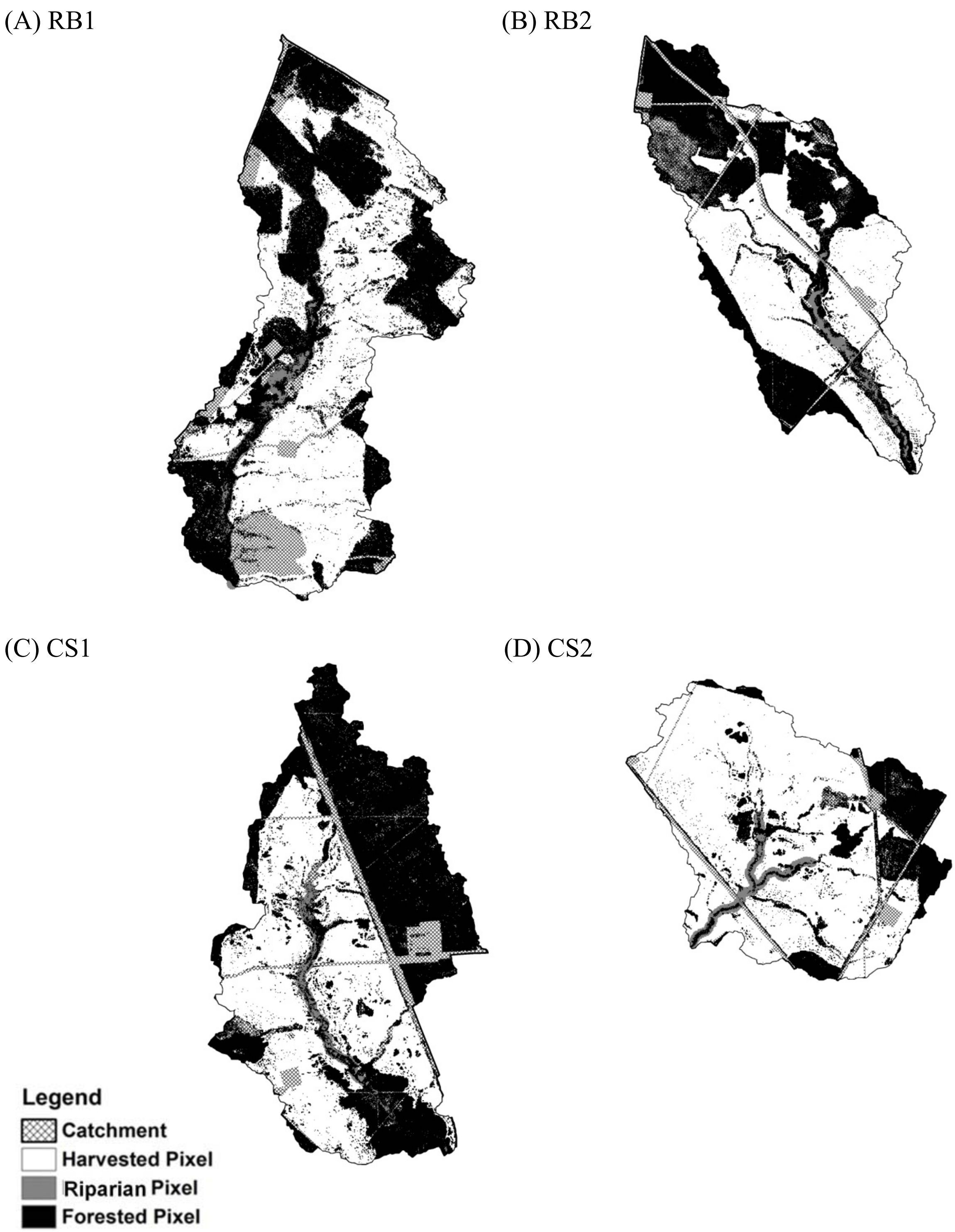

Figure 2.3: Maps of the harvested watersheds (hatched background) overlaid with riparian pixels (white), riparian pixels (gray), and forested pixels (black); (A) Riparian Buffer 1 (RB1), (B) Riparian Buffer 2 (RB2), (C) Cut-to-Shore 1 (CS1), (D) Cut-to-Shore 2 (CS2).

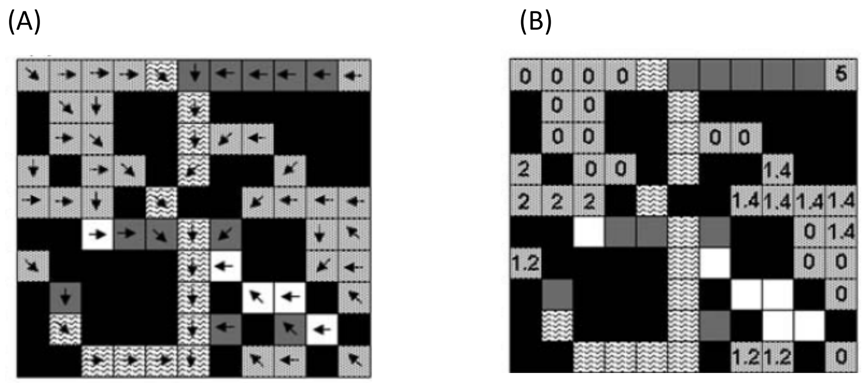

Figure 2.4: (A) Hypothetical maps showing the results of flow-paths from harvested pixels (light gray) through forested pixels(dark gray) distributed along a stream channel (waves), pixels isolated from the flow-paths (black), and unclassified pixels (white) (B) The calculated forested flow-path length for each of the harvested pixels.
(Baker et al. 2006)

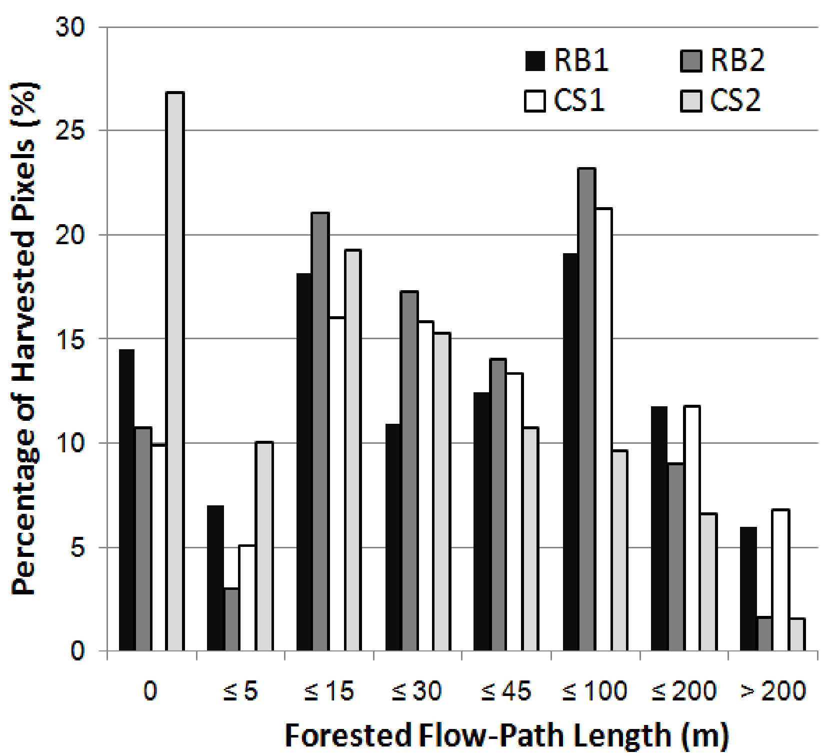

Figure 2.5: Histogram of forested flow-path length for harvested pixels (%) with the upper bound of the bin displayed on the x-axis, except the last bin with the lower bound displayed, for the study watersheds of Riparian Buffer 1 (RB1, n=241,734), Riparian Buffer 2 (RB2, n=170,657), Cut-to-Shore 1 (CS1, n=190,801), and Cut-to-Shore 2 (CS2, n=228,073).

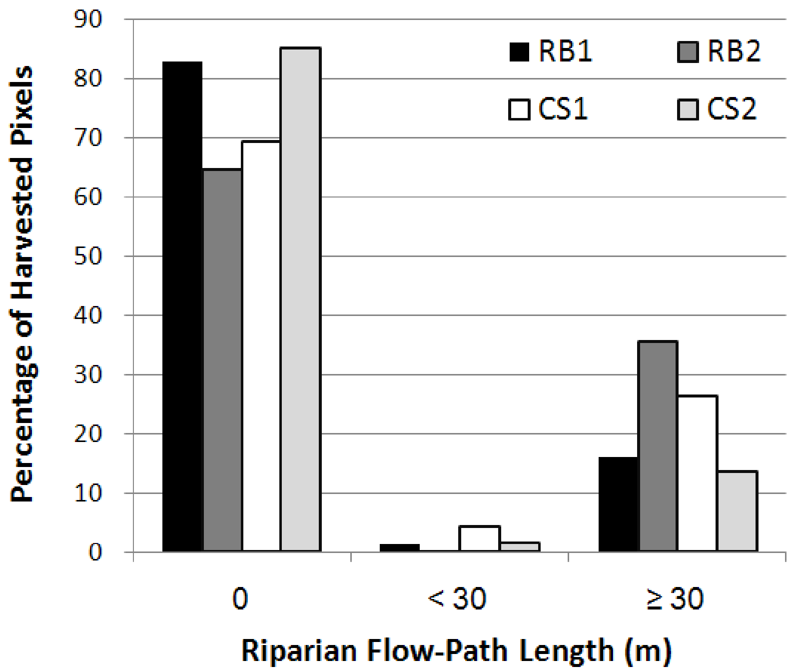

Figure 2.6: Histogram of riparian flow-path length for harvested pixels (%) with the upper bound of the bin displayed on the x-axis, except the last bin with the lower bound displayed, for the study watersheds of Riparian Buffer 1 (RB1, n=241,734), Riparian Buffer 2 (RB2, n=170,657), Cut-to-Shore 1 (CS1, n=190,801), and Cut-to-Shore 2 (CS2, n=228,073).

