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THE INFLUENCE OF RIPARIAN FOREST AGE AND COMPLEXITY IN THE RECOVERY OF POST-HARVEST "AT-RISK" STREAMS AND RIPARIAN AREAS

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EXECUTIVE SUMMARY

Streams and their riparian areas were reassessed 5-14 years after an initial post-harvest determination of an “at-risk” status in order to identify whether their functioning condition had changed over time. Most (77%) of the sample sites had at least 10 m of treed buffer width retained after harvest. Nearly half of the thirty-one sites sampled showed a net improvement in at least one of the stream or riparian indicators used in the assessment, and overall functioning condition status improved by at least one category at 35% of the sites. Twenty-nine percent of the sites showed a net deterioration of at least one indicator with an overall downgrade in condition at 23% of the sites. There was no net change in functioning condition in the remaining 42% of the sites. One of the main factors that influenced the deterioration of the condition indicators was historical logging in the riparian zone, which resulted in young, second-growth riparian buffers. Detrimental effects were largely due to the reduced resiliency of these stands which led to a higher level of disturbance to the channel compared to streams with a mature riparian area. After outside variation was accounted for, a breakpoint of 115 years was found that represented the age of the stand at which functional processes either declined (<115) or improved (>115) on average. Site characteristics such as channel width, gradient, substrate, and upstream disturbance were also contributing factors in the response to the residual effects of logging. Planning and operational recommendations to mitigate impacts and facilitate the recovery of streams associated with harvest activity are given.

1.0 INTRODUCTION

The Forest and Range Evaluation Program (FREP) routinely conducts annual assessments of resource values in or adjacent to recently-harvested areas. Sites are selected each year from a randomly-generated master list of cutblocks harvested 1-3 years previously, and a field evaluation is completed to give a snapshot of the effectiveness of forestry-related practices in relation to a particular resource value at each site. To date, there have been few instances when a site has been reassessed to determine whether conditions have improved, remained the same, or deteriorated over time. While the initial post-harvest assessment is a useful tool to provide timely feedback to the forest licensee about specific management strategies, there is increasing interest in repeated sampling to give a longer-term perspective on recovery trends, which is important for ecosystems that evolve with stand age.

This special project set out to specifically reassess *streams and riparian areas* that were initially evaluated to be "at-risk" or "at high-risk" of becoming not properly functioning after harvest and identify potential site characteristics or management activities that might have facilitated their recovery or decline. The results of this study may be used to guide future riparian management planning and practices.

2.0 METHODS

The FREP *Riparian Management Routine Effectiveness Evaluation* (RMREE) protocol used in this study has been in effect to assess streams and their associated riparian areas since 2006. It is utilized at stream reaches inside or adjacent to (within 2 riparian management area widths) a harvested cutblock. The length of the sample reach is a minimum of 100 m or 30 channel widths, whichever is greater. There are up to 120 (depending on stream morphology) measures, counts, or observations that are recorded to evaluate 38-60 biological or physical attributes represented in sub-indicator questions. The attributes have been previously described as key indicators of disturbance in other field assessments (BC Ministry of Forests 1995; 1996) and include metrics such as length of disturbed banks, frequency of pools, substrate composition, and type/ frequency of large woody debris (LWD). The data are compared to benchmark values representing the boundaries of natural variation in order to answer sub-indicator questions, and these are rolled up to answer 15 main questions (yes/no) that each represent a specific category. For example, there are 4 different sub-indicator attributes that are measured to answer the main question on whether the channel banks are intact. A negative response to any of the main questions indicate that the threshold representing natural variability for that particular category has been exceeded and the indicator is considered impaired. Lastly, the negative answers to the main questions are tallied to give an overall "functioning condition" outcome for the site (Table 1). For more information on the protocol, including the indicators and attributes that are measured, please see: https://www2.gov.bc.ca/gov/content/industry/forestry/managing-our-forest-resources/integrated-resource-monitoring/forest-range-evaluation-program/frep-monitoring-protocols/fish-riparian

Table 1. *Number of negative responses to the 15 main indicator questions and corresponding functioning condition categories.*

Number of Negative Responses	Condition Ranking
0-2	Properly functioning
3-4	Functioning, but at risk
5-6	Functioning, but at high risk
>6	Not properly functioning

Stream reaches located in 10 provincial resource districts that had been evaluated previously and were found to be *functioning, but at risk* or *functioning, but at high risk* were reassessed in this study using the most current version of the RMREE protocol at the time of sampling (Tripp et al. 2020). Sites were selected for reassessment from a master random list generated from existing FREP data that had been filtered to include reaches that had been initially assessed more than 5 years previously and were determined to be in one of the two "at-risk" conditions categories. The direction for site selection was to ensure a minimum of 15 sites were sampled in each of the non-alluvial and alluvial stream morphologies and to strive for a mix of "at-risk" and "at high-risk" sites. For efficiency, fieldwork was completed in the resource districts where other FREP training and sampling activities were planned by the assessor (Fig. 1).

