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Biological bank protection: trees are more effective than grasses at resisting erosion from major river floods

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ABSTRACT

Although it is recognized that streamside vegetation can reduce river bank erosion, the relative effectiveness of forest versus grassland has been unclear. To compare erosion resistance of the two vegetation types, we studied the free-flowing Elk River in British Columbia, Canada from 1993 to 2014, including major floods in June 1995 and 2013. Interpretation of aerial photographs from 1994 and 2000 were used to examine the correspondence between floodplain vegetation and the extent of channel change after the 1995 flood. Along a 23 km reach with alternating forest and grassland, 15 locations displayed substantial change as the river moved a channel width (45 m) or more with meander migration, or up to 200 m with channel avulsion. All ten locations with major change (>75 m) occurred where the floodplain zones were occupied by grasslands, sometimes with small shrubs. In contrast, channels flanked by forest were minimally altered (<15 m), and deciduous (black cottonwood, *Populus trichocarpa*) or mixed deciduous-coniferous groves were effective at resisting erosion. Some changes accompanied the 1995 flood and further changes followed as the destabilized banks were vulnerable to smaller floods in 1996 and 1997. Providing another comparison, a position that was dramatically scoured in 1995 when it was grassland had subsequent cottonwood colonization, and the 4 m trees resisted erosion from the 2013 flood. Thus, trees were more resistant than grassland to flood-associated bank erosion. We recommend that riparian forests should be conserved to provide bank stability and to maintain an equilibrium of river and floodplain dynamics. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS channels; cottonwoods; ecological service; floodplain; *Populus*; riparian

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INTRODUCTION

Rivers and floodplains are interconnected landscape features that involve flowing water, alluvia (mobile sediments) and riparian vegetation. These components interact to produce river and floodplain forms that are dynamic, especially because of high flows that mobilize sediment and scour vegetation. It has long been recognized that riparian vegetation can resist river bank erosion, but the effectiveness of different vegetation types has been unclear (Renner, 1936; Malanson, 1993; Montgomery, 1997; Lyons *et al*., 2000). In particular, there are contrasting views regarding the stabilizing influences of riparian grassland versus forest (Simon and Collison, 2002).

Forests include trees with mechanically rigid roots and shoots. Their trunks resist flood flows thus reducing shear stress while the extensive root systems include large rigid roots and smaller roots that produce interwoven networks that bind the substrate. Consequently, it might be predicted that trees should better resist river bank erosion, as indicated by various physical models and tests (Abernethy and Rutherfurd, 2000; Wynn and Mostaghimi, 2006; Langendoen *et al*., 2009). Supporting this prediction, along some streams, channel locations bordered by riparian forests have migrated more gradually than unforested positions (Hickin, 1984; Johannesson and Parker, 1985; Odgaard, 1987; Burckhardt and Todd, 1998; Micheli *et al*., 2004), although this pattern has not always been found (Murgatroyd and Ternan, 1983; Harmel *et al*., 1999).

Opposing their stabilizing influence, when trees are undercut and toppled into the stream, the large woody debris may accelerate bank erosion by creating localized zones of redirected flow and hydraulic scour (Trimble, 1997). Additionally, grassland zones lack shading from the forest canopy, and consequently, there could be more complete vegetation cover of the floodplain surface. The grasses may display a rhizomatous growth form with extensive shallow and surface root and shoot linkages that weave together the vegetation and substrate to produce dense mats (Murgatroyd and Ternan, 1983). Subsequently, some researchers have concluded that riparian grasslands would be more effective than forests at resisting bank erosion (Trimble, 1997).

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There has been little direct comparison of the effectiveness of riparian forest versus grassland in resisting erosion (Malanson, 1993; Gurnell, 1997). Flume studies confirm differential erosion resistance across plant types (Dunaway *et al.*, 1994; Gran and Paola, 2001), but these small model systems are unsuitable for trees. Field comparisons have primarily focused on small streams and the contributions by Murgatroyd and Ternan (1983), Trimble (1997) and Davies-Colley (1997) confirmed the prior observation by Zimmerman *et al.* (1967) that narrower stream channels can be associated with grassland rather than forest, suggesting that grasses better resist bank erosion.