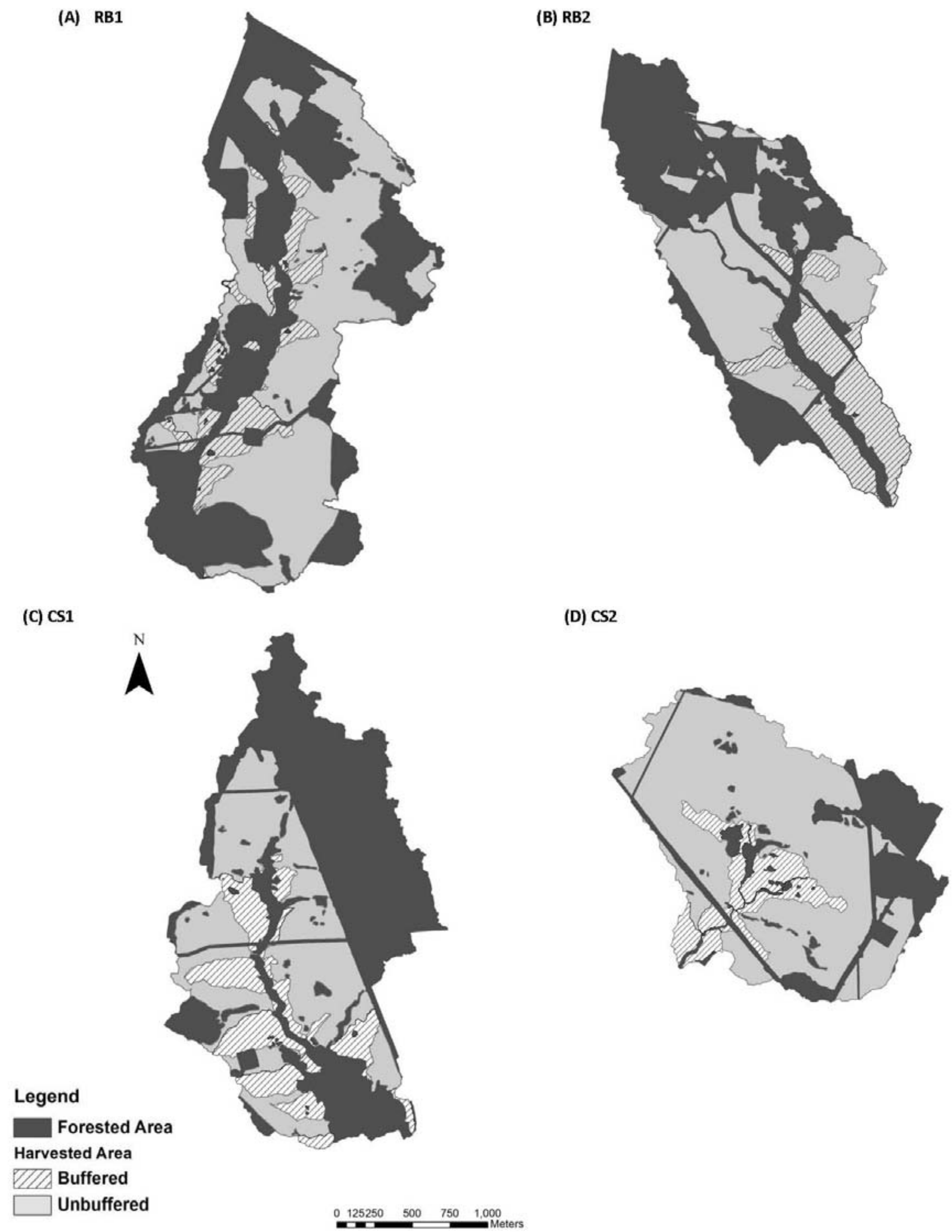

Figure 2.7: Maps of the harvested watersheds showing locations and sizes of buffered (lined) and non-buffered (light gray) harvested pixels along with undisturbed areas (dark gray); (A) Riparian Buffer 1 (RB1), (B) Riparian Buffer 2 (RB2), (C) Cut-to-Shore 1 (CS1), (D) Cut-to-Shore 2 (CS2).

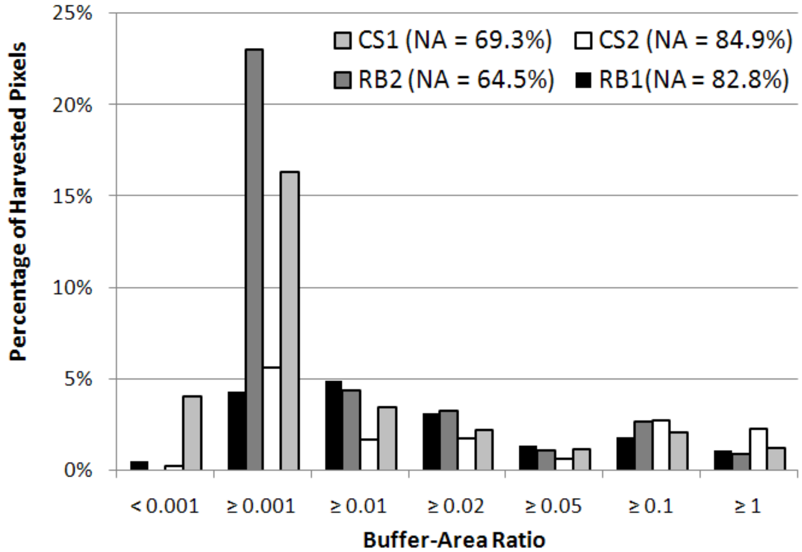

Figure 2.8: Histogram of buffer-area ratio for riparian flow-path pixels (%)with the lower bound of the bin displayed on the x-axis, except the first bin with the upper bound displayed, for the study watersheds of Riparian Buffer 1 (RB1, n=41,582), Riparian Buffer 2 (RB2, n=60,608), Cut-to-Shore 1 (CS1, n=58,495), and Cut-to-Shore 2 (CS2, n=34,370), (buffer-area ratio = riparian flow-path area/upslope contributing area).

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Chapter 3

PRECISION CONSERVATION OF RIPARIAN ZONES CONTAINING PREFERENTIAL FLOW-PATHS FROM HARVESTED LANDSCAPES

Introduction

Riparian buffers are areas of natural vegetation located adjacent to a stream channel. These vegetated strips are left undisturbed as an effort to reduce the effects of landscape changes on water quality associated with anthropogenic disturbances (Dosskey *et al.* 2010; Hoffmann *et al.* 2009). Riparian vegetation communities often have high structural and compositional diversity and have a critical role as terrestrial habitat within the forest landscape (Richardson *et al.* 2012).

Current forest management practices often restrict the harvesting of riparian vegetation within a fixed distance from the stream network (i.e. a fixed width buffer) to protect both terrestrial and aquatic ecosystems (Richardson *et al.* 2012). However un-harvested riparian buffers often become unnatural old growth forests, which can be isolated for several decades from natural disturbances. Older stands in the riparian buffers are protected by adjacent upland areas that contain newly planted or self-seeded stands that are more resilient to fire and insect disturbances (Everett *et al.* 2003; Smith *et al.* 2003). Protection and isolation of riparian buffers has now led to the appearance of unnatural patterns of older-growth forests in linear strips along streams and concentric circles around lakes (Buttle 2002; Steedman *et al.* 2004). These unnatural patterns of older-growth forests may negatively impact the sustainability of the forest ecosystem, whose biota often requires natural stand-replacing disturbances (Moore and Richardson 2012). For instance the reduction of riparian wildfire could result in decreased complexity of the channel and riparian habitat areas (Eaton and Giles 2009). Thus the emergence of unnatural patterns of forested landscapes has led to the desire for forest management practices that better emulate natural disturbances (MacDonald *et al.* 2004; Long 2009; Sibley *et al.* 2012).

The ecological consequences of failing to emulate natural disturbance within riparian buffers has led to the adoption of selective harvesting within buffers, to generate a more natural shoreline habitat pattern (Kardynal *et al.* 2009). Selective harvesting within buffers has also been used for ecological restoration when fire suppression has led to undesirable ecological changes (Beche *et al.* 2005). Selective harvest within riparian buffers has now become an accepted practice in over 80% of jurisdictions in North America (Lee *et al.* 2004). When selective harvesting within riparian zones was allowed, the guidelines were often relatively restrictive but did not require a modification to buffer width. However jurisdictions within the Boreal, Northeast, and Pacific regions already required a buffer width greater than the regional average. Thus the practice of selective harvesting within these jurisdictions resulted in a similar density of trees within the riparian zone, compared to a jurisdiction that did not allow selective harvesting, but required a buffer width less than the regional average (Lee *et al.* 2004). Although when selective harvesting within riparian buffers was allowed, the required buffer width was not modified due to the selective harvesting. As selective harvesting of riparian buffers becomes an accepted practice, various restrictive measures are being developed to strike a balance between mitigating the negative effects of clear-cutting and producing the ecological benefits of natural disturbance.

