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Contrasting Landscape Influences on Sediment Supply and Stream Restoration Priorities in Northern Fennoscandia (Sweden and Finland) and Coastal British Columbia

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Abstract Sediment size and supply exert a dominant control on channel structure. We review the role of sediment supply in channel structure, and how regional differences in sediment supply and landuse affect stream restoration priorities. We show how stream restoration goals are best understood within a common fluvial geomorphology framework defined by sediment supply, storage, and transport. Landuse impacts in geologically young landscapes with high sediment yields (e.g., coastal British Columbia) typically result in loss of instream wood and accelerated sediment inputs from bank erosion, logging roads, hillslopes and gullies. In contrast, northern Sweden and Finland are landscapes with naturally low sediment yields caused by low relief, resistant bedrock, and abundant mainstem lakes that act as sediment traps. Landuse impacts involved extensive channel narrowing, removal of obstructions, and bank armouring with boulders to facilitate timber floating, thereby reducing sediment supply from bank erosion while increasing export through higher channel velocities. These contrasting landuse impacts have pushed stream channels in opposite directions (aggradation versus degradation) within a phase-space defined by sediment transport and supply. Restoration in coastal British Columbia has focused on reducing sediment supply (through bank and hillslope stabilization) and restoring wood inputs. In contrast, restoration in northern Fennoscandia (Sweden and Finland) has focused on channel widening and removal of bank-armouring boulders to increase sediment supply and retention. These contrasting restoration priorities illustrate the consequences of divergent regional landuse impacts on sediment supply, and the utility of planning restoration activities within a mechanistic sediment supply-transport framework.

Keywords Aggradation · Channel structure · Coastal British Columbia · Degradation · Finland · Fish habitat · Large wood · Sediment supply · Stream restoration · Sweden

Introduction

Channel structure plays a central role in the ecology and restoration of stream ecosystems. Channel gradient, water velocity, particle size, and the proportion of pool and riffle habitat affect ecological attributes as diverse as primary production, invertebrate community structure, and the abundance and distribution of fish (e.g., Schlosser 1991; Rosenfeld and Hudson 1997; Fausch and others 2002; Roni 2002; Roy and others 2003). However, many restoration projects fail because of a poor understanding of historic

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factors and the processes that control channel structure (Roni and others 2008a). Biologists involved in restoration of stream ecosystems and fish populations therefore require a solid understanding of the processes that control habitat structure (Leopold and others 1964; Montgomery and others 1996a; Montgomery and Buffington 1998; Beechie and others 2010).

Sediment supply is a key factor influencing channel structure (Leopold and others 1964). The size and quantity of sediment (i.e., particles ranging from sand to boulders) in the stream channel influence most aspects of channel morphology, including substrate size, channel structural heterogeneity, and bedform type and distribution (Church 2002). Variation in sediment supply in turn affects the quantity and quality of spawning and rearing habitat for fish, as well as the production, storage and retention of organic matter (Lepori and others 2005, Negishi and Richardson 2003) and therefore production rates of benthic invertebrate prey. Recognizing the divergent consequences of increases or decreases in sediment supply is critical for habitat management, because human impacts on sediment supply (and corresponding restoration priorities) vary dramatically across landscapes (Kondolf and others 2002; Liebault and others 2005; Gurnell and others 2009).

Large wood (trees, logs, and root wads) interact with sediment to critically affect channel structure (Sedell and Froggatt 1984; Montgomery and others 1996a). Wood obstructions induce scour by locally accelerating flow (Lisle 1986) and are the major pool-forming mechanism in small alluvial streams with intact riparian zones (Beechie and Sibley 1997; Rosenfeld and Huato 2003) as well as larger rivers where lateral or channel-spanning log jams replicate the function of individual logs in smaller streams (Collins and others 2002). Large wood also retains sediment and organic matter, provides cover for fish, and generally reduces velocities and sediment transport by increasing hydraulic roughness at the reach scale (Buffington and Montgomery 1999).

In this article, we review how sediment and wood affect channel structure and the quality and distribution of fish habitat, and consider restoration within an explicit sediment supply-transport framework. We focus on salmonids, although we recognize the broader management goal of restoring overall function and biodiversity (Dudgeon and others 2006). We show how a 2-dimensional phase space with axes defined by sediment supply and transport can be used as a general geomorphic framework for understanding the effects of landuse and restoration on channel structure. We then document divergent trajectories of streams in this phase space as a consequence of contrasting landuse impacts on sediment supply in northern Fennoscandia (Sweden and Finland) and coastal British Columbia, and subsequent differences in regional stream restoration priorities.