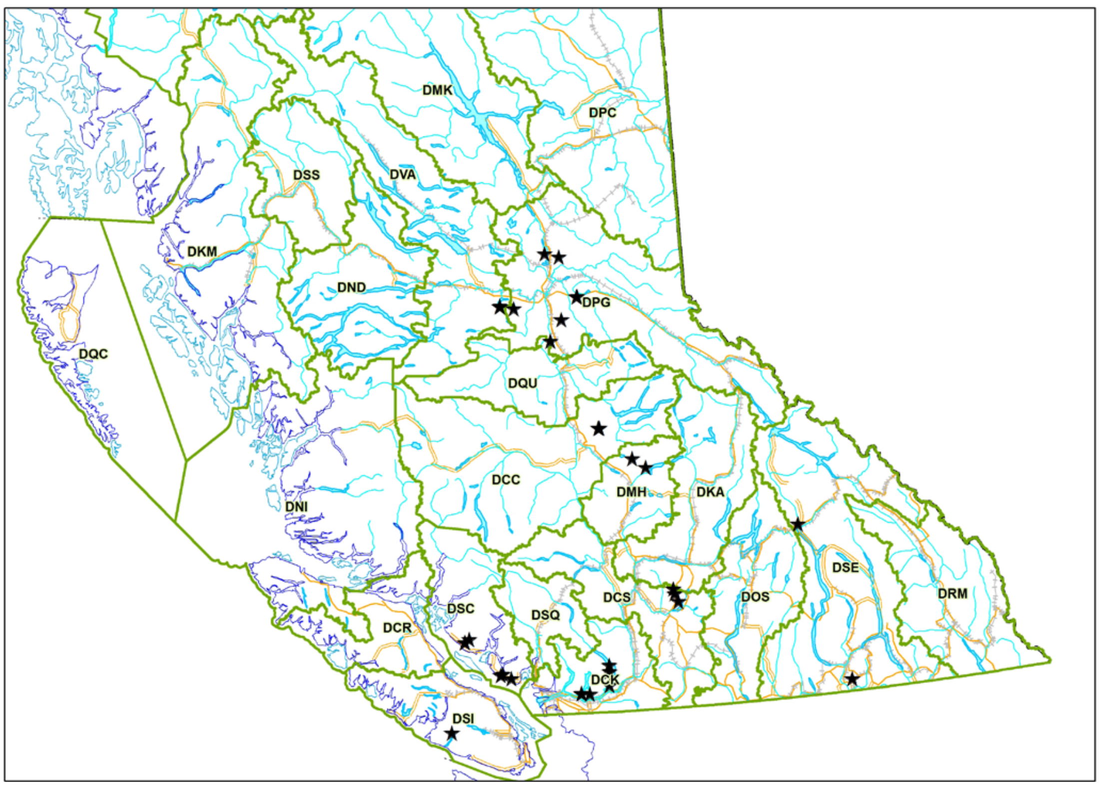

Figure 1. *Locations of study sites.*

The assessments were conducted by a seasoned FREP trainer with more than a decade of experience in the RMREE protocol and timing coincided with low flows in August and September of 2020. The sample reaches were a mix of both fish bearing and non-fish bearing streams with widths ranging from 0.5 m – 5.1 m and gradients from 1 – 45 % across the sample population (Table 2).

Table 2. Study site characteristics.