Currently multiple restrictive measures are applied to the selective harvesting of riparian buffers throughout the various jurisdictions of North America. Although restrictive measures on selective harvesting differed between jurisdictions there were many similarities. Common themes of restrictive measures on selective harvesting included: retaining at least half the canopy cover, minimizing ground and vegetation disturbances, preventing direct shoreline erosion, and requiring spatially dispersed cutting (Lee *at al.* 2004). An underlying concept in selective harvesting within riparian buffers is that harvest intensity should increase with distance from shore, since riparian structure, function and biota are likely to decrease with distance from the stream side (Palik *et al.* 2000). The suggested gradient of harvest intensity from the water's edge would be continuous, from: no harvest, to single tree selection, to small group selection, to large group selection to finally clear-cutting within the upland areas (Ilhardt *et al.* 2000). The idea of multiple-management zones along water bodies has become a practice in a number of Pacific jurisdictions that found selective harvesting had little ecological effect (Lee *et al.* 2004).

If selective harvesting within riparian buffers is carefully executed with the proper restrictive measures, many of the anticipated ecological impacts can be minimized. In the Boreal Shield increased fine sedimentation in streams as a result of riparian harvest could be mitigated with winter harvesting and the avoidance of immediate harvesting within 3 m of the stream-side (Kreutzweiser *et al.* 2010). Similarly in the Boreal Plain no effect could be found on fine sedimentation or temperature in streams from riparian harvesting on frozen soils during winter (Prepas *et al.* 2008). In both the province of British Columbia and the state of Mississippi, when soil disturbance was minimized, harvesting within riparian buffers did not increase suspended sediment content in streams (Macdonald *et al.* 2003; Keim and Schoenholtz 1999). Similarly in the states of

Washington and Oregon, selective harvesting within riparian buffers has been reported to reduce the deposition of large organic debris to streams (McDade *et al.* 1990; Bilby and Ward 1991). Harvesting of the riparian canopy around Boreal Shield lakes reduced allochthonous inputs of small woody debris by 90% (France *et al.* 1996). In British Columbia with the harvest of riparian buffers, allochthonous materials deposited in streams from forested systems have declined (Kiffney and Richardson 2010). Therefore harvesting of riparian buffers may lead to an overall reduction in deposition of allochthonous materials to streams, even when sediment transported from harvested areas is considered.

Within forested landscapes, flow-paths progress typically from sheet flow, to rills and gullies before discharging to an ephemeral or higher order stream. Since the majority of the surface water transverses the fixed-width riparian buffer through rills and gullies, and not as uniform sheet flow, zones within the buffer would receive disproportionate amounts of flow (Desmet *et al.* 1999; Dosskey *et al.* 2002). Rills and gullies within riparian buffers, referred to as preferential flow-paths, have yet to be incorporated into guidelines for selective harvesting within riparian buffers (Kreutzweiser *et al.* 2012). Preferential flow-paths can have a major impact on the sensitivity of harvesting a particular area within the riparian buffer. In the state of Iowa for example, only 6% of the riparian buffer had a contributing area greater than 10 ha, while 80% of the riparian buffer had a contributing area of less than 0.4 ha (Tomer *et al.* 2003). On the Boreal Plain in western Canada the fixed-width riparian buffers contained preferential flow-paths, for the majority of the surface runoff experienced upslope contributing areas exceeding the buffer areas by two orders of magnitude (Chapter 2). In a New Zealand watershed it was discovered that 28% of the riparian buffer accounted for 85% of the upslope contributing area (McGlynn and Seibert 2003). Therefore the inclusion of flow-paths analysis is critical in design of selective harvesting, because small areas of riparian buffers will experience the majority of the surface flow, while major portions of the buffer will experience no flow at all.

In this study, the concept of selective harvesting will be applied to four watersheds that were previously analyzed with flow-path metrics (Chapter 2). A 30-m fixed-width riparian buffer adjacent to 1st order streams was retained in two of the four harvested watersheds. The remaining two watersheds were cut-to-shore wherever possible. Post-harvest high resolution light detection and ranging (LiDAR) topographical data were available for all four watersheds after harvesting. The LiDAR data were used to determine the landscape flow-paths, including the ephemeral stream network, and to assess the effects of selective harvesting within riparian buffers. The forested flow-path length from harvest locations to the stream channel will be calculated for all four watersheds, for varying harvest intensities in the riparian buffer. It is hypothesized that: 1) zones of the fixed-width riparian buffer have no upslope contributing area from the cut-blocks; 2) that small zones of the fixed-width riparian buffers within natural landscapes are critical in the buffering of the harvested landscape from the stream channel; and 3) that the majority of the riparian zone within forested landscapes can be precision harvested without increasing the connectivity between harvested landscapes and the stream channel.

Methods

Study watersheds

The sensitivity of selective harvesting on landscape flow-paths was performed on four commercially harvested watersheds (Table 2.1) located in the Boreal Plain ecozone. Over the past decade the Boreal Plain has experienced an increased intensity of forest disturbance, due to both harvesting for timber and pulp production, and clearing for oil and gas extraction (Alberta Economic Development 2008). These four watersheds are part of the Forest Watershed and Riparian Disturbance (FORWARD) research program located in the Swan Hills, 240 km northwest of the City of Edmonton, province of Alberta, Canada (Fig. 2.1). A reference watershed could not be implemented in the flow-path analysis study because a harvested area was required for the initiation of a flow-path.

The study watersheds are forested with trembling aspen (*Populustremuloides* Michx.), balsam poplar (*P. balsamifera* L.), white spruce (*Piceaglauca* (Moench) Voss), black spruce (*P. mariana* (Mill.) BSP), lodgepole pine (*Pinuscontorta* Dougl. Ex Loud. var. *latifolia* Engelm.), and tamarack (*Larixlaricina* (Du Roi) K. Koch). The dominant soil class is deep, fine, Orthic Gray Luvisols (Whitson *et al.* 2003), but Organics and Brunisols are also present (Ecological Stratification Working Group 1996).The Boreal Plain is a semi-arid to sub-humid region (Zoltai *et al.* 1998), subject to substantial inter-annual variation in precipitation (total annual precipitation at the City of Whitecourt, Alberta, 50 km to the southeast of the study sites, ranged from 364 to 786 mm between 1980 and 2004).

The area of the four harvested watersheds ranged from 268 to 420 ha (Table 2.1). Harvest intensity of the watershed area for the 2004 winter clear-cut varied from 47 to 77 per cent (%) and was organized into large cut-blocks (Fig. 2.2). A 30-m fixed-width riparian buffer (measured perpendicular to the 1st order stream channel) was retained in two of the four watersheds (RB1 and RB2), while the remaining two watersheds (CS1 and CS2) were harvested to the stream channel (cut-to-shore) whenever possible. The fixed-width buffer was in accordance with Alberta's provincial guidelines regulating a 30-m wide buffer strip along permanent watercourses, and was intended in part to limit nutrient and sediment loading to surface waters after harvest (Alberta Sustainable Resource Development 2006). In addition the four harvested watersheds were treated with post-harvest mechanical site preparation along with the application of glyphosate to limit the colonization by grasses and shrubs. The outlet location of each watershed was monitored for streamflow rate, and nutrient concentration before and after harvest

Geographic data sources

LiDAR and geographical data provided by industrial partner Millar Western Forest Products Ltd. were analyzed to determine elevation, and delineate stream channels and land cover types with GIS. A digital elevation model (DEM) with 3-m resolution was created for each watershed from the LiDAR xyz data. From the DEM, the number of upslope pixels, each having an area of 9 m^2, contributing to each downslope pixel was estimated based on the standard flow accumulation technique available in Arc/Info (ESRI, Inc) geographic information system (GIS) (O'Callaghan and Mark 1984; Jenson and Domingue 1988).

Stream channels for all four watersheds were formed based on the flow accumulation results, with a contributing area threshold defined for the heads of the stream network. A contributing area threshold of 50 ha was estimated to define the heads of 1st order streams. A 50-ha threshold corresponds to the initiation of the fixed-width riparian buffer in watershed RB1 and RB2. A threshold of 5 ha was estimated for ephemeral streams from the visual detection of gullies in the hill-shaded DEM. The stream network for all four watersheds was formed from these contributing area thresholds and the flow accumulation results. The locations of the streamflow and water quality monitoring stations were used to represent the watershed outlets in GIS. The watershed catchments were then delineated from the flow accumulation results, with the upslope contributing area to the watershed outlet pixel.

Vegetation height was derived by subtracting the LiDAR ground surface DEM from the LiDAR top of canopy DEM. The industrial partner also provided cut-block areas that were imported as GIS shape files. The area stipulated by current provincial regulations to maintain a fixed-width riparian buffer (buffer area), was delineated in all four watersheds at a constant distance of 30 m perpendicular to the 1st order streams. The buffer area in RB1 and RB2 represented an actual forested area, while in CS1 and CS2 the buffer area was harvested wherever possible.