Subsequently, some researchers have questioned policies that encourage reforestation of degraded floodplains, and Lyons *et al.* (2000) suggest that grassy vegetation should be encouraged, and management should discourage the reestablishment of woody vegetation. They thus proposed that riparian agricultural practices that promote dense grassy turf, including intensively managed livestock grazing, are suitable for the remediation of degraded stream ecosystems. This contradicts the view that livestock use in riparian zones should be restricted in order to promote riparian woodlands that could improve bank stability and favour the health of the riparian and aquatic ecosystems (Belsky *et al.*, 1999).

River valley management should consider sufficient temporal and hydrologic scales including the influences of floods. Floods could be particularly relevant to bank erosion, and we have observed major floods and bank and riparian consequences along a number of rivers of western North America (Rood *et al.*, 1998; Kalischuk *et al.*, 2000; Samuelson and Rood, 2004). Of these, we have extensive familiarity with the Elk River, which experienced major floods in June of 1995 and 2013. This provided an opportunity to compare the influence of different riparian vegetation types on bank stability.

Because of the Elk River's size and power, we hypothesized that forest would be more effective at resisting channel erosion than grassland. We further hypothesized that the pioneer black cottonwoods, *Populus trichocarpa*, could be especially erosion-resistant because of their deep roots (Rood *et al.*, 2011a) and because cottonwoods are well adapted to the immediate streamside zones. Thus, our study investigated the possible correspondence between channel change and riparian vegetation type following major floods along a Rocky Mountain river.

METHODS

Study area

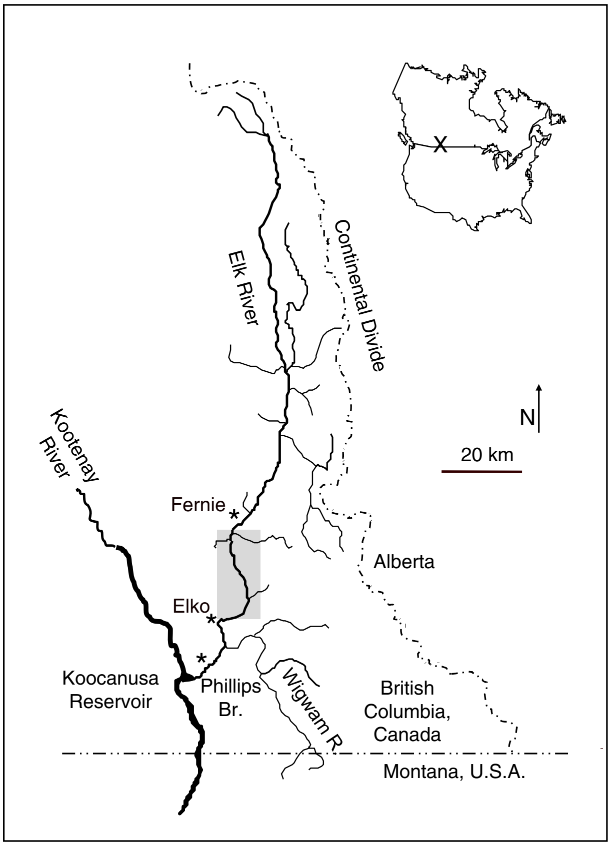

Figure 1. Map of the Elk River in southeastern British Columbia, Canada, showing the study reach (shaded rectangle) and hydrometric gauge locations (*). The small Elko Dam is near the Elko gauge (*).

The Elk River drains the Rocky Mountains in southeastern British Columbia (Figure 1). At 170 km in length, the stream elevation ranges from 1720 m at the headwaters to 750 m where it outflows into Koocanusa reservoir (Polzin and Rood, 2000). The river is free-flowing from the headwaters through the town of Fernie to the small Elko Dam, and the present study extended along the 23 km reach from Fernie to the Elko reservoir, a segment with a fairly consistent and moderate channel slope of about 0·2%. The riparian zones were naturally forested with cottonwoods and successional conifers, white spruce (*Picea glauca*) and western red cedar (*Thuja plicata*), with an understory of shrubs. In some locations, the trees have been cleared to develop grassy fields used for hay production or cattle grazing; these cleared locations are irregularly positioned, reflecting landowner preferences.