#	Resource District	Channel morphology	Stream class (site plan)*	Dominant Substrate	Stream Order**	Channel Width (m)	Channel Depth (m)	Channel Grade (%)	Years btwn assessment
1	Cariboo-Chilcotin	Non-alluvial	S6	Cobbles	0	0.8	0.3	5	14
2	South Island	Non-alluvial	S5	Boulders	1	3.2	0.3	30	11
3	Chilliwack	Non-alluvial	S6	Sand	0	0.6	0.2	45	7
4	Chilliwack	Non-alluvial	S6	Gravel	0	0.5	0.2	13	7
5	Chilliwack	Non-alluvial	S6	Boulders	1	2.1	0.4	20	7
6	Chilliwack	Non-alluvial	S3	Boulders	1	4	0.3	35	10
7	Chilliwack	Non-alluvial	S3	Boulders	2	2.6	0.5	12	10
8	Chilliwack	Non-alluvial	S5	Boulders	1	5.1	0.3	22	12
9	Sunshine Coast	Non-alluvial	S4	Cobbles	1	0.7	0.2	3	12
10	Sunshine Coast	Non-alluvial	S6	Cobbles	1	1.8	0.3	14	11
11	Sunshine Coast	Non-alluvial	S4	Cobbles	0	1.1	0.2	15	9
12	Cascades	Non-alluvial	S4	Gravel	1	0.6	0.2	2	11
13	Selkirk	Non-alluvial	S6	Boulders	0	1.5	0.3	45	14
14	Selkirk	Non-alluvial	S6	Cobbles	0	0.7	0.2	15	13
15	Prince George	Non-alluvial	S6	Cobbles	0	0.8	0.2	26	8
16	100 Mile House	Riffle or cascade-pool	S4	Cobbles	0	1.2	0.3	4	5
17	Cariboo-Chilcotin	Riffle or cascade-pool	S6	Cobbles	1	0.7	0.3	13	12
18	Sunshine Coast	Riffle or cascade-pool	S3	Cobbles	1	1.9	0.2	4	8
19	Sunshine Coast	Riffle or cascade-pool	S3	Sand	1	1.7	0.2	2	5
20	Sunshine Coast	Riffle or cascade-pool	S3	Cobbles	1	1.7	0.2	5	12
21	Cascades	Riffle or cascade-pool	S3	Sand	4	2.7	0.3	1	11
22	Cascades	Riffle or cascade-pool	S4	Boulders	3	1.1	0.2	2	11
23	Prince George	Riffle or cascade-pool	S3	Cobbles	1	1.7	0.3	5	11
24	Prince George	Riffle or cascade-pool	S4	Sand	1	1.1	0.3	2	6
25	Stuart-Nechako	Riffle or cascade-pool	S3	Cobbles	2	1.7	0.2	3	8
26	Stuart-Nechako	Riffle or cascade-pool	S4	Fines	1	1	0.2	1	6
27	Prince George	Riffle or cascade-pool	S4	Cobbles	1	0.8	0.2	4	9
28	Prince George	Riffle or cascade-pool	S3	Cobbles	2	1.5	0.2	2	7

29	Prince George	Riffle or cascade-pool	S3	Boulders	2	5	0.3	3	12
30	Quesnel	Riffle or cascade-pool	S4	Cobbles	2	0.8	0.2	3	12
31	100 Mile House	Non-alluvial	S4	Boulders	3	1.3	0.2	20	12

* Stream classes described here taken from harvest site plans. Fish streams = S1-S4, depending on channel width. Non-fish streams = S5, S6 (see *Forest Planning and Practices Regulation*; Sec. 47).

**Stream orders as per Strahler (1952). Stream order "0" is encountered in the field, but not visible on 1:20 000 spatial layers.

The RMREE protocol used for this study included refinements to how some of the indicators are measured compared to earlier versions. Although it is recognized that there could be some variability in a few of the indicator results that are related to differences in methodology, the overall functioning condition roll-up is comparable across versions. For example, in previous assessments, a road crossing may have been either included within the sample reach or it may have been avoided, which could affect how bare erodible soil or compacted ground and aquatic habitat connectivity is measured. This is in contrast to the most recent version of the protocol which requires an integrated and standardized approach to evaluating a road crossing specifically as it contributes to hydrologically-connected bare erodible soil or compacted ground and habitat connectivity. Additionally, refinements to how large woody debris is evaluated within the channel include considering stability and function rather than simply age (ie. pre/post harvest). Although these refinements may have modified the way a specific sub-indicator is measured, the end result of determining whether there is impairment to functioning condition was consistent over time and overall differences owing to modified methodology were tested and found to be insignificant.

The initial sample design included 15 riffle or cascade-pool stream reaches and 15 non-alluvial reaches with similar proportions that had been initially assessed to be *functioning but at risk* or *functioning but at high risk.* However, once in the field it was realized that one of the *high risk*, non-alluvial sites had degraded from a stream to a "non-classified drainage" status, meaning it no longer met the definition of a stream as per the *Forest Planning and Practices Regulation* (B.C. Reg. 14/2004). This site was given an arbitrary score to indicate it was no longer properly functioning as a stream and an additional non-alluvial site was added to the sample size for a total of 31.