Pixel Categories

Three categorical pixel descriptors, namely harvested, forested, and riparian, were used in the summation of forested flow-path lengths for a set of selective harvest scenarios. The various selective harvest scenarios differed in the percentage of riparian pixels that were simulated as forested. For each pixel within the watershed, it was determined if any of the three possible categorical descriptors should be applied (Table 2.2, Fig. 2.3). A pixel was deemed harvested if it was located within a cut-block shape file. If the pixel was within the buffer area, regardless if it was harvested, it was labeled as riparian. Finally if the vegetation height of a pixel was greater than 3.05 m and not a riparian pixel, the pixel was considered forested. Within the cut-block areas, LiDAR still detected the presence of very small isolated patches of trees resulting in a few pixels being labeled both harvested and forested. However for each of the selective harvest scenarios a riparian pixel could be simulated as either forested or not regardless if a tree was observed or not. Each riparian pixel was simulated at least once as either a forested or a harvested pixel throughout the sensitivity analysis. A logic routine determined for each of the selective harvest scenarios if a riparian pixel would be simulated as forested or not. The percentage of riparian pixels that were forested differed in each of the selective harvest scenarios and ranged from 0 to 100%.

Selective Harvest Routine

A selective harvest routine was developed to assess the effects of conversion from forest to non-forest within the fixed-width riparian buffer on the flow-path from harvested pixels. A forested flow-path analysis was completed for each of the selective harvest scenarios produced by the select harvest routine. The select harvest routine would successively select forested riparian pixels from the previous selective harvest scenario and convert the pixel to harvested. Thus each subsequent selective harvest scenario would have a decreased percentage of riparian pixels that were forested. For each of the four watersheds, 100% of the riparian pixels were considered forested in the initial selective harvest scenario and all of the riparian pixels were simulated as harvested in the final selective harvest scenario. The selective harvest routine used the upslope harvested contributing area to a forested riparian pixel to determine if it would be converted to a harvested riparian pixel. A forested riparian pixel would be converted if the upslope harvested contributing area to the pixel was less than the prescribed pixel threshold for a particular selective harvest scenario.

All riparian pixels were specified as forested in the first selective harvest scenario. A threshold of 1 pixel for the upslope harvested contributing area was used for the second selective harvest scenario. Therefore the second selective harvest scenario represented the harvesting of zones within the fixed-width riparian buffer which had no upslope contributing area from a cut-block. For each subsequent selective harvest scenario the pixel threshold was increased on a logarithmic scale (e.g. 1, 2, 3, …, 9; 10, 20, 30, …, 90; 100, 200, 300, .., etc.) until all of the forested riparian pixels were converted to harvested riparian pixels. The flow-path metrics were calculated for each of the selective harvest scenarios in the four study watersheds.

Flow-path Metric Calculation

Flow-path length was quantified within a harvested watershed using the LiDAR DEM to identify the surface transport pathway (flow-path) following the steepest descent from each harvested pixel. The flow-paths from the harvested pixels to the stream network were produced based on topographic analysis techniques that are available within GIS software applications (Jenson and Domingue 1988). Next the summed length of flow path segments that occurred through forested pixels along the flow-path from each harvested pixel to the stream was determined (Baker et al. 2006, example in Fig. 2.3). For example, consider the flow-path from a harvested pixel that transverses straight through three harvested pixels, then diagonally through four forested pixels, then through seven harvested pixels and finally straight through ten riparian pixels, of which only five are forested, before entering a stream. Based on the flow-path metrics established above, the forested flow-path length for this example is 32 m [4 x (3√2, four diagonal forested) + 5 x (3, straight forested)= 32 m.

The forested flow-path lengths were then calculated, for each of the selective harvest scenarios, in each watershed. The average forested flow-path length and the percentage of forested riparian pixels converted to harvested riparian pixels was tabulated for each selective harvest scenario. In addition the percentage of harvested pixels with a forested flow-path length <30 m was recorded for each selective harvest scenario. Finally the percentage of harvested pixels with a forested flow-path of 0 m, labeled as non-forested flow-path pixels, was also calculated for each selective harvest scenario.

The difference in forested flow-path lengths between selective harvest scenarios illustrated the sensitivity of various zones within the fixed-width riparian buffer. The difference in forested flow-path lengths between study watersheds demonstrated the effect of size and location of the cut-blocks within a study watershed. Percentage of harvested pixels with a forested flow-path length of <30 m illustrates the effects of selective harvesting on riparian buffer efficiency. Finally percentage of non-forested flow-path pixels quantifies the formation of gaps within the riparian buffer caused by selective harvesting.

Results

Throughout the flow-path analysis, watersheds RB1, RB2, and CS1 showed similar trends and differed from watershed CS2. A variation in trends was expected due to the difference in harvest intensity between RB1 (52%), RB2 (50%), and CS1 (47%) and the harvest intensity of CS2 (77%) (Table 2.1). Larger harvest intensity causes a difference in trends as a result of reduction in non-harvested stands upslope of the fixed-width riparian buffer. Non-harvested stands are categorized as forested pixels and would be included in the flow-path analysis. Due to the increased harvest intensity of watershed CS2 there were often no forested pixels upslope of the fixed-width riparian buffer along the flow-path from a harvested pixel. In contrast, watershed RB1, RB2, and CS1 often had numerous forested pixels upslope of the fixed-width riparian buffer along the flow-paths from the harvested pixels. Therefore the abundance of upslope forested pixels within watershed RB1, RB2, and CS1 continued to intercept flow from the cut-blocks as it moved toward the stream network regardless of the entire fixed-width riparian buffer being harvested.

Upslope Harvested Contributing Area

For each riparian pixel the area with no harvested pixels within its upslope contributing area was delineated (Fig. 3.1). The upslope contributing areas of harvested pixels were compiled from only the 1st selective harvest scenario with all riparian pixels simulated as forested. The majority of riparian pixels in watersheds RB1 (79%), RB2 (70%) and CS1 (66%) had no harvested pixels within their upslope contributing area. In comparison, only 14% of the riparian pixels in watershed CS2 had no harvested pixels within their upslope contributing area (Table 3.1), but over 50% of the riparian pixels had less than 5 harvested pixels within their upslope contributing area (Fig. 3.2). Zones of grouped pixels within the fixed-width riparian buffers that have minimal harvested upslope contributing area, could be disturbed, without creating a direct connection between cut-blocks and stream networks (Fig . 3.2). In all four watersheds, 5% or less of the riparian buffer had a harvested contributing area greater than 1 ha. Therefore the majority of the flow from the cut-blocks through the fixed-width riparian buffer was limited to 5% of the buffer, with large portions having no harvested flow at all.

Average Forested Flow-Path Length

Forested flow-path lengths were determined for each harvested pixel and averaged for each watershed. In each harvest scenario, average forested flow-path length was compared to the percentage of the riparian pixels converted from forested to harvested (Fig. 3.3). The greatest difference in average forested flow-path lengths for watersheds RB1, RB2, and CS1 between two consecutive harvest scenarios was observed in the 1st and 2nd selective harvest scenarios (Table 3.2). The reason for the large disparity of average forested flow-path length between 1st and 2nd selective harvest scenarios, was that over 60% of the riparian pixels were converted from forested to harvested pixels (Table 3.1). The increase in harvested pixels ranged from 6 to 11% in RB1, RB2, and CS1 (Table 3.1), and the newly harvested pixels would usually have a forested flow-path length less than 30 m. The forested flow-path length for a harvested riparian pixel would usually be less than 30 m, since the pixel would be within the 30-m fixed width from the stream network. Therefore the majority of the fixed-width riparian buffer within watersheds RB1, RB2, and CS1 could be harvested without impacting the average forested flow-path length from the original cut-block.

In watershed CS2 a slight difference between the 1st and 2nd selective harvest scenario was observed, for the number of riparian pixels converted from forested to harvested was 14% (Table 3.1). Correspondingly the increase in harvested pixels between the 1st and 2nd scenario was less than 1% (Table 3.1). The average forested flow-path length in CS2 was also slighter greater than 30 m and would not be impacted by the addition of harvested riparian pixels with a forested flow-path length of approximately 30 m as well. A greater number of harvested pixels on the fringe of the fixed-width riparian buffer were also observed in watershed CS2, compared to the other three watersheds due to the higher harvest intensity (Table 2.1). An increase in harvested pixels on the fringe of the riparian buffer resulted in a lower average forested flow-path length and rogue harvested pixels flowing through the buffer. Therefore it was important to include a flow-path analysis from the harvested landscapes to determine zones with the fixed-width riparian buffer that were required to isolate the cut-blocks from the stream network.

The average forested flow-path length for the last, or 61st scenario, ranged from 25 to 46 m in the four watersheds. The average forested flow-path length for the last scenario, where all riparian pixels were harvested, was at least 50% of the average forested flow-path length for the 1st scenario, where all the riparian pixels were forested. There was a greater difference in average forested flow-path length between watersheds CS1 (63 m) and CS2 (32 m) in the 1st harvest scenario than the difference in average forested flow-path length in CS1 between the 1st and last scenario (46 m). Therefore the variance in average forested flow-path length was more dependent on the size and location of cut-blocks, rather than any prescribed harvesting strategy in the riparian buffer.