River hydrology

The Elk River displays a natural snowmelt-dominated hydrograph with a mean annual flow of 46 $m^3 s^{-1}$ at Fernie (Polzin and Rood, 2006). Flows are low through the winter and rise with spring snowmelt and rains. The high-flow interval extends from mid-May through June, and flood flows consistently occur in this interval. Within the study period, large floods occurred in 1995 and 2013 as a result of widespread, intense rain events on the watershed that was already partly saturated because of spring snowmelt and prior rains.

Annual maximum mean daily discharges were obtained through Environment Canada's Hydat database for the Elk River at Elko (1914–1922 and 1925–1944), Phillips Bridge (1926 to 1996) and Fernie (1926–1927 and 1970–2013; estimate for 2013). A composite annual maximum series was derived for Fernie and shows that 1995 and 2013 were the two largest floods on record with discharges of 642 and 881 $m^3 s^{-1}$, respectively (Figure 2). These correspond to approximately 1-in-50 year and 1-in-200 year flood events (Polzin and Rood, 2006).

Patterns of riparian vegetation and channel change

We have observed the river regularly since 1993, and we analysed riparian sites to assess sediment erosion and deposition, and vegetation changes emphasizing the recruitment of black cottonwoods, the dominant riparian tree (Polzin and Rood, 2000, 2006). We floated the study reach at least twice annually and undertook a low altitude (180 m) flight on 8 August 1996 to assess post-flood conditions and to capture oblique photographs with sufficient resolution to characterize the riparian shrub communities.

For the analysis of channel change, we analysed 1:15 000 scale (1 mm = 15 m) true colour aerial photographs from 1994 (22 July and 10 August, mean daily *Q* at Fernie: 34 $m^3 s^{-1}$) versus 2000 (16 and 17 September, 24 $m^3 s^{-1}$). Highway #3 and the Canadian Pacific Railway line facilitated accurate overlays from which changes in channel position were measured with a ruler along river tracings at 5 mm intervals (=75 m).

To assess riparian forest distribution, we analysed the 1994 aerial photos using sequential 3 (cross section) × 5 mm quadrats positioned adjacent to both the left and right river margins. Two independent methods were used to assess vegetation type and density. With the 'manual method', each quadrat was assessed with a five-point forest density scale from 1 (no trees) to 5 (completely treed). Two assessors undertook the analysis for the 23-km study reach, and the results were very consistent; for quadrats with different ratings, the two reconsidered to reach agreement.

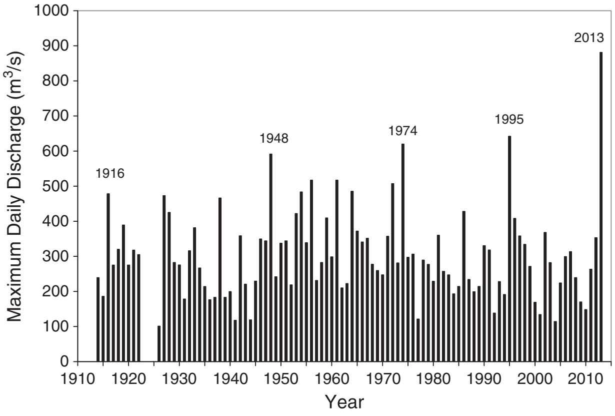

Figure 2. Annual maximum daily discharges for the Elk River at Fernie for the period of record from 1914 to 2013, including values extrapolated from the Elko and Phillips Bridge records.

The second method involved digital image analysis using ImageJ (http://imagej.nih.gov/ij/). The aerial photos were scanned at 600 dpi, the stream was digitized, and colour filters (Split channels tool) and threshold value criteria were applied to optimize the discrimination of four surface types: (1) forest/trees, (2) grassland, (3) barren surfaces including gravel and cobble bars and (4) water. We used ImageJ to measure the number of pixels designated as forest/trees compared with total pixels in the delineated quadrat, resulting in a proportional measure incorporating treed area and density.