The number of negative responses to the indicator questions from the initial assessment was compared to the number from the reassessment, with a resulting negative change indicating improvement (decrease in impaired indicators) and a positive change indicating deterioration.

Statistical tests on the data collected included t-tests and analyses of variance (ANOVA) to identify any significance in the results among sites categorized by initial assessment outcome, stream morphology, geographic area (interior, coast), retention width, and time between initial surveys and reassessments. Ordinations (PCA) were run on transformed (log(x+1)) data to explore related natural and development factors that contributed to the variance in the dataset, including channel width, depth, slope, substrate size (D50; D95), stand age, percent upstream development, number of road crossings and stream classification. Subsequent factor analyses identified the sub-set of potential covariates to use when accounting for external influences on recovery.

When the entire dataset was required to further explore relationships across time and space, a generalized linear model was utilized to identify and minimize the effect of potential influence from the sub-set of significant covariates suggested from previous analyses and produce adjusted values for the indicators. A breakpoint regression analysis (SegReg; Oosterbaan 2005) was run on adjusted values to determine whether there was a significant stand age that related to recovery vs deterioration in riparian form and function in response to post-harvest effects after natural variation was minimized. SegReg utilizes seven different function types in an attempt to identify one that maximizes the coefficient of explanation and passes a test of significance based on an alpha value of 0.05.

3.0 RESULTS

3.1 Change in Indicators and Functioning Condition

Overall, 35% of the sites improved in functioning condition (see Table 1 for condition categories) since the initial assessment. The specific indicator results varied to some extent between the initial and reassessment events at a selection of the sites, alluding to the dynamic nature of ecosystem response, even when there may not have been a net change in the sum of indicators tallied. An example of this is where an area of exposed soil may have become re-vegetated over time, allowing the recovery of one indicator, but the vegetation consisted of mainly disturbance-increaser plants or invasive species, causing the deterioration of another. Changes to the net number of impaired indicators occurred at 24 of the 31 sites; 15 of these showed overall improvement of at least one indicator, while 9 indicated deterioration since the initial assessment (Table 3).

The reassessment sampling design required equal proportions of non-alluvial and alluvial stream reaches as well as sites that had been assessed previously as *functioning at-risk* or *functioning at high-risk* so that any differences related to these variables could be identified. However, the results were not found to be significantly different between stream morphologies, their initial assessed condition categories, or the combination of both (ANOVA; $p > 0.05$). This could partly be because in some cases, a stream that had been initially identified as non-alluvial (doesn't contain enough power to actively erode, transport, sort, and deposit bed and bank materials) but contains erodible soils, will function much like an alluvial system if peak flows increase post-harvest, and this could subsequently affect channel bed and bank integrity (Hogan and Luzi 2010). Recent bank erosion and deposition of materials was evident at several of the sites that had been classed as non-alluvial, confirming this rationale (Fig. 2).

Figure 2. *Erosion of bed and bank material in a non-alluvial stream.*

The time between the initial assessment and reassessment ranged from 5 to 14 years across all sites, but also was not found to be a significant factor in recovery. Sites were then grouped by their general locations in the province (coast, interior) and the reassessment results were found to be significantly different between the two areas with the change in impaired indicators higher for the coast compared to the interior (t-test; $p < 0.001$).

Seven of the 13 (54%) sample reaches on the coast were assessed as having one or more additional impaired indicators since the initial evaluation (Table 3) resulting in a in a downgrade in functioning condition status for 6 of them. Functioning condition improved for one coastal site while the remainder were unchanged. There were two interior sites where the change in impaired indicators increased, and one of these was downgraded from a *functioning, but at risk* to a *high-risk* condition while the status for the other site remained unchanged. Thirteen of the 18 interior streams displayed a net decrease in the number of impaired indicators, indicating recovery. Ten of these sites were upgraded to a better functioning condition category than previously, 5 of which achieved a *properly functioning condition* status.

Table 3. *Change in impaired indicators and condition status for coastal and interior sample sites.*

Change in total indicator status	Coast (n = 13)	Interior (n = 18)	Total
Improvement	15%	72%	48%
No Change	31%	17%	23%
Deterioration	54%	11%	29%
Change in overall condition status			
Improvement	8%	56%	35%
No Change	46%	39%	42%
Deterioration	46%	5%	23%

3.2 Factors Influencing Recovery

Lack of riparian tree retention is often a causal factor for impacts to small streams, especially those that are non-fish bearing, which are more common on the coast because of steeper gradients. However, more than 75% of the reassessed sites on the coast and 80% in the interior had at least 10 m of treed retention in this study. Retention width (within the RMA) was entered as a covariate in an analysis of variance to explore whether it influenced the difference in reassessment condition results or recovery, but it was not found to be significant. This is likely because there was either enough retention at most sites to maintain many of the riparian indicators or there were other factors that were contributing to the results.