<u>Forested Flow-Path Length < 30 m</u>

Average forested flow-path length should not be used alone, to quantify the degree to which disturbed lands were riparian in each watershed. The average flow-path lengths were not normally distributed, and harvested pixels would have forested flow-path lengths that exceeded 400 m (Chapter 2). The average forested flow-path length should be calculated along with the percentage of harvested pixels with a forested flow-path length < 30 m in each selective harvest scenario (Fig. 3.4). Percentage of forested flow-path length < 30 m experienced the greatest increase between two consecutive scenarios in the 1^{st} and 2^{nd} selective harvest scenarios for watersheds RB1, RB2, and CS1. As with the average forested flow-path length, a difference in percentage of forested flow-path length < 30 m would be expected in RB1, RB2, and CS1 due to the increase in harvested pixels. However the difference in percentages of harvested pixels with a forested flow-path < 30 m (RB1 4%, RB2 3%, CS1 3%) between the 1^{st} and 2^{nd} scenario was less than the increase in harvested pixels within the riparian buffer in the 2^{nd} scenario (RB1 11%, RB2 6%, CS1 6%). Therefore in watersheds RB1, RB2, and CS1, the majority of fixed-width riparian buffer with no upslope harvested contributing area could be converted from forested to harvested, and have a forested flow-path length greater than 30 m.

The percentage of harvested pixels with a forested flow-path length < 30 m was always greater than 40% for all four study watersheds and selective harvest scenarios. Regardless of the harvesting practices conducted within the riparian buffer, over 40% of the harvested area will not be adequately buffered. The difference between the percentage of forested flow-path lengths < 30 m between the first and last selective harvest scenario were 16, 21, 17 and 8% for watersheds RB1, RB2, CS1, and CS2 respectively. Thus at most, any selective harvesting practice in the riparian buffer could cause up to a quarter of the harvested area to no longer be “well” buffered with a forested flow-path length greater than 30 m. The low percentage of harvested pixels impacted by selective harvesting practices was expected, since on average 75% of the harvested pixels do not even flow through the fixed-width riparian buffer (Chapter 2). Therefore zones within the fixed-width riparian buffer were identified for the majority of the buffering of disturbed landscapes.

Non-forested Flow-Path Length

Percentage of harvested pixels with a forested flow-path length < 30 m does not quantify the integrity of the fixed-width riparian buffer. To quantify the gaps within the fixed-width riparian buffer the percentage of harvested pixels with a non-forested flow-path length (i.e. a forested flow-path length of 0 m) was calculated for each harvest scenario in each of the study watersheds. Any harvested pixel with a non-forested flow-path length would be directly connected to the stream network, without any type of barrier. Unlike percentage of forested flow-path lengths < 30 m, the percentage of non-forested flow-path lengths actually decreased between the 1st and 2nd scenarios (Table 3.4). The percentage of non-forested flow-path length decreased because no gaps were created between the first and second selective harvest scenario, but the number of harvested pixels that have a flow-path length > 0 m was increased. It was not until the last 5% of the riparian buffer was harvested, that the formation of gaps in the fixed-width riparian buffer began to occur (Fig 3.5). The formation of gaps in the riparian buffer was not dependent on the percentage of riparian pixels converted from forested to harvested, but rather on riparian pixels with an upslope harvested contributing area > 1 ha converted from forested to harvested. Therefore if the 5% of the riparian pixels were harvested with preferential flow-path (i.e. upslope harvested contributing area > 1 ha), it would affect the forested flow-path lengths similarly to the entire riparian buffer being harvested.

Harvesting of the preferential flow-paths doubled the harvested area that was directly connected to the stream network in watersheds RB1, RB2, CS1. The impact of harvesting the preferential flow-paths in CS2 was not as profound because of the high percentage of non-forested flow-paths from the higher harvest intensity. To avoid an increased connectivity between the cut-blocks and the stream network, the riparian pixels with large upslope harvested contributing areas should be avoided in selective harvesting (Fig. 3.6). Therefore a flow-path analysis can be implemented to determine zones within the fixed-width riparian buffer that are crucial in buffering landscape disturbances to surface water quality and quantity.

Discussion

Average Forested Flow-Path Length

Average forested flow-path length did not properly quantify the importance of various zones within the fixed-width riparian buffer. Within agricultural landscapes, average flow-path lengths are one calculation that can be used to quantify the buffering effectiveness of a fixed-width riparian buffer (Baker at al. 2006). However in agricultural landscapes typically the upslope contributing area to the fixed-width riparian buffer does not contain up to 50% forested landscapes. Thus the average forested flow-path lengths were equivalent to average riparian flow-path lengths and provided a proper quantification of the how well the disturbed landscapes were buffered. Conversely in forested landscapes that were disturbed, the undisturbed forested areas upslope of the fixed-width riparian buffer would also act as a buffer. Upslope undisturbed forested area could increase the forested flow-path lengths to over 400 m, and caused the distribution of forested flow-path lengths to not be normal (Chapter 2). Therefore average forested flow-path length should be avoided in describing disturbed forested landscapes. Average flow-path length should only be used in landscapes where riparian flow-path length and forested flow-path length are interchangeable (e.g. cultivated agricultural lands without wetlands and forests).

Forested Flow-Path Length < 30 m

Percentage of forested flow-path length < 30 m was a better indicator than average forested flow-path length for the effectiveness of the fixed-width riparian buffer and the impact of harvesting it. It was demonstrated that the percentage of forested flow-path length in watersheds RB1, RB2, and CS2 went on average from 46% in the 1st harvest scenario to 49% in the second harvest scenario to 64% in the final scenario (Table 3.3). Over 50% of the fixed-width riparian buffer was converted from forested to harvested with only a slight impact on the number of harvested pixels flowing through at least 30 m of forested pixels. Actually the main reason for the increase in percentage of forested flow-path length was not because of the cut-blocks being less riparian, but because of the increase in harvested pixels within the fixed-width riparian buffer that had a forested flow-path length < 30 m. Between the 1st and 2nd harvest scenarios, only the riparian pixels with an upslope harvested contributing area of 0 pixels were converted. Therefore the majority of the fixed-width riparian buffer could be harvested without diminishing the buffering potential of flow-paths from harvested landscapes.

The percentage of forested flow-path lengths < 30 m remained relatively constant until the last 5% of the fixed-width riparian buffer was harvested. When the zones with an upslope harvested contributing area of > 1 ha (Fig 3.1) were harvested, the average percentage of forested flow-path lengths for watersheds RB1, RB2, and CS1 went from 49 to 64% (Table 3.3). Within watersheds with a harvest intensity of 50%, the presence of a fixed-width riparian buffer influenced the buffering potential of on average 15% of the harvested pixels; most of these harvested pixels influenced by the buffer would consist of the newly converted riparian pixels from forested to harvested. Therefore the riparian management practices are inconsequential to buffering disturbed landscapes relative to the impact that cut-block size and location had on percentage of forested flow-path lengths < 30 m.

When watershed CS2 was analyzed, cut-block size was the largest factor influencing the percentage of forested flow-path lengths < 30 m. Watershed CS2 had a harvest intensity of 77% and the percentage of forested flow-path lengths < 30 m remained constant in the 1st and 2nd scenario at 65% and increased to 73% in the last (61st) scenario (Table 3.3). For the 1st scenario in watershed CS2 the percentage of forested flow-path lengths < 30 m (65%) exceeded the average percentage of forested flow-path lengths < 30 m for the other three study watersheds (64%). Therefore restriction should be placed on harvesting practice throughout the entirety of all watersheds, and not only within a fixed-width of a stream side, to ensure that a maximum percentage of forested flow-path length < 30 m is not exceeded.

<u>Non-forested Flow-Path Length</u>

Finally the integrity of the fixed-width riparian buffer was evaluated using the percentage of non-forested flow-path lengths. Percentage of non-forested flow-path lengths directly represents the gaps in a buffer design, or the percentage of harvested pixels which do not flow through any forested pixels before discharging to the stream network. The percentage of non-forested flow-path lengths in watersheds RB1, RB2, and CS1 decreased on average from 12% to 11% between the 1^{st} and 2^{nd} scenario (Table 3.4). The decrease in percentage of non-forested flow-path lengths demonstrated that the majority of the riparian pixels could be converted from a forested to harvested condition without diminishing the integrity of the fixed-width riparian buffer. However the average percentage of non-forested flow-path length doubled from 11% to 22% in the last (61^{st}) selective harvest scenario, mostly due to the conversion of harvested pixels within the buffer, not the cut-block. In watershed CS2 with an increased relative cut-block area, the percentage of non-forested flow-paths ranged from 26% in the 1^{st} and 2^{nd} scenario, to 34% in the last selective harvest scenario. Therefore the presence of a fixed-width riparian buffer had very little impact on the connectivity of harvested landscapes to the stream network in comparison to the size and location of the cut-block.

Areas Sensitive to Selective Harvesting

It was evident from this study on the Boreal Plain that approximately 5% of the riparian buffer area is hydrologically sensitive. Average forested flow-path length remained relatively constant from the 2^{nd} selective harvest scenario until the last 5% of the riparian pixels were converted from forested to harvested (Fig 3.3). A similar trend was also present with percentage of harvested pixels with a forested flow-path length < 30 m and non-forested flow-path length, where the selective harvest scenarios had very little effect until the last 5% of the riparian buffer was harvested (Fig. 3.4, 3.5). The 5% of the riparian buffer that was sensitive to selective harvesting had an upslope harvested contributing area of at least 1 ha. Therefore fixed-width riparian buffers are not uniformly sensitive to harvesting with respect to buffering hydrologic impacts from harvested lands, yet preferential flow-path analysis is used in forestry planning or other practices which alter forested lands.