For the analysis of channel change, we assessed positions with 'moderate change' as those with movement of 45 m in the channel position, which would correspond to 3 mm in the aerial photos, and this approximates the mid-summer channel width. This was regarded as a suitable threshold based on the precision enabled by the scanned photographs and channel tracings. 'Major change' required movement of at least 75 m (5 mm). For the analysis of vegetation cover, the correlation between the two vegetation assessment methods (manual method and ImageJ) was first examined. Subsequently, for correspondence between channel change and vegetation type and density, we primarily considered the manual method, as described. For statistical consideration, the vegetation assessments of all quadrats were summed for each of the five categories for a study sub-segment from position 1 to position 210 (approximately 16 km), after which the river valley was narrower, the channel was straighter, and there was very little clearing of the riparian forest. Subsequently, a χ^2 analysis considered the distribution of the vegetation for the positions with moderate and major channel change (observed values) versus the overall distribution of the vegetation types (to calculate expected values) for the full 16 km sub-segment.

RESULTS

Field observations

Road and raft trips from June through August 1995 and 2013 revealed the immediate consequences of the two major floods. While there were areas of severe erosion where human developments had involved clearing of the riparian forest (Figure 3), probably the most prominent observation was the slight erosional impact along zones that retained the natural forests.

The flood flows did scour some banks resulting in the undercutting and toppling of some streamside trees that were commonly black cottonwoods. Toppled trees were

Figure 3. An oblique aerial view of major erosion Site 5 (49°24 40″N: 115°05 00″W) in which the Elk River avulsed and moved from a left bend (lower left barren zone) to the right, through a prior grassland hayfield. The river swept right until it reached the Highway 3 roadway that was subsequently armoured with large boulders.

subsequently tumbled with the flood flow, and this resulted in the shearing off of branches, whereas the root balls remained more intact. With receding flows, the root balls anchored drifting trunks, causing them to become aligned with the flow direction, and these stabilized some channel sites and led to downstream sediment deposition and island initiation. Log jams were also abundant, particularly at the onset of river bends, on upstream ends of islands and meander lobes, and at the upstream ends of side channels where they often blocked flows into the side channels.

Aerial photo analyses of vegetation types and channel change

The manual method and ImageJ method (Figure 4) were generally consistent in the interpretations of the particular quadrats, with 68% overall correspondence for vegetation density assessment (Figure 5). The deviations primarily represented quadrats that incorporated the highway or railway line in which the manual method viewers disregarded those elements, but the digital image analysis provided mean densities for the full quadrat. We subsequently present the longitudinal correspondence plot for the manual method because this avoided the slight challenge in the ImageJ results from the roadway and railway positions.

The comparisons of channel configuration in the 1994 versus 2000 aerial photos revealed 15 locations with substantial channel position change (Figure 6). Of these, ten provided *major* erosion sites, with channel movement >75 m, as indicated by one to ten on Figure 6, and five provided *moderate* erosion (45–75 m), indicated by a to e. There was no instance of moderate or major channel change that involved heavily forested riparian zones (‘5’ = fully forested). Of the 15 position with moderate or major erosion, seven occurred in positions in which the floodplain along the eroding bank was grassland without trees (‘1’). Four were assessed as ‘2’, with some trees, and three were in positions with ‘3’, a mixed zone with similar proportion of forest and clearing. A single position with moderate change was flanked by a floodplain zone with considerable forest, assessed as ‘4’.

The study quadrats provided fairly similar proportions across the five vegetation categories with 80, 84, 104, 61 and 83 for 1 through 5, for the 412 total quadrats along both banks. These proportions allowed for the calculation of the expected numbers for 15 samples, and this was compared with the observed numbers. The subsequent χ^2 was 9·88 indicating that the observed distribution differed significantly ($p < 0{\cdot}05$) from that expected based on the frequencies of the different vegetation types. This confirmed that the positions of channel change occurred particularly in locations with grassland, or conversely that the forested positions were more stable.