Other studies have shown that harvest activities may result in increased wind effects (Beese et al. 2019) and peak stream flows (Green and Alila 2012; Schnorbus and Alila 2013; Winkler et al. 2017) which can impact riparian buffers and stream channel integrity. Much of the forest on the B.C. coast is currently in a "second growth" state, and observations during field sampling suggest that these younger riparian forests are not as robust (lacking complexity) and less resilient to these secondary effects of new harvesting. Multivariate ordination (PCA) identified riparian stand age as a strong factor that explained the variance within the dataset. Large-class substrate size (D95), channel width, channel gradient, and percent upstream watershed developed were also identified in the resulting factor analysis and together, these attributes explained 77% of the variance in the data. The natural and development-related factors were used in combination with general location (coast, interior) in a statistical model (GLM) to minimize external variation and produce adjusted values for indicator recovery.

Segmented regression analysis was conducted on the adjusted values resulting from the GLM. A breakpoint of 115 yrs was identified at which there is a significant difference in the recovery of young (<115 yrs) and mature (>115 yrs) riparian areas (Type 6 breakpoint with 95% significance; see Oosterbaan 2005 for significance tests on function types). The two age groups were plotted to compare results and not only were they significantly different in terms of response after harvest, but the adjusted mean value of the younger group was positive, indicating that the number of impaired indicators increased on average for this group and condition had deteriorated. This is in contrast to the negative mean value of the mature group, which suggests that impaired indicators had decreased, and condition had improved (Fig. 3).

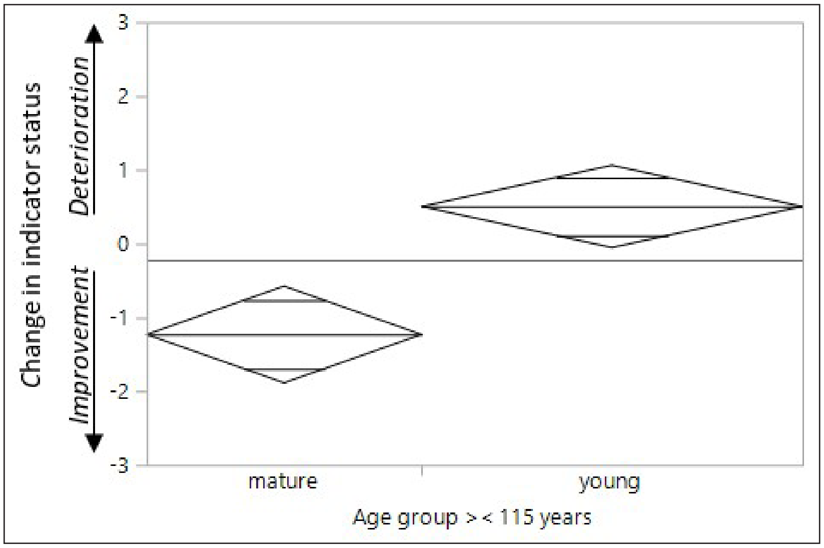

Figure 3. *Distribution around a standardized mean for change in condition indicators between sampling events at sites with mature (>115 yrs) and young (<115 yrs) riparian forests. Diamond heights are 95% confidence intervals, with spread in proportion to sample size. Diamond center horizontal line is group mean; graph horizontal line is grand mean.*

The quicker recovery of streams within the older stands lends credence to the greater resiliency of complex forest structure. Keeton et al. (2017) found that riparian vegetation composition and structure were directly related to channel geomorphic processes including degradation, aggradation, widening, and change in planform and concluded that streams within riparian forests of greater structural complexity are more likely to exhibit channels in better geomorphic condition. Anecdotal results from annual random FREP assessments on the B.C. coast indicate streams within maturing riparian forests (100+ yrs) that show signs of self-thinning and diversity of layers are more effective at resisting erosive forces than those in younger second-growth stands (Fig. 4).