Role of Sediment Supply and Wood in Channel Structure

Influence of Sediment Supply on Channel Structure

Sediment supply and transport vary spatially across landscapes and from hourly to geologic time scales as continents erode. Sediment transport capacity is usually defined as the maximum sediment load that a river can carry. Transport capacity is driven largely by water depth and channel gradient, since greater slope and depth increase shear stress on the stream bed and hence the maximum size and quantity of particles that can be moved (Newbury and Gaboury 1993; Knighton 1999).

The volume of sediment stored in a channel is influenced by the abundance of retentive structures in the stream (e.g., large boulders, wood, and log jams; Montgomery and others 1996a) and the supply rate relative to the transport capacity (Bravo-Espinosa and others 2003); this is illustrated in Fig. 1, where sediment storage in the channel and floodplain increases from the top left (steep high power streams) to the bottom right corner of the figure (low gradient valley bottom streams). When sediment supply to a channel exceeds transport capacity, the increased sediment load is first accommodated by fining of the bed surface (Dietrich and others 1989), and then by

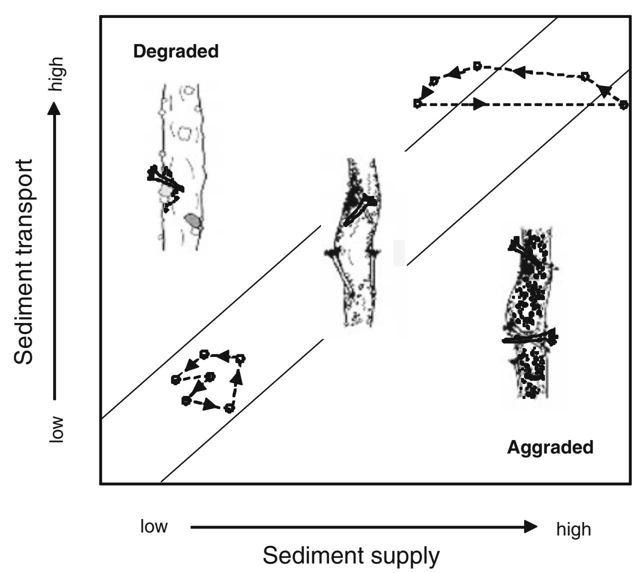

Fig. 1 Two-dimensional phase space for understanding the effects of sediment supply and transport on channel structure. Degraded (armoured) or aggraded channels fall above or below (respectively) the central confidence band where sediment input and transport are roughly in equilibrium. The effect of large wood is to further increase sediment storage in the stream channel. Channel structure may vary over time according to temporal variation in sediment inputs (denoted by arrows), which may be relatively small (lower trajectory) or large (upper trajectory, indicating a stream with a large stochastic sediment input such as a debris flow)

infilling of pools (Lisle 1982; Madej and Ozaki 1996). If sediment supply greatly exceeds transport capacity, then a channel will aggrade (Fig. 1), leading to increased bed elevation and channel width (Lisle 1982; Alexander and Hansen 1986; Aslan and Autin 1999; Madej 1999), creating streams that are dominated by continuous riffle (Lisle 1982). Aggradation is common on river deltas, alluvial fans, or braided valley bottoms where sediment supply from steep tributaries exceeds the transport capacity of the lower gradient stream on the valley floor.

Degradation occurs when transport capacity exceeds sediment supply, resulting in coarsening of the streambed surface as the more easily transported fine sediment fraction is moved downstream (Fig. 1 upper left). This results in bed armouring, where the average surface particle size is larger than the average sub-surface particle size (Dietrich and others 1989). Differential transport of fines causes some degree of bed surface armouring in most streams, but significant bed armouring results in a bed surface layer that is resistant to movement because higher shear stress (discharge) is required to initiate movement of the larger bed surface particles (Jackson and Beschta 1982). Degradation may eventually result in loss of gravel bars and bed elevation, in some cases leading to deeply incised stream channels under particular conditions (Beechie and others 2008).

Average substrate size typically depends on geomorphic context (Montgomery and MacDonald 2002; Buffington and others 2004); for example, particle size is generally larger and availability of spawning gravel lower in steep headwaters with a high transport capacity (top of Fig. 1, extreme right of Fig. 2; Kondolf and others 1991; Montgomery and others 1999). However, local sediment sources may reset longitudinal declines in bed particle size along the river continuum (Rice and others 2001; Arp and others 2007; Davey and Lapointe 2007), and a channel may switch from a relatively aggraded to a relatively degraded state or vice versa by land use impacts that alter sediment inputs (Fig. 2; Madej and Ozaki1996; Province of British Columbia 1996; Hogan and others1998). For instance, logging and livestock grazing may increase sediment supply to streams (Kondolf and others 2002; Liebault and others 2005), whereas trapping of sediment above dams may cause channel degradation or downcutting below reservoirs (Ligon and others 1995; Grant and others 2003).