There were some common patterns and some distinctive aspects at the different major erosion positions. We consequently conclude that substantial erosion requires not only the vulnerable flanking vegetation but also the hydraulic context such as whether the position involved a cut bank along the outside of a meander or channel braiding. In location #1 (Figure 6), the river eroded a concave bank flanked by a grassland hayfield. Considerable erosion occurred along that cut bank and a meander sequence followed with limited erosion along the subsequent opposite bank (#2) that was the only position with erosion of an intermediate density forest (vegetation density 3). The river then rebounded left with major erosion through a cleared floodplain zone (#3).

A somewhat similar pattern occurred along the next zone of alteration. Again, a meander sequence became established through a reach that was previously straighter. The shallow meander sequence involved slight erosion on the right bank (d), followed by more extensive erosion (#4) as the new meander sequence differed from the prior sequence, and a prior convex meander lobe was scoured and became a concave cut-bank. The river continued this new meander sequence at major erosion position #5, the location along the study reach with the greatest channel change. Here, the river cut through a prior livestock pasture creating an entirely new channel (Figure 3).

Extensive erosion occurred in the flood year 1995, and the pasture grasses and finer sediments were scoured to expose cobble. In late summer 1995, the river returned to the pre-flood channel, but with more scour occurring during the 1996 high flow, the river switched to the new channel. This major channel change thus represented an avulsion, an abrupt channel relocation, and in this case, it was apparently enabled by the clearing to create a hayfield. During an inventory of riparian vegetation prior to the 1995 flood (Jamieson *et al.*, 1997), we had identified this