Figure 4. *North Island resource district riparian area age 112 years (left), and ~ 50 years (right).*

The measured attributes most frequently affected at the sites that displayed a net increase in impaired indicators (deterioration) since the initial assessment were associated with habitat connectivity issues (jams or other barriers), poor riparian vegetation structure and health, channel bank disturbance, excessive fine sediments, moss abundance/ vigor, and channel bed disturbance (Table 4). Sites that had shown overall improvement also had a high percentage of the connectivity indicator impaired (73%), but much lower proportions of other disturbance indicators compared to the group that deteriorated overall.

Table 4. *Percent of sites with impaired indicator by overall recovery status.*

Main Indicator	Deteriorated	Improved	No change
Bed disturbance	63	13	14
Bank disturbance	88	40	43
In-channel LWD processes	25	13	0
Morphology	13	0	0
Connectivity	100	73	100
Fish cover	13	7	14
Moss	63	40	71
Fine sediment	75	53	71
Invertebrate diversity	0	0	0
Windthrow	50	13	0
Exposed soil/ compacted ground	25	0	0
LWD Supply/root network	0	0	14
Bank microclimate	0	0	0
Invasive plants	0	0	14
Riparian vegetation	100	47	71

The riparian vegetation indicator involves a standardized comparison of the sample site riparian vegetation with that which would be expected under natural, unmanaged conditions. The assessment of this indicator requires entering data on abundance, form, and vigor into attribute tables containing each of the following forest components: overstory trees, understory trees, tall shrubs, low shrubs, herbs, mosses, lichens, coarse woody debris, snags, and canopy gaps. The values are tallied and averaged to estimate forest composition and health, then compared to benchmarks representing a natural, unmanaged forest (Tripp et al. 2020). The calculated value for riparian forest composition provides a relative estimate of stand structure or complexity among sites. The average composition value of 74% at sites that showed overall improvement in condition indicators was significantly higher than those sites that displayed deterioration over time (ANOVA; $p = 0.01$). Riparian forest composition was intermediate (63%) at the sites where no net change in indicators was detected (Fig 5).

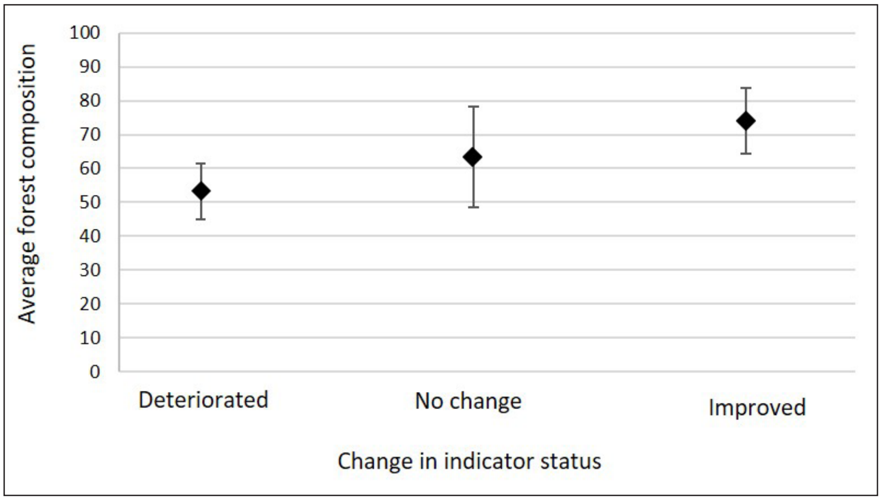

Figure 5. *Average riparian vegetation composition grouped by sites that deteriorated, improved, or showed no net change in condition indicators. Diamonds represent means of each group; error bars are 95% confidence intervals. One outlier was identified and removed that represented a very small stream (0.5 m channel width) with low transport capacity (D95 = 2 cm).*

3.3 Other Notable Factors

Causes of specific indicator impairment are identified when known as part of the field assessment but are not quantified in detail here because of uncertainties associated with the longer time period since harvest and the potential interaction of causal factors. However, there were effects noted from animal disturbance, windthrow, recreation trails, and a watercourse diversion that merit mention here.

Livestock was the primary cause of animal disturbance and linked to at least one impaired indicator at 7 of the sites, followed by ungulates (2 sites) and beavers (2 sites). Though these factors are not a direct result of logging, animal disturbance to riparian areas (Fig. 6) can increase when surrounding habitat is reduced or access to a stream is made easier through the removal of timber or the construction of roads.