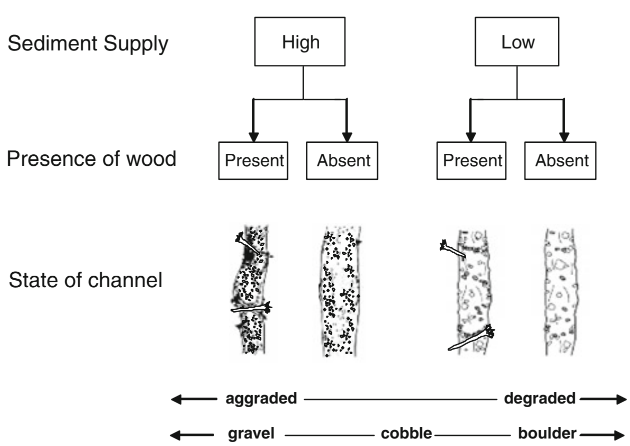

Fig. 2 Schematic diagram illustrating hierarchical effects of sediment supply and the presence of wood on channel structure in terms of a continuum of substrate size and aggradation

Influence of Sediment Supply on Wood Function

Large wood (typically defined as wood greater than 1 m long and 15 cm in diameter) has several geomorphic functions of relevance to fish habitat that are modulated by sediment supply. First, wood as individual pieces or jams locally reduces the cross-sectional area of stream channel, thereby obstructing flow and inducing scour through flow convergence leading to pool formation (Lisle 1986; Montgomery and Buffington 1997; Buffington and others 2002).

The ability of wood to force scour pools depends on bed particle size, which increases with channel gradient (Buffington and others 2002). Although wood contributes to step-pool formation and retention of sediment and organic matter in steep gradient streams (Hassan and others 2005; May and Gresswell 2003), wood has a lesser impact on pool formation in steeper fish-bearing channels where boulders are the dominant obstruction inducing flow convergence and scour, and wood obstructions usually generate insufficient shear stress to cause movement of boulders (Province of B.C. 1996; Beechie and Sibley 1997; Buffington and others 2002; Sweka and Hartman 2006). Armouring of the stream bed surface by larger particles in degraded streams will similarly reduce the geomorphic functionality of wood such that its ability to generate scour pools is reduced.

In the opposite extreme, the ability of wood to induce pool formation will be reduced if excessive bedload infills pools in aggraded channels. Sediment supply thus directly mediates the effectiveness of wood as a geomorphic feature causing pool formation. Wood can be expected to facilitate pool formation most effectively in channels with intermediate levels of sediment (diagonal band in Fig. 1), where bed surface particle size is small enough to allow scour and transport at high flow and sediment is sufficiently abundant to deposit bars downstream of wood obstructions without infilling the entire channel (Everest and others 1987; Province of British Columbia 1996; Buffington and others 2002).

Pool-forming scour also affects the quality of spawning habitat in adjacent riffles. Scour from convergent flow at an obstruction (wood, boulder, or stream bank) transports sediment out of the pool at high discharge and deposits it in the downstream riffle. As discharge declines, velocities tend to reverse (Keller 1971; Harrison and Keller 2007), and pools become relatively depositional while riffles become erosional (Wilkinson and others 2004). This process of scour and fill creates well-sorted bed material (i.e., substrate patches of homogenous particle size) in riffles below pools. The hydraulic head created by the elevation of the upstream pool, in conjunction with the open interstices of well-sorted gravel, facilitates interstitial flow (Kondolf 2000a), making the tailout of pools and head of riffles ideal sites for egg incubation (Peterson and Quinn 1996; Greig and others 2007). This is offset to some extent by a greater probability of egg scour below riffle crests at high discharge (Lapointe and others 2000; Schuett-Hames and others 2000), but egg scour can be minimized if eggs are buried sufficiently deep or lateral to the thalweg (Holtby and Healey 1986; Montgomery and others 1999; May and others 2009).

Finally, wood contributes to the maintenance of spawning habitat through retention of sediment upstream of log jams (Fig. 2; Montgomery and others 1996a; Buffington and others 2004). Large wood effectively displaces low gradient reaches and high quality spawning habitat much further upstream than would otherwise be the case if the downstream bed profile were uniform (Montgomery and others 1996a; Hogan and Bird 1998; Faustini and Jones 2003).