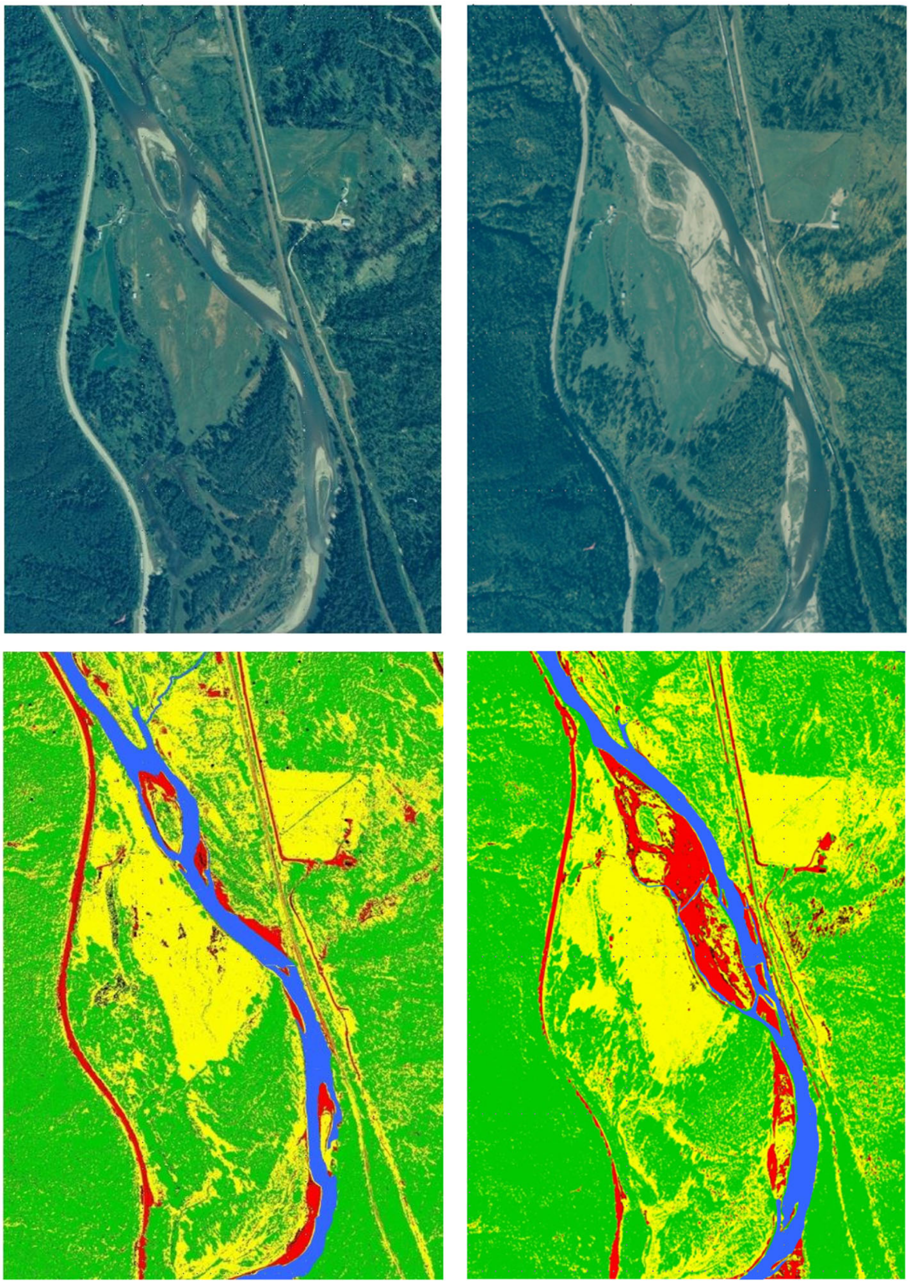

Figure 4. Aerial photographs from 1994 (top left) and 2000 (top right) of the Elk River showing major erosion Site 6 (49°22 28″N: 115°00 38″W) before and after the 1995 flood, and the same images following digital interpretation using ImageJ for vegetation analysis to display: forests (green), grassland and low shrubs (yellow), barren zones, primarily gravel and cobble bars and also transportation lanes (red), and the river water (blue). The 2000 aerial photos display the extensive zone of erosion, which is prominent as the red areas in the digitized image.

location as potentially vulnerable to river erosion because of the woodland clearing.

Next, change location #6 involved the most extensive area of floodplain scour (Figures 4 and 6). Unlike most of the prior change locations in which meander sequences became established, at this location, the river became less sinuous as a prior meander sequence and island were scoured and the river undertook a more linear course. Erosion of the concave cut bank was retarded as the channel approached the heavily armoured railway line. The principal area of floodplain scour thus occurred along the inside of the broad meander as the river eroded the grassland.

Finally, channel change locations #8 through 10 were quite similar to the #1 through 3 sequence as the river established a meander sequence through a reach that was previously relatively straight. Alternating scour of the right and left banks largely involved island and bar zones that

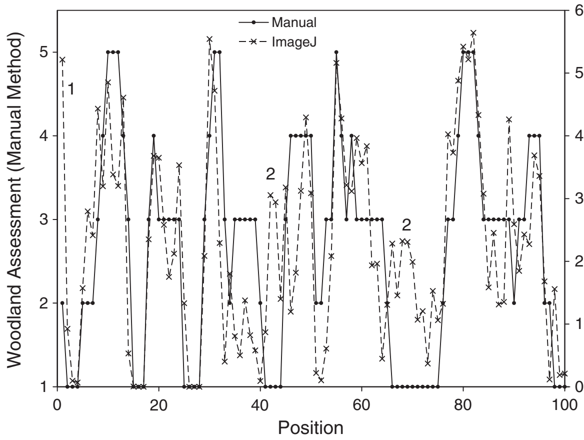

Figure 5. Comparison of the two assessment methods (the manual method and ImageJ) for determining vegetation densities in 100 sequential 75 × 45 m quadrats along the right bank of the Elk River. Numbers indicate positions with differing results because of ‘1’ a building and ‘2’ Highway 3. The correspondence displayed is typical for both banks and along the full study reach.

were relatively barren of vegetation. The extent of scour at each location was restricted by the riparian forest such that the river eroded the prior banks up to the forest zones. Subsequent erosion of these forest zones was slight and generally less than 15 m.

The flood of 2013

Our analyses emphasized the 1995 flood and a further comparison arose with the subsequent 2013 flood (Figure 2). Upstream from the study segment and immediately downstream from the Hosmer Bridge, a grassland hayfield was extensively scoured in 1995 even though it was along the inside of a gradual meander, like the situation at site #6. This scoured zone was subsequently colonized by cottonwoods, and by 2013, they were typically 3 to 5 m tall with a density of about 1/m^2. In 2013, this juvenile cottonwood grove withstood the flood flow, with limited erosion. This provided a further comparison in which a single location was highly vulnerable to erosion when the floodplain was covered by grassland, but the same location was resistant to erosion when covered by a cottonwood grove.