Preferential flow-paths are the result of flows originating across the surface of the terrain being concentrated through rills and gullies instead of a creating a uniform sheet flow. In the analysis conducted, the cell widths were 3 m and an upslope harvested contributing area of 1 ha resulted in a preferential flow-path. In comparison if the boundary of the watershed was 500 m from the stream's edge and completely harvested, then the upslope harvested contributing area would be 0.15 ha with perfectly uniform sheet flow. Typically any harvested pixel greater than 500 m from the stream's edge would have drained into an ephemeral stream, and not through the fixed-width riparian buffer. The areas within the riparian buffer that had the greatest impact on forested flow-path lengths had at least 6 times the flows from harvested lands, than expected under a uniform hill-slope process. Therefore precision conservation of zones within the riparian buffer that contain preferential flow-paths have great importance in preventing increased erosion of soils adjacent to the stream side, due to increased flow volumes from harvested areas.

Tables

Table 3.1: Area of fixed-width riparian buffer with no harvested pixels within their upslope contributing area for each study watershed. The study watersheds are designated Riparian Buffer 1 (RB1), Riparian Buffer 2 (RB2), Cut-to-Shore 1 (CS1), and Cut-to-Shore 2 (CS2).

	No Upslope Harvested Contributing Area		
Watershed (name)	Area (ha)	Area of Buffer (%)	Area of Harvest (%)
RB1	23.0	78.8	10.6
RB2	9.7	70.3	6.3
CS1	10.5	66.2	6.1
CS2	1.5	14.0	0.7

Table 3.2: Average forested flow-path length (m) for 1st, 2nd, and last selective harvest scenario for each study watershed. Selective harvest scenario: 1) all of riparian pixels are forested, 2) all riparian pixels with an upslope harvested contributing area equal to 0 pixels were converted from forested to harvested, remaining riparian pixels were forested, Last) was the 61st scenario and all riparian pixels are harvested. The study watersheds are designated Riparian Buffer 1 (RB1), Riparian Buffer 2 (RB2), Cut-to-Shore 1 (CS1), and Cut-to-Shore 2 (CS2).

	Average Forested Flow-Path Length for Selective Harvest Scenarios		
Watershed (name)	1st (m)	2nd (m)	Last (m)
RB1	58.4	53.9	44.5
RB2	50.8	48.5	33.3
CS1	62.7	59.7	45.7
CS2	31.7	31.6	25.3

Table 3.3: Percentage of harvested pixels with a forested flow-path length < 30 m for the 1st, 2nd, and last selective harvest scenarios for each study watershed. Selective harvest scenario: 1) all of riparian pixels are forested, 2) all riparian pixels with an upslope harvested contributing area equal to 0 pixels were converted from forested to harvested, remaining riparian pixels were forested, Last) was the 61st scenario and all riparian pixels are harvested. The study watersheds are designated Riparian Buffer 1 (RB1), Riparian Buffer 2 (RB2), Cut-to-Shore 1 (CS1), and Cut-to-Shore 2 (CS2).

	Forested Flow-Path Length < 30 m for Selective Harvest Scenarios		
Watershed (name)	1st (% of Pixels)	2nd (% of Pixels)	Last (% of Pixels)
RB1	48.8	52.7	64.8
RB2	46.3	48.9	67.5
CS1	41.4	44.2	58.5
CS2	65.1	65.3	72.7

Table 3.4: Percentage of harvested pixels with a non-forested flow-path length (i.e. a forested flow-path length of 0 m) for the 1st, 2nd, and last selective harvest scenarios for each study watershed. Selective harvest scenario: 1) all of riparian pixels are forested, 2) all riparian pixels with an upslope harvested contributing area equal to 0 pixels were converted from forested to harvested, remaining riparian pixels were forested, Last) was the 61st scenario and all riparian pixels are harvested. The study watersheds are designated Riparian Buffer 1 (RB1), Riparian Buffer 2 (RB2), Cut-to-Shore 1 (CS1), and Cut-to-Shore 2 (CS2).

	Non-Forested Flow-Path Lengths for Selective Harvest Scenarios		
Watershed (name)	1st (%) (% of Pixels)	2nd (%) (% of Pixels)	Last (%) (% of Pixels)
RB1	14.5	13.1	27.9
RB2	10.6	9.9	19.6
CS1	9.9	9.3	19.5
CS2	25.7	25.5	33.6

Figures

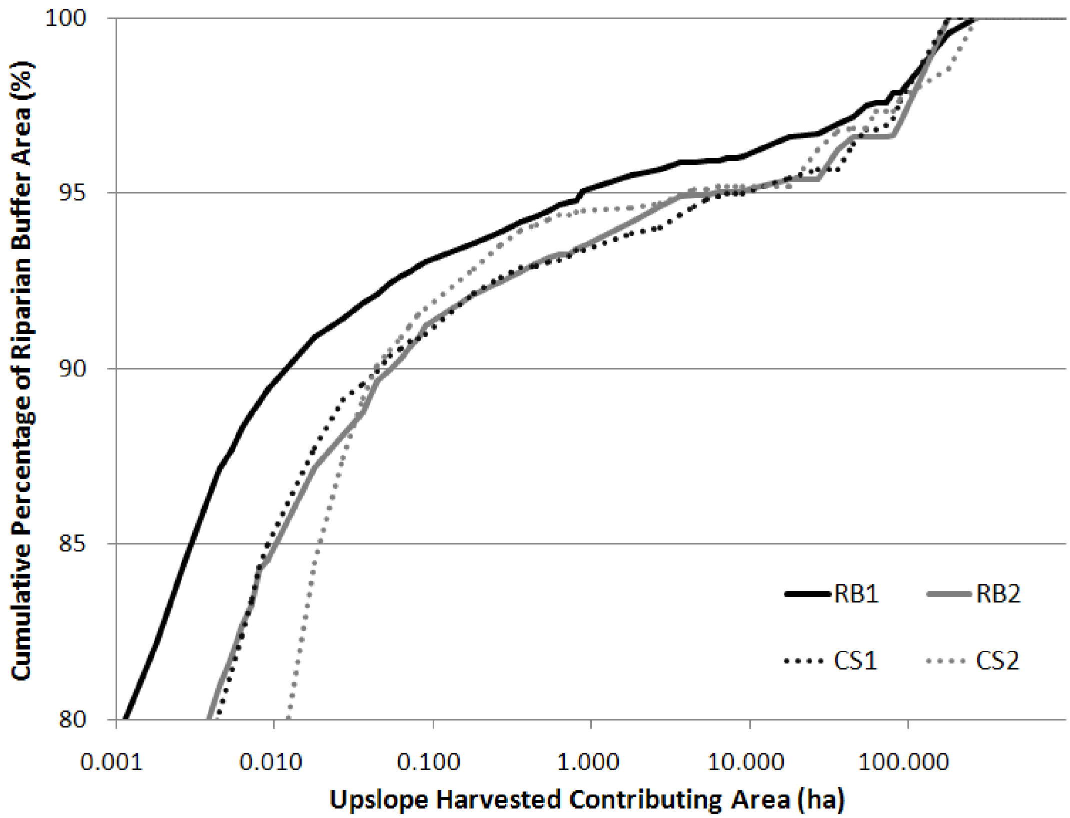

Figure 3.1: Cumulative percentage of the 30-m fixed-width riparian buffer area versus harvested area within the upslope contributing area. The study watersheds are designated Riparian Buffer 1 (RB1, solid black), Riparian Buffer 2 (RB2, solid grey), Cut-to-Shore 1 (CS1, dashed black), and Cut-to-Shore 2 (CS2, dashed grey).