Sediment Supply and Fish Habitat Quality

Sediment supply directly affects fish by altering the depth and velocity of available habitat for all life history stages (Sear and DeVries 2008), and indirectly through sediment effects on the abundance and productivity of invertebrate prey. The quantity and quality of spawning habitat is particularly sensitive to sediment supply. Fish populations in streams with very low sediment supply or high transport capacity may be limited by the absolute area of available spawning habitat (e.g., Kondolf and others 1991; Palm and others 2007), which may generate insufficient recruits to saturate juvenile or adult habitat. Streams with excessive sediment inputs may be limited more by the quality of spawning habitat, resulting in insufficient recruits as a consequence of poor egg survival (Lisle 1989; Greig and others 2007).

Proper embryo development requires interstitial flows of well-oxygenated water, and fine sediment that decreases interstitial flow can greatly reduce egg survival (Sear and others 2008). Post-spawning deposition of thick surface sediment may entomb fry and prevent emergence, although light sediment seals may enhance egg survival (Meyer and others 2005). Excessive sediment supply that decreases channel stability (i.e., increases the frequency of bed movement) may also increase scour depth at high flows, potentially causing significant egg mortality (Montgomery and others 1996b). In contrast, annual bioturbation by a large population of spawning adults may improve spawning gravel quality through downstream transport of fines during redd excavation (Kondolf and others 1993).

Loss of deep pool habitat through infilling of pools may directly reduce the volume of habitat suitable for juvenile and adult life history stages (e.g., Madej 1999). Extreme aggradation may also result in intermittent surface flow and consequent fish mortality during periods of drought (May and Lee 2004). Loss of large wood often accompanies increased sediment supply and may exacerbate loss of pool habitat (Reeves and others 1993; Montgomery and others 1995). Habitat complexity associated with large wood also provides juvenile rearing habitat (Solazzi and others 2000), essential cover from predators (Lonzarich and Quinn 1995), and hydraulic refuges during high flows (Bell and others 2001). Loss of habitat complexity can also be expected at very low sediment supplies when both pool formation and large wood effectiveness are reduced (e.g., Madej 1999, Buffington and others 2002).

Deposition of fine sediment may directly affect the base of the aquatic food chain by smothering epilithic algae (Davies-Colley and others 1992), and increased bed mobility at high sediment supplies may further reduce primary production (Biggs and others 1999). Benthic invertebrate abundance tends to be correlated with the biomass of detrital resources stored in bed surface complexity or in substrate interstices (e.g., Culp and others 1983; Muotka and Laasonen 2002; Negishi and Richardson 2003). Excessive fine sediment that fills gravel interstices will reduce the ability of substrate to trap the organic detritus that supports detritivorous invertebrate production. Reduced interstitial flow and volume will also affect habitat availability for benthic invertebrates, and ultimately the availability of benthic and drifting prey for fish (Angradi 1999; Suttle and others 2004; Cover and others 2008).

Effective restoration of process and structure in streams therefore requires understanding how sediment supply and large wood interact to influence habitat availability for fish, as well as the trophic resources that drive invertebrate prey abundance.

We now consider how divergent land-use impacts on sediment supply affect stream trajectories within the sediment supply-transport phase space illustrated in Fig. 1.

Contrasting Sediment Supplies, Landuse Impacts, and Stream Restoration Priorities in British Columbia and Northern Fennoscandia

Sediment Supply and Landuse

Like other mountainous regions throughout the world (Griffiths 1979; Gurnell and others 2009), geologically young landscapes like coastal British Columbia with steep relief, high precipitation, erodible bedrock, and abundant glacial deposits generate large quantities of sediment that are delivered to streams through surface erosion, landsliding, episodic debris flows in steep headwaters, and bank erosion where streams traverse glacial or alluvial deposits (Table 1; Reeves and others 1995; Hartman and others 1996; Benda and Dunne 1997a, b; Liebault and others 2005). Streams in high yield landscapes have significant quantities of sediment and wood that generate suitable habitat for all life stages of salmonids (Montgomery and others 1996a), placing unperturbed coastal BC streams near the center of the sediment supply-transport phase space (Fig. 3b).

In contrast, streams and rivers in geologically older, Precambrian landscapes with lower relief have much lower sediment supplies (Table 1) associated with generally harder bedrock and gentler hillslopes, leading to larger average substrate size for a given channel width and gradient. Representative locations include northern Sweden and Finland as well as parts of the Precambrian Shield in central Canada. Even when there are localized sources of sediment (e.g., when rivers traverse glacial deposits; Ashmore 1993; Davey and Lapointe 2007), downstream transport is frequently truncated by low gradient reaches or mainstem lakes (Arp and others 2007), further contributing to decreased sediment supply to lower river reaches. In many streams contemporary substrate size and composition result from selective erosion of finer particles and exhumation of boulders deposited by historic glacial and weathering events, resulting in a mismatch between stream gradient (power) and average particle size, i.e., channels may be dominated by boulders and cobbles even at lower gradients (Fig. 4a). This contrasts with truly alluvial channels in landscapes with higher sediment supplies, where channel morphology is shaped by episodic high discharge events that are capable of mobilizing most particle sizes present, and substrate size decreases with downstream location on the river continuum (Leopold and others 1964; Knighton 1999).