DISCUSSION

Complementary methods for aerial photograph interpretation

The close correspondence in results from the two differing methods of air photo interpretation indicates that both were accurate relative to riparian forest assessment. The manual method is easily applied and requires only the photos and a viewing system. We do not consider that matched stereoscopic pairs are required, although this may simplify the assessment of taller mature, versus shorter juvenile forest zones. An advantage of the manual method is that the observer can readily deal with unusual portions within the image polygon, and in the current case, this primarily represented the road and railway lines.

Conversely, the digital image analysis is more objective, although the threshold criteria are manually applied. It also provides continuous quantitative scaling rather than the discrete five-point ranking and may thus be better suited for subtle discriminations. It would also be well suited to multi-spectral or hyper-spectral approaches that would offer further land-cover differentiation.

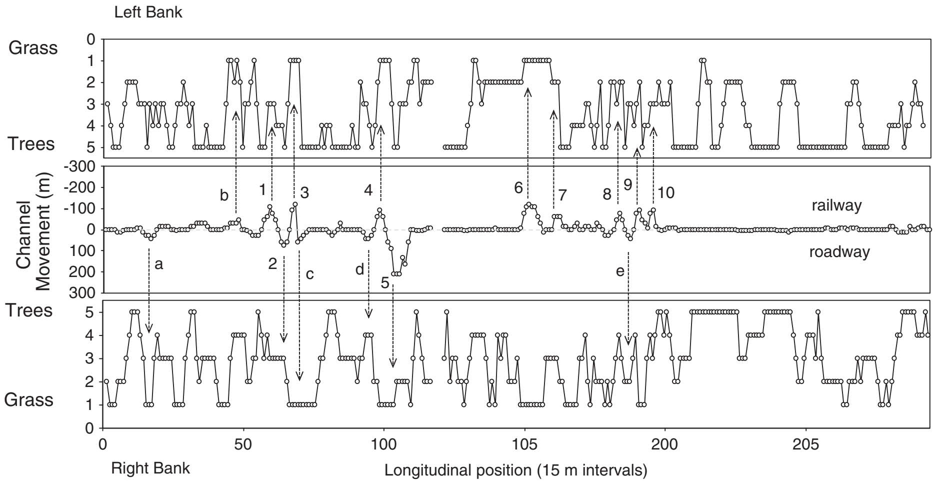

Figure 6. Longitudinal analyses of 1994 riparian vegetation density along the left (top) and right (bottom) banks of the Elk River based on the manual method of aerial photo interpretation and extent of channel position change with the major flood of 1995 as determined by comparing positions in 1994 versus 2000 aerial photos (middle). Each data point represents a 75 m segment with vegetation densities assessed in 75 × 45 m quadrats straddling that channel position. The locations of major channel change are sequentially numbered from one to ten, and the five positions with moderate change are designated from a to e.

Only trees resist big flows

The study outcome was quite confident with respect to the relative efficacy of trees versus grassland in resisting river bank erosion. All locations of major channel erosion occurred through floodplain zones with grassland or a mix of grass and shrubs. This was despite there being many positions in which concave cut-banks occurred adjacent to forested riparian zones. Thus, the trees more effectively stabilized the banks.

With respect to the contrast between this study result and some other studies that concluded that grassy pastures were more erosion-resistant than forests, there are probably three considerations. First, our study involved major floods that would provide higher river velocities and stages, increasing the shear stresses and competence for erosive scour (Wolman and Miller, 1960; Hawkins *et al.*, 1997). It is possible that grassy mats might be effective for moderate flows, but only woody shrubs and trees would be capable of withstanding major flood flows (Griffin and Smith, 2004; Smith, 2004).