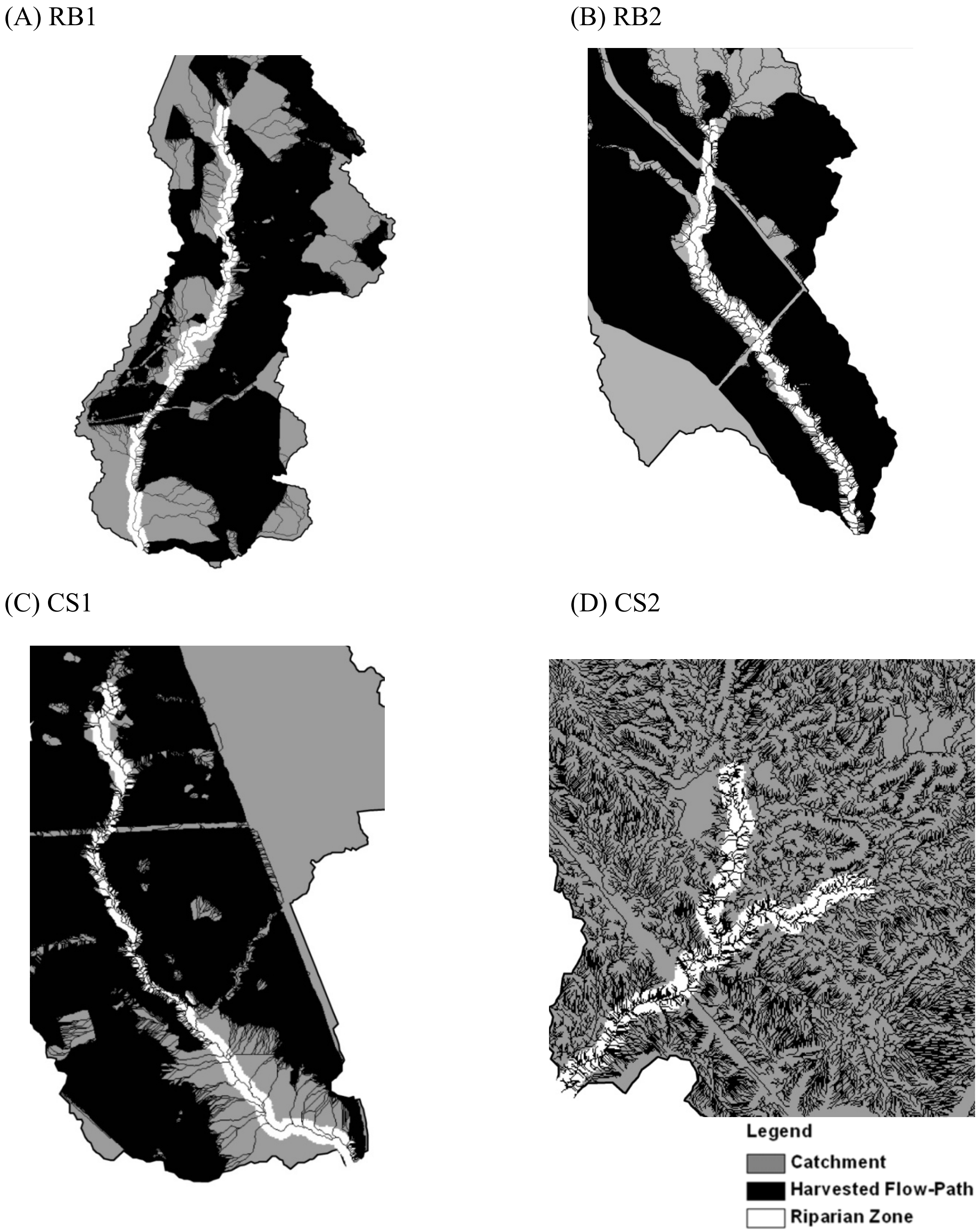

Figure 3.2: Maps of riparian zones showing the location and areal extent of flow-paths with a harvested pixel in the upslope contributing area (black) and riparian pixels with no harvested pixel in the upslope contributing area (white) for (A) Riparian Buffer 1 (RB1), (B) Riparian Buffer 2 (RB2), and (C) Cut-to-Shore 1 (CS1), while (D) Cut-to-Shore 2 (CS2) required at least 5 harvested pixels for the flow-paths (black) and riparian pixels (white).

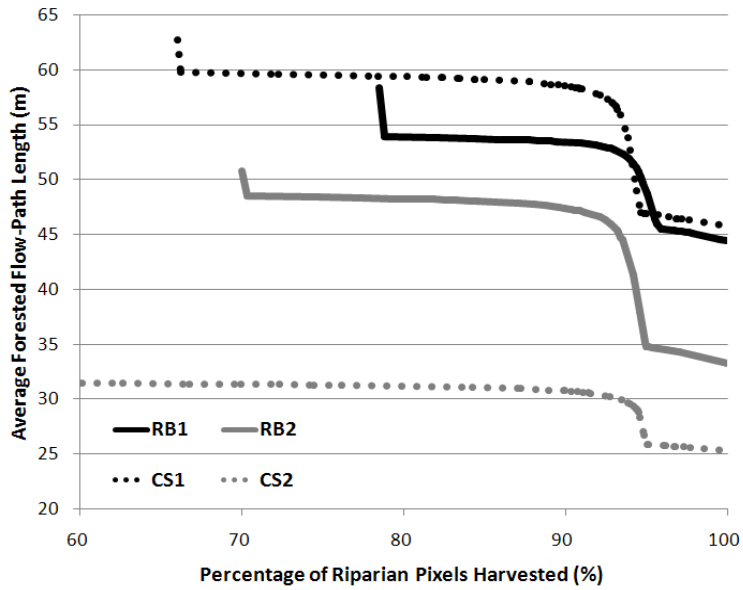

Figure 3.3: Average forested flow-path length of harvested pixels versus the percentage of area harvested within the 30-m fixed-width riparian zone for each study watershed. The study watersheds are designated Riparian Buffer 1 (RB1, solid black), Riparian Buffer 2 (RB2, solid grey), Cut-to-Shore 1 (CS1, dashed black), and Cut-to-Shore 2 (CS2, dashed grey).

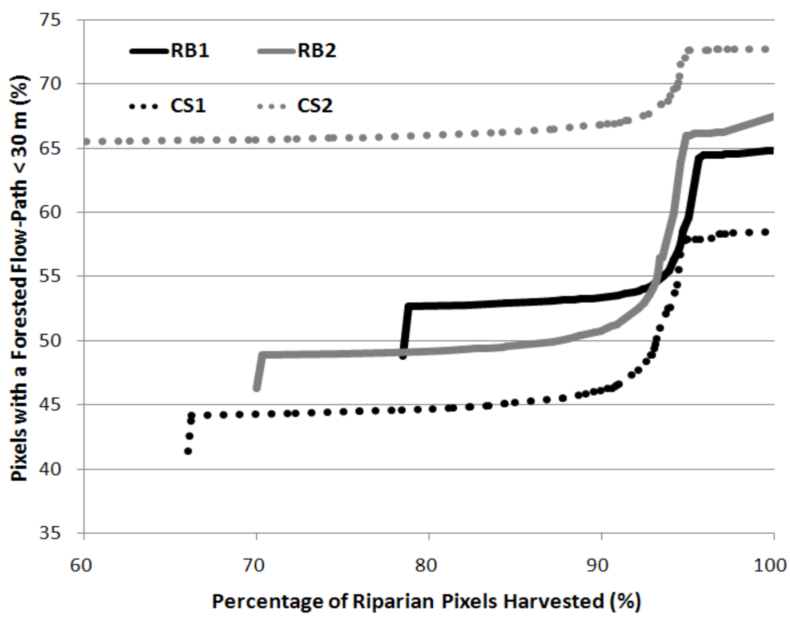

Figure 3.4: Percentage of harvested pixels with a forested flow-path length <30 m versus the percentage of area harvested within the 30-m fixed width riparian zone for the study watersheds. The study watersheds are designated Riparian Buffer 1 (RB1, solid black), Riparian Buffer 2 (RB2, solid grey), Cut-to-Shore 1 (CS1, dashed black), and Cut-to-Shore 2 (CS2, dashed grey).

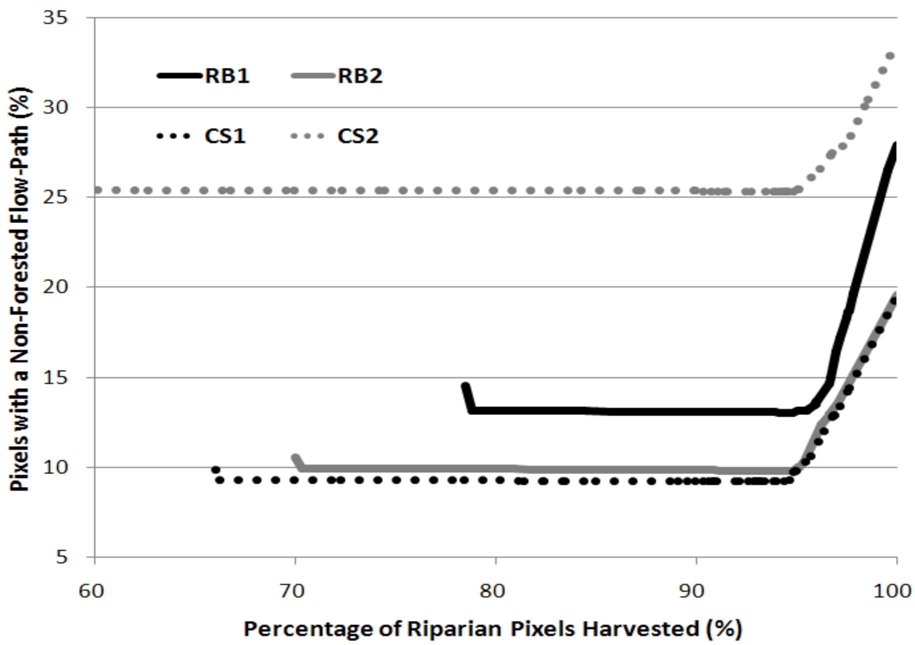

Figure 3.5: Percentage of harvested pixels with a non-forested flow-path length (i.e. a forested flow-path length of 0 m) versus the percentage of area harvested within the 30-m fixed width riparian buffer for the study watersheds. The study watersheds are designated Riparian Buffer 1 (RB1, solid black), Riparian Buffer 2 (RB2, solid grey), Cut-to-Shore 1 (CS1, dashed black), and Cut-to-Shore 2 (CS2, dashed grey).