Table 1 Literature reports of regional sediment yields (tons km^{-2} yr) for streams from Sweden, Finland, and coastal British Columbia

Coastal British Columbia	Sweden and Finland	Reference
250–500	0–50	Walling and Webb (1983, 1996)
50–100	0–10	Strakhov (1967)
200–1000	0–20	Lvovich and others (1991) (cited in Walling and Webb 1996)
171 (±166)	–	Church and others (1989)

Values represent suspended load only, which dominates total sediment export (Church and others 1989) and is assumed representative of yield of larger bedload particles

Regional differences in sediment supply are further modified by landuse impacts from forestry, agriculture, flow regulation, and urban development (Kondolf and Larson 1995; Harding and others 1998; Beechie and Bolton 1999; McIntosh and others 2000; Kondolf and others 2002; Liebault and others 2005; Wohl 2006). Historic land use has generally increased sediment yields in British Columbia, although in some cases scour associated with splash damming (Sedell and others 1991) or loss of channel-spanning large wood jams have severely reduced sediment storage (Montgomery and others 1996a; 2003; Buffington and others 2004). The overall impacts of forestry on sediment supplies in coastal British Columbia have been to increase them dramatically (e.g., Hogan 1986), shifting them to a more aggraded state in the sediment supply-transport phase space (Fig. 3b). Stream bank erosion and subsequent channel destabilization from logging of riparian zones has been a major source of sediment (Hartman and others 1996), and much of the landbase in British Columbia has been historically logged without effective riparian protection (e.g., Figs. 3a, 4d). Timber harvest and road-building on steep hill slopes have also greatly increased the frequency of debris flows and landslides that deliver large quantities of sediment to streams and rivers (Hogan 1986; Hogan and others 1998), as have poor road building practices that result in chronic production and delivery of sediments (Reid and Dunne 1984; Jones and others 2000). Consequently, many streams in coastal British Columbia have been significantly aggraded, and a major restoration goal has been to decrease sediment inputs through bank and hillslope stabilization (Hartman and others 1996; see Table 2).

Streams in northern Fennoscandia have also been heavily impacted by logging. However, in contrast with forestry impacts in coastal British Columbia, forestry tended to reduce sediment inputs to channels that were already naturally sediment starved (degraded) in these post-glacial landscapes (Fig. 3b). The dominant forestry impact in northern Fennoscandia has been stream channelization (Figs. 4b, 5). Thirty thousand kilometres of stream and river in Sweden and 40,000 kilometres in Finland were channelized by the early 1900s to facilitate downstream transport of logs, until a road network was developed in the 1950s as an alternative to timber floating (Nilsson and others 2005). Channelization involved two primary components: removal of emergent boulders and wood from the

Fig. 3 Effects of different land management practices on sediments inputs and channel structure (**a**). Using boulders to narrow channel width and armour stream banks for timber floating in northern Fennoscandia has decreased sediment inputs and increased downstream transport. In contrast, sediment inputs (indicated by open arrows) to streams in coastal British Columbia have increased from logging-related landslides, surface erosion from logging roads, and bank erosion. Net impact of landuse (**b**) has been to generally aggrade channels in coastal British Columbia, and to degrade them in Northern Fennoscandia (broken circles represent historic condition, solid circles represents modern state)