Second, our study involved a medium-sized Rocky Mountain river in contrast to smaller streams with shallower gradients that were involved in some prior studies (Trimble, 1997; Lyons *et al.*, 2000). The Elk River is characterized by swift flood velocities, and the channel bed and banks include extensive cobble that is only mobilized by high flows. Although this mountain river would produce higher erosion and transport energies, studies in flatter regions also concluded that shrubs and trees were more resistant to bank erosion associated with major floods (Hawkins *et al.*, 1997; Griffin and Smith, 2004; Vincent *et al.*, 2009). Our conclusion that only big plants resist big flows would be broadly applicable across river and vegetation community types.

Third, some prior studies established correlative patterns that were interpreted as causal associations. Authors concluded that channels were narrower along pasture zones because of increased erosion resistance. An alternate explanation could be that the channel width and riparian vegetation could both reflect a confounding covariate such as sediment textures that were not investigated (Dunaway *et al.*, 1994).

Our study was also primarily correlative, although the final analysis of the same site with grass erosion in 1995 versus tree stabilization in 2013 favours causal association. For our longitudinal correlation, we are unaware of any confounding physical basis for the occurrence of the forest versus grassland locations and believe that this reflects the particular preferences of the landowners.

While we conclude that trees provide better bank protection than grasses, there could also be substantial variation in the resistive capacity across different grasses and across different shrubs and trees. The contribution to bank stability would partly reflect the root distribution (Abernethy and Rutherfurd, 2001; Wynn *et al.*, 2004), which varies across riparian plants (Rood *et al.*, 2011a). While we expect that the large and rigid woody roots and shoots of shrubs and trees would provide superior bank protection, some deeply rooted mat-forming grasses could also provide substantial erosion resistance. In particular, we have observed the invasive riparian plant, reed canary grass (*Phalaris arundinacea*; Lavergne and Molofsky, 2004) during flood flows along the Kootenai River, and there was minimal scour and removal. This apparent erosion resistance may contribute to its persistence and invasiveness along streams throughout the Pacific Northwest.

Across the shrubs and trees, we predict that deeper-rooted species would be more effective. This would especially involve the riparian phreatophytes including some willows (*Salix* spp.) and cottonwoods (riparian *Populus* spp.). Saltceder, an introduced riparian phreatophyte, has also been shown to provide significant bank stability and saltceder removal along the Rio Puerco resulted in significant erosion compared with reaches where vegetation was left intact (Vincent *et al.*, 2009). Unlike most trees that are largely dependent upon shallow soil moisture from precipitation, phreatophyte roots penetrate down to the capillary fringe above the groundwater table. Along alluvial reaches and especially in drier climates, the water table represents a horizontal extension from the river, and thus, the root zone extends almost down to the elevation of the summer river stage (Rood *et al.*, 2011a, 2013). Consequently, cottonwoods should provide substantial resistance to bank erosion.

We might also anticipate that across plant species, the capacity to resist erosion and removal would reflect their natural occurrence in streamside zones. For most regions across North America, sandbar willow, *Salix exigua*, is the lowest elevation woody plant as this obligate riparian shrub occurs at the interface between land and water (Rood *et al.*, 2011b). It is very inundation-tolerant and also apparently erosion-resistant (Griffin and Smith, 2004), and it would be likely that the shoot and root architecture would contribute to its adaptation to this physically dynamic streamside zone. We thus expect that plants such as reed canary grass and sandbar willow will provide insight into the structural forms that resist river erosion, in addition to the probable advantage of the large, rigid roots of trees.

Application – riparian forests should be conserved

This study demonstrates that riparian forest was more effective than grasslands at resisting bank and floodplain erosion from major floods. At least for a mountain-region river, this conclusion rejects the prior proposal that grasslands are better able to resist bank erosion than forests. We thus reject the prior recommendation that trees should be discouraged or cleared in an effort to reduce bank erosion, and we further reject the proposal that riparian livestock grazing should be encouraged in an effort to control shrubs and trees that could increase bank erosion. Conversely, we conclude that riparian forests should be conserved and restored in order to stabilize river banks and resist flood-associated erosion. We do not encourage a static river channel because river and riparian zones are naturally dynamic with episodic surges associated with flood events. We do support the conservation of riparian forests as a strategy to retain the natural dynamics of river and floodplain systems that in turn underlie the healthy dynamics of the associated aquatic and riparian ecosystems.

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