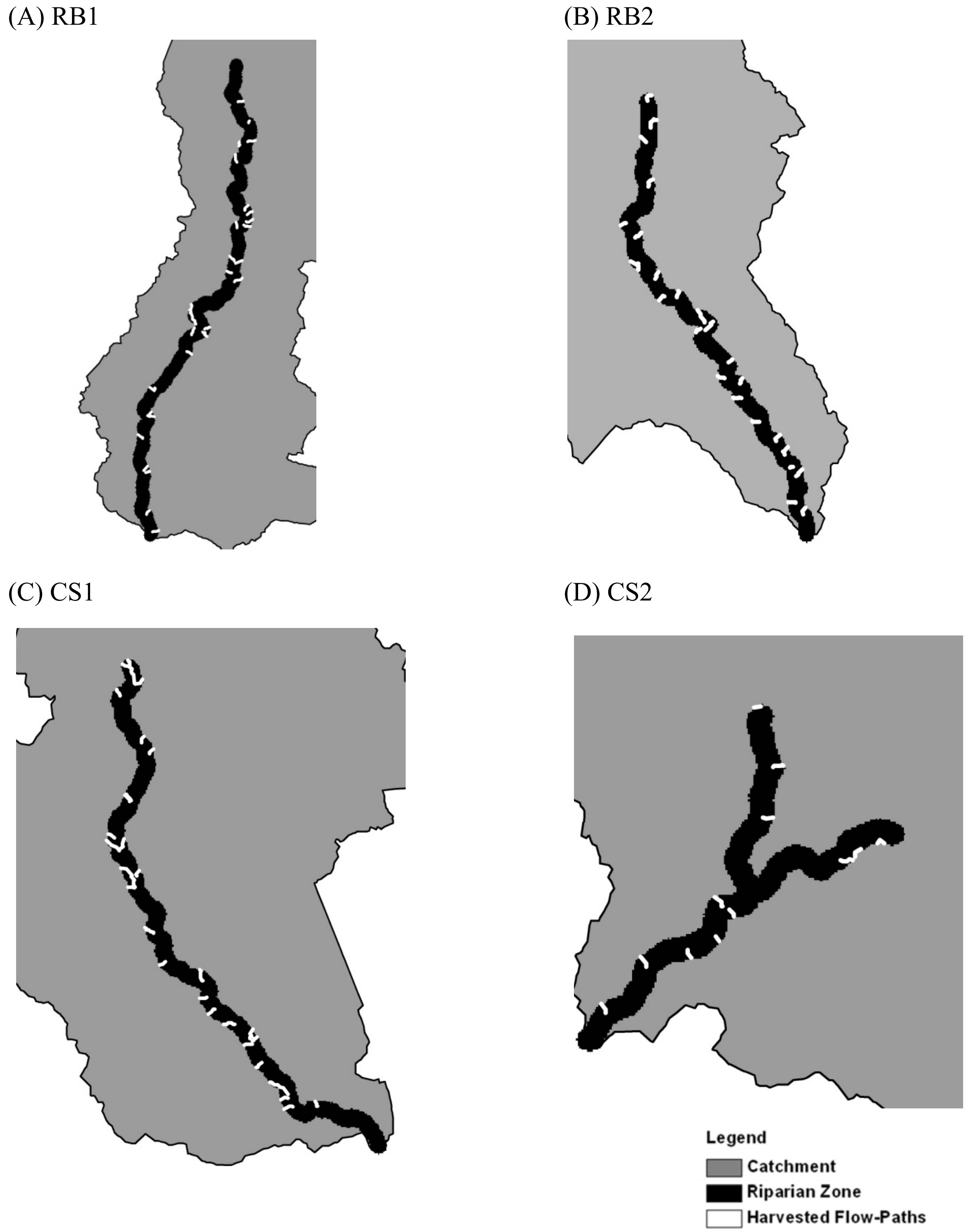

Figure 3.6: Maps of fixed-width riparian buffers (black) showing the location and areal extent of zones required of precision conservation (white) due to the presence of preferential flow-paths with an upslope harvested contributing area > 1 ha; (A) Riparian Buffer 1 (RB1), (B) Riparian Buffer 2 (RB2), (C) Cut-to-Shore 1 (CS1), (D) Cut-to-Shore 2 (CS2)

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Chapter 4

Conclusion

Within North America, policymakers and practitioners are increasingly applying ecohydrology to the land management. Ecohydrology allows for policy planners to develop management principles based upon the whole ecosystem and its connection to harvested landscapes (Kimmins 2004). Sustainable forest management practices must simultaneously provide the required habitat for the diverse abundance of species found across the landscape, and sustain that biodiversity by understanding the role of disturbance (Hunter 1999; Lindenmayer *et al.* 2006). However if the future of forest management is ecosystem-based, unnatural barriers (i.e. fixed-width riparian buffers) will need to be replaced as a planning tool by practices that better emulate natural disturbances (Long 2009). Forest practices have begun to shift paradigms from timber production to eco-system management by harvesting landscapes in patterns that resemble natural disturbances, required for critical processes in conserving biodiversity (OMNR 2001; Sibley 2012). However in the practice of creating spatial patterns similar in size and forest structure to natural disturbances, it becomes crucial that unwanted cumulative downstream impacts are minimized in the attempt to improve forest ecosystem resilience.

With the advances of high-resolution LiDAR data and GIS, the application of precision conservation has become a valuable tool in the managing of landscapes. Precision conservation has been extensively applied to agriculture landscapes, from identifying spatial patterns of erosion to linking site specific properties of soil and crops with buffers (Berry *et al.* 2005). Recently an entirely new paradigm has emerged on linking flow-paths from terrain analysis to the efficiency of riparian buffers in regional urban landscapes (Baker *et al*. 2006). The importance of preferential flow-path and the connectivity of harvested lands to ephemeral channels had never been quantified. Numerous studies have hypothesized their importance but lacked in the availability of tools and data to complete a detailed flow-path analysis. To my knowledge this is the first time a detailed flow-path analysis has been applied on a harvested landscape to fully understand the connectivity of harvested landscapes to ephemeral channels and the impacts on forestry practices. A flow-path analysis was performed on both current and future forest management practices to gain valuable insight into, not only current forestry practices, but future ones as well.

A great deal of insight in the hydrological processes within fixed-width riparian buffers was discovered in the four harvested study watersheds within the Boreal Plain ecozone, in the province of Alberta, Canada, from a flow-path analysis (Fig 2.1, Table 2.1). It was demonstrated from the flow-path analysis that fixed-width riparian buffers were an inefficient policy in buffering sediments generated from harvested landscapes. In the four study watersheds, water from an average 75% of the harvested landscapes did not even flow through the fixed-width riparian buffer (Table 2.4). The ineffectiveness of fixed-width riparian buffers was further illustrated when both of the fixed-width riparian buffer watersheds, RB1 and RB2, had a greater percentage of harvested pixels with a non-forested flow-path length (15%, 11% respectively) than the cut-to-shore watershed CS2 (10%) (Table 2.3). Current land management policies that prescribe a buffer based on a fixed-width and not on a flow-path analysis may inadvertently be leaving large portions of harvested landscapes completely un-buffered (Chapter 2). Therefore if future landscape disturbance are to be buffered properly, a flow-path analysis should be completed to accurately determine and minimize the non-forested connectivity between the disturbance and the aquatic eco-systems.

As ecologists begin to demonstrate the negative consequence of fixed-width riparian buffers on aquatic and terrestrial habits formed from disturbances, the emulation of natural disturbance is gaining acceptance (Kreutzweisr *et al.* 2012; Moore and Richardson 2012). However there is no natural disturbance equivalent to the impacts from the mechanical disturbance of the soil (Gomi *et al.* 2005). The potential for transport of fine sediment from disturbed landscapes to surface waters is still an ecological issue with serious consequences for aquatic eco-systems (Cooke and Prepas 1998). Therefore riparian management practices should consider engineered solutions to both emulate natural disturbance for the creation of terrestrial and aquatic habitat and isolate disturbed soils from surface waters. Precision conservation is a solution that would allow for a riparian management practice that can accomplish all desired goals. In our study, flow-path analysis was used to illustrate that only 5% of the riparian zone served as the hydrologic disconnect between forest removal and aquatic eco-systems (Fig. 3.5). The majority of the riparian zone actually had no harvested lands within the upslope contributing area and did not act as a buffer between cut-blocks and streams (Table 3.1). Therefore natural disturbance emulation will need to be modified to ensure preferential path-ways from harvested lands flow through an appropriately placed treed zone.

The future of landscape management and the reduction of impacts from natural resource extraction will require a detailed understanding of the hydrologic connections to ecosystems within a watershed. By implementing a flow-path analysis, it is possible for the precision conservation of hydrologic connections between soil disturbances and aquatic ecosystem. Small areas within the four study watersheds were responsible for buffering of upslope harvested areas, before discharging into the stream network. The concept of a fixed-width riparian buffer falsely assumes that the area responsible for buffering disturbed landscapes is along 1^{st} or high order streams, and that areas along the stream side are equivalent in importance in buffering upland disturbances. Due to the heterogeneity of both land-use changes and the geomorphology of individual watershed, it may be impossible for a buffer design that is effective in all cases. However with high-resolution LiDAR data and a flow-path analysis, detailed quantitative descriptors of percentage of forested flow-path length < 30 m and percentage of non-forested flow-path length, can now be determined. These quantitative results of forested flow-path length, allow natural resource extraction practitioners to easily evaluate and tailor an individual design for each disturbed watershed. Forested flow-path lengths can be used in the design of buffers for disturbed landscapes, which would be superior to the prescribed fixed-width riparian buffer currently implemented.

My thesis was able to advance the study of ecohydrology with the understanding of the impacts of flow-paths from harvested landscapes to fixed-width riparian buffers. In my thesis I successfully delineated the flow-paths of our four study watersheds within the Boreal Plain ecozone in the province of Alberta, Canada. From my evaluation of flow-paths from harvested landscapes the following goals, proposed in my thesis, were accomplished: (1) determined the importance of ephemeral streams on the efficacy of fixed-width riparian buffers; (2) developed preliminary relationships between buffer characteristics and the landscape to be advanced in future studies; (3) illustrated the need to quantify the impacts of the location and size of cut-blocks with flow-path metrics; (4) determined the zones of preferential flow-paths with riparian buffers from harvested landscapes; (5) quantified the relationship between buffering disturbed landscapes and harvesting within fixed-width riparian buffers; and (6) delineated the zones within riparian buffers that require precision conservation to preserve the integrity of the buffer.

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