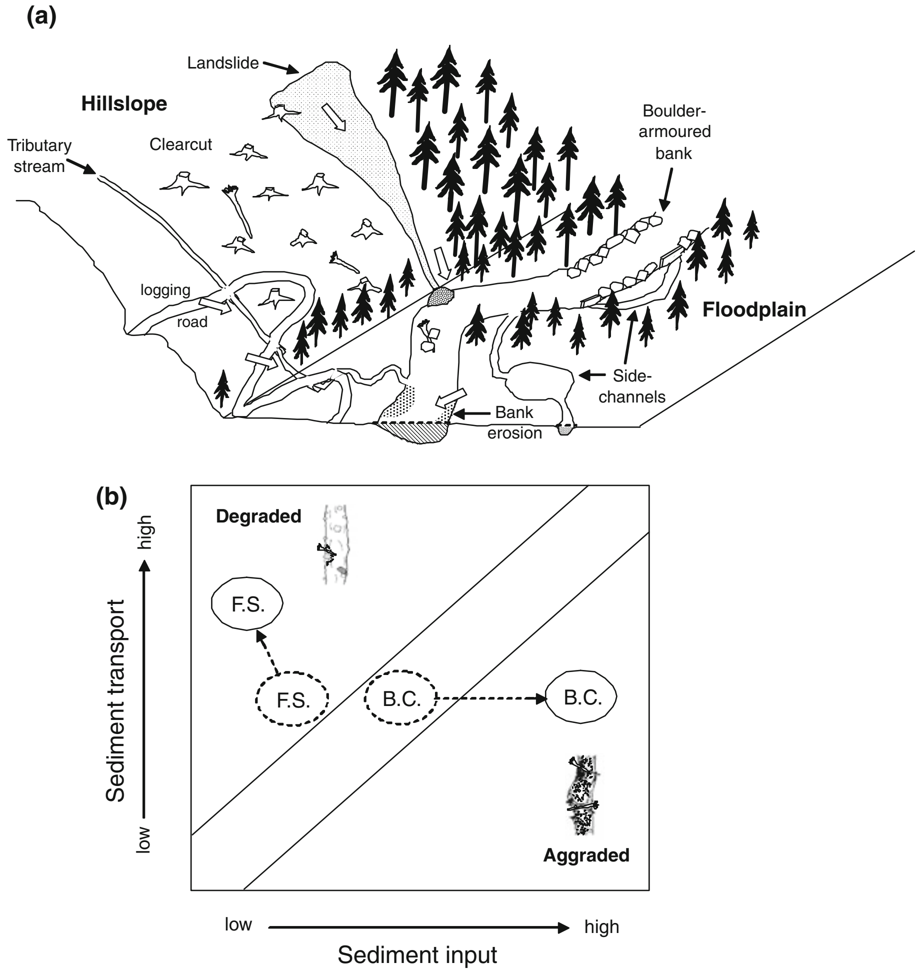

Fig. 4 (**a**) Minimally impacted Swedish stream with relatively low sediment supply and large substrate. (**b**) Channelized stream with a narrow channel and armoured banks, further reducing sediment supply and storage. (**c**) Minimally impacted coastal British Columbia stream with abundant instream wood and moderately aggraded gravel substrate. (**d**) Severely aggraded coastal stream channel from excessive sediment inputs (note non-functional wood and subsurface flow)

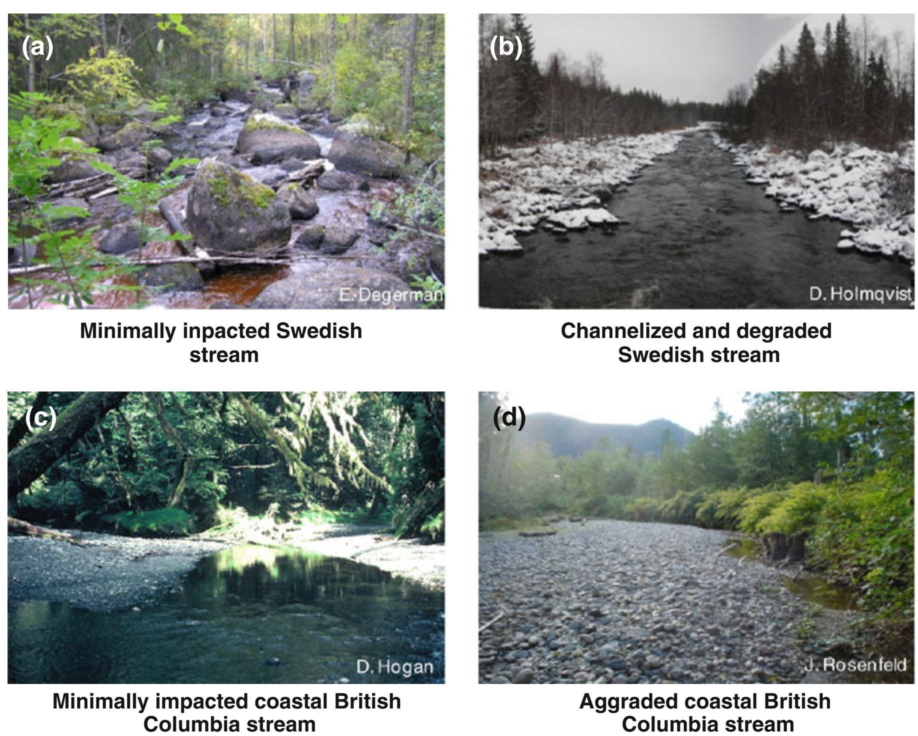

Table 2 Breakdown of stream restoration activities in northern Fennoscandia and coastal British Columbia, showing a greater emphasis on bank and hillslope stabilization activities to reduce sediment yields in British Columbia, and an opposite investment in removal of stabilizing bank armour in Fennoscandia