Excessive windthrow is defined in the assessment as windthrow that exceeds a benchmark percentage over and above what occurs naturally at a site, with the percentage depending on whether or not there is a reserve zone within the riparian management area. Excessive windthrow was recorded in both coastal (3) and interior (3) regions, and it was readily apparent that it was the result of increased exposure to wind after harvest. In addition to triggering the main windthrow indicator in the assessment, the up-turned root wads (Fig 7) and high levels of woody debris associated with downed timber near the stream edge influenced other indicator results by contributing excessive fine sediments, channel bank disturbance, and within-channel debris jams. While the value of retaining riparian timber for fish and riparian habitat cannot be overstated, it is also imperative that windthrow is managed to be within the range of natural variation to avoid undue affects to other ecological processes.

Figure 6. *Cattle damage to stream bed and banks.*

Figure 7. *Upturned root wad in riparian area.*

Recreational trails contributed to disturbance at one site, compacting channel banks and impacting native vegetation. Similar to the effects of cattle, this type of disturbance weakens the channel bed and banks, facilitating erosion and sediment transfer to the stream. In addition, the exposed soil promotes growth of shallow-rooted disturbance or invasive plant species.

Diversion of a watercourse associated with an unmaintained, upstream road crossing resulted in the degradation of a stream to non-classified drainage (NCD). In this case, the assessment could not be properly applied as the NCD no longer had a continuous and definable channel bed as per the *Forest Planning and Practices Regulation* (B.C. Reg. 14/2004).

4.0 CONCLUSIONS

Sites with riparian areas consisting of young, second-growth stands demonstrated an average deterioration in condition indicators between the sampling periods compared to those within more mature and complex forests. This finding is consistent with other studies that show clear linkages between riparian forest structure, stream geomorphology, instream biota and habitat characteristics (Bilby and Ward 1991; Keeton et al. 2007, 2017; Naiman et al. 1998, 2000; Richmond and Fausch 1995; Warren et al. 2016). Past modelling has identified an approximate age of 90-100 years as the point at which Douglas fir riparian forests are able to contribute 95% of naturally occurring LWD to a stream (Beechie et al. 2000). This study indicates that it may take additional time for the stand to increase in structural complexity enough to resist effects from new logging-related activities such as increased stream flows. After adjusting for the effects of outside variability, our analysis identified a breakpoint of 115 years, above which the streams and their riparian areas showed an average improvement in the condition indicators since the initial assessments. Under natural conditions, this age could vary with differences in forest type, stream and watershed characteristics, as well as the extent of any upstream disturbance. For example, a larger or steeper stream will carry more erosive power than a smaller stream, finer bank materials will be more susceptible to erosion, and the magnitude of any post-harvest change in peak flows could vary with upstream disturbance.

The hydrological sensitivity of a watershed in terms of disturbance within it can be variable. Even in undisturbed watersheds, peak stream flows on the coast are often reached in a matter of hours because of intense periods of rainfall including rain on snow events, shallow soils, steep slopes, soil piping and the presence of bedrock that limits the capacity of the soil to store large amounts of water quickly (Hetherington 1998). If any multiplying factors such as canopy removal and ground compaction are introduced, these will have magnified effects on peak flows within a watershed. Where roads are present, surface and subsurface flows are concentrated and quickly transported to streams via ditch lines (Gilbert, 2002; Wemple and Jones, 2003) and mass wasting is a risk where roads interrupt sub-surface drainage and affect soil properties on steep slopes (Jones et al. 2000). Long term studies in the Carnation Creek watershed on the south-west coast of Vancouver Island have shown that effects of riparian clearcutting, such as accelerated bank erosion, streambed scour, loss of stable in-stream wood and sediment movement downstream, may persist for decades (Tschaplinski and Pike, 2017). Considering these influences, absent or narrow second-growth Riparian Management Zones (RMZ) on the coast are unlikely to provide the protection needed to maintain stream bank or channel stability when peak flows and sediment inputs increase further as a result of repeated harvesting upstream.

Post-harvest windthrow was found to be a frequent causal factor of negative effects to the condition indicators. Single-tree windthrow is a naturally reoccurring process that self-thins a maturing stand, providing canopy gaps and daylight to the understory while maintaining large trees as a sustaining beneficial large woody debris supply. However, excessive windthrow can facilitate increases in sediment transfer and channel erosion in watersheds that may already be in a sensitive state from harvesting (Poulin et. al 2000).