Restoration activity	Northern Fennoscandia[a] (Sweden and Finland)		Coastal British Columbia[b]	
	Number of projects	Proportion of total (%)	Number of projects	Proportion of total (%)
Instream habitat enhancement (e.g., wood and boulder complexing)	70	35	80	30
Spawning habitat enhancement (e.g., gravel addition)	25	13	19	7
Side channel construction (groundwater, surface, wetland)	0	0	45	17
Hillslope (e.g., stabilization, tree planting, road de-commissioning)	0	0	30	11
Riparian (e.g., tree planting for bank stabilization, cattle fencing)	0	0	55	20
Fish passage (e.g., culvert and barrier removal)	52	25	40	15
Removal of bank-armouring boulders and channel widening	55	27	0	0

Note that removal of bank-armouring boulders in Fennoscandia usually accompanies instream habitat enhancement, because boulders from the stream bank are redistributed in the stream channel. Although side-channel construction in Fennoscandia is rare, removal of berms that were historically constructed at the upstream end of natural side channels to prevent log jam formation is common. Instream enhancement and improving fish passage are restoration activities common to both regions

[a] Based on completed stream restoration projects from northern Sweden (Palm 2008, unpublished data)

[b] Based on completed stream restoration projects from Vancouver Island region from 1989 to 2004 (Department of Fisheries and Oceans 2008, Fisheries Project Registry, http://www.canbcfpr.pac.dfo-mpo.gc.ca/fpr/Qf_frames.asp)

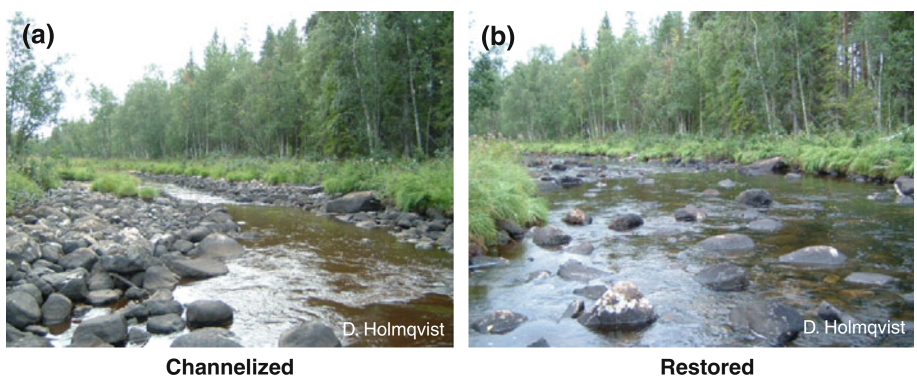

Fig. 5 Channelized stream reach in Sweden (**a**) before and (**b**) after restoration. Note the narrow, deeper channel with boulders removed to the stream banks in the channelized state. Restoration focuses on returning the channel to its original width and replacing boulders in the thalweg, thereby decreasing average channel velocity while increasing channel volume and structural complexity

stream channel to increase thalweg depth and prevent snagging of logs and creation of log jams; and placement of boulders extracted from the thalweg onto the channel margins, thereby armouring the banks and narrowing and deepening the channel to facilitate downstream transport of logs (Nilsson and others 2005). Bedrock outcrops and boulders that were too large to move were commonly dynamited (Palm and others 2007).

The net effects of channelization in northern Fennoscandia were to decrease channel complexity by removal of the major structuring elements present (large boulders and wood); to armour the stream bank with boulders; to straighten the channel, increasing gradient and reducing bar-pool formation; to deepen the thalweg; and to increase water velocities through channel narrowing and removal of larger boulders that generate hydraulic resistance, thereby increasing the net transport of gravel to downstream low gradient reaches and lakes that act as sediment traps (Lepori and others 2005; Nilsson and others 2005; Palm and others 2007). Armouring also dramatically reduced sediment supply by stabilizing stream banks and preventing normal recruitment of sediment through channel migration and bank erosion (e.g., Florsheim and others 2008), while elevated channel velocities simultaneously increased sediment transport rate and further accelerated armouring of the stream bed and banks (Palm and others 2007). The consequence of decreased sediment supply and increased transport in northern Fennoscandia was widespread channel degradation—an opposite trajectory to streams in coastal British Columbia (Fig. 3b).