5.0 RECOMMENDATIONS

This study reinforces the importance of maintaining resilient riparian vegetation through successive passes of harvesting and planning at a watershed scale to mitigate or remediate potential cumulative effects of existing and future activities in previously-harvested areas. Consider the extent of past harvesting and other development in the watershed to estimate the potential cumulative effect of additional harvesting and strive to achieve a no net increase in peak flow or sediment transfer where the hazard is currently moderate or high. Cumulative effects assessments that model risk or hazard with respect to peak flows and sediments using metrics associated with development are a good starting point. Restoration of more vulnerable catchments may be accomplished in part by removing old crossing structures and stabilizing/revegetating the road prism and clearing width.

Young, second-growth forests do not have the same structural complexity as older forests, and this was found to be a factor in the deterioration of the condition indicators over time. Enhancing the RMZ to promote understory growth is recommended in dense second-growth stands. Conifer forests with high stocking densities and closed canopies typically have reduced diameter growth rates, simple stand structure, poor tree species diversity and a delayed progression to a more structurally complex state (Poulin et al. 2000). Strategic harvesting in these stands could accelerate the successional process. For example, leaving windfirm dominant stems within the RMZ while harvesting adjacent competitors to allow for “crown release” has been shown to be effective in accelerating tree growth (Lamson et al. 1990; Smith et al. 1994; Comfort et al. 2010) for a quicker but stable future LWD supply to aquatic and riparian ecosystems. In addition to accelerating the development of dominant trees, thinning increases canopy gaps which promote the growth of understory layers (Singer and Lorimer 1997). However, the level of harvest in the RMZ should be less intensive if it is immediately adjacent to the stream (S4-S6) in order to maintain important temperature regulation properties (Roon et al. 2021).

In all stream reaches where a no-harvest reserve zone (RRZ) is required, a windfirm buffer is important in the adjacent riparian management zone (RMZ) to protect the reserve from windthrow. Options to reduce risk of windthrow in a reserve zone include widening and realigning the boundary of the RMZ to a natural windfirm edge or an angle that will be stable to prevailing winds, removing unsound trees, and/or employing edge stabilization treatments such as feathering and topping or pruning (B.C. Ministry of Forests and B.C. Ministry of Environment, 1995).

In cases where there is no required RRZ, any treed retention in the RMZ should be windfirm and robust enough to protect trees nearest the stream from windthrow using the techniques described above. Avoid leaving wind-prone trees in riparian areas with narrow retention strips. Studies have shown that a fully intact 10 m riparian zone can be effective at buffering the stream from harvest-related effects, regulating water temperatures, suppling the channel with LWD, and facilitating the consistent delivery of nutrients and organic matter to downstream reaches (Gomi et al. 2006; Nordin et al. 2009; Clinton 2011; Rex et al. 2011; Nordin et al. 2017). Therefore, where narrow buffers are prescribed, it is important to ensure these are protected from windthrow. It should also be noted that what might be assumed to be an adequate retention width in older forests, may not be the case in second growth stands. Mitchell (2000) explains that when similar-aged trees compete for nutrients and space, the resulting stand is comprised of slender trees with high crowns, which increases the risk of windthrow.

Harvesting the RMZ in its entirety should only occur when a qualified professional has determined that doing so will not impact the streamflow characteristics (flow and temperature regimes); will not affect the channel bed and bank structure and resilience in response to increases in peak flows; and the riparian area does not contain the habitat characteristics to support any local species at risk. An example would be a small, seasonal headwater reach within a low-gradient or non-erodible (bedrock dominated) catchment.

To minimize damage to the stream channel and avoid future debris jams, consider full suspension methods for moving timber across streams. When conventional ground-based harvesting, avoid falling trees into streams or yarding across, especially those streams that have high debris transport capability, contain fish, or are important non-fish streams. Carefully extract excessive or unstable introduced debris following harvesting.

Proper deactivation of roads after harvest will help to minimize issues associated with non-maintained or abandoned crossing structures that may not be sized appropriately for future increases in peak flows. Road deactivation will also discourage recreational and cattle access, while promoting faster revegetation of exposed soil.

Any new or upgraded roads should be designed, constructed, and maintained to minimize the transfer of surface water and sediment to a stream. Both B.C. and Washington state recommend that ditch flow be diverted to the forest floor before reaching a stream crossing and that exposed soils subject to erosion such as cut and fill slopes, be stabilized and promptly revegetated (Washington Dept of Natural Resources 2013; BC FLNRORD 2019).

Conduct a post-harvest assessment and implement remedial measures where necessary, including placing coarse woody debris onto bare erodible slopes, revegetating riparian soils that have been exposed as a result of machinery or windthrow disturbance, or re-establishing altered drainage networks.

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