Removal of wood to facilitate navigation and timber floating was also a common practice in North American rivers (Sedell and Froggatt 1982; Collins and others 2003). While wood removal greatly reduced channel complexity, banks of North American streams were not systematically armoured and channelized to the same degree as in northern Sweden and Finland; consequently, reductions in sediment supply did not generally accompany removal of wood as the major channel structuring element in North American streams as with boulder removal and bank armouring in northern Fennoscandia. The potential for regeneration of riparian forest and subsequent wood inputs also allowed for a measure of natural recovery in western North America that was not possible for Swedish rivers, where large boulders extracted from the channel could not be redistributed through natural processes, or had been removed altogether by dynamiting.

One of the consequences of channelization in northern Fennoscandian rivers was to reduce the quantity of gravel substrate suitable for spawning, a serious impact that may have significantly reduced fish populations in degraded streams where spawning habitat was likely already limiting (Palm and others 2007). Increased channel velocity and habitat simplification likely also reduced suitable rearing habitat for both juvenile and adult salmonids. Aggradation of streams in western North America also likely reduced rearing habitat through infilling and loss of heterogeneity, and degraded spawning habitat as well, but through increased fines and decreased channel stability. Extreme aggradation or degradation both tend to reduce fish habitat quality and quantity, suggesting an optimal channel structure for fish production under intermediate sediment supply and storage conditions (Everest and others 1987; Province of British Columbia 1996).

Restoration Priorities

Restoration prescriptions need to reverse the trajectories that have displaced streams from the center of the sediment supply-transport domain (Fig. 3b). Restoration activities to reduce sediment inputs to streams of coastal British Columbia and the Pacific Northwest have focused on riparian protection and revegetation, stabilization of upslope sources of sediment through reforestation, re-establishment of natural drainage patterns disrupted by roadbuilding, and road decommissioning (Table 2; Kauffman and others 1997; Beechie and Bolton 1999; Roni and others 2002; Saldi-Caromile and others 2004). Because wood plays a more important structural role in moderately aggraded channels than in severely degraded ones, restoration has also focused on addition of wood until forest regeneration re-establishes natural recruitment of wood from riparian zones.

In contrast, boulders were likely the dominant structuring elements in many Fennoscandian streams, although instream wood was likely also abundant and of significant (but somewhat lesser) importance to channel structure. Restoration in northern Fennoscandia has therefore focused on removal of bed armouring boulders from the stream banks, and their redistribution in the thalweg (Table 2, Fig. 5; Nilsson and others 2005). Channel widening, reduced thalweg velocities, and increased channel roughness and retention capacity (water volume in the channel) are associated outcomes of this restoration (Fig. 5). Removal of bank armouring should also help restore sediment inputs by allowing bank erosion and limited channel migration to resume (Florsheim and others 2008). Restoration has included both the addition of spawning gravel as well as local removal of bed armouring to allow spawning in exhumed gravel (Palm and others 2007), and addition of large wood where appropriate. Increasing habitat complexity and reconnecting floodplain side channels are restoration strategies common to both northern Fennoscandia and coastal British Columbia (Table 2).

These contrasting case histories demonstrate that an understanding of the magnitude of local sediment supply and how it affects channel morphology is essential for determining whether the goal of restoration is to adjust (increase or decrease) sediment supply (Fig. 3b), or to focus on re-introducing large scale structural elements, or both. However, the general goal should be to restore the local and catchment-scale processes whose disruption initiated the original change in sediment yield (Kauffman and others 1997; Kondolf and others 2002; Roni and others 2002; Beechie and others 2010), and to push channels back to their original positions in the sediment supply-transport phase space (Fig. 3b).

Unfortunately, it may not always be logistically or economically feasible to reverse trajectories by restoring catchment-scale processes (Kondolf and others 2006), in which case local remediation to sediment starved channels can include sediment additions (Merz and others 2004; Saldi-Caromile and others 2004) or removal of bed armouring to expose spawning gravel (Palm and others 2007). Downstream export of exhumed gravel exposed by removal of bed armouring can be reduced by placement of boulders downstream of exposed gravel patches to reduce bed shear stress at high flows (Palm and others 2007). Boulder and wood jam structures can also be used to retain upstream sediment (Saldi-Caromile and others 2004; Roni and others 2008b). However, the long-term effectiveness of these interventions will depend on the rate at which sediment is exported from the restored reach, and they cannot be expected to be self-sustaining in the absence of a restored sediment supply (e.g., Merz and others 2006). Similarly, if sediment supplies cannot be reduced in highly aggraded streams, then local interventions such as channel narrowing to create higher velocities and addition of small-scale flow obstructions (e.g., wood, boulders) to facilitate local scour and fill may permit higher transport rates and local coarsening of the streambed. Larger channel-spanning habitats can also be engineered to generate local scour and fill and deposition of suitable spawning substrate (e.g., Newbury and Gaboury 1993).

While restoration priorities will be sensitive to changes in sediment supply, the role of pre-disturbance channel structure in habitat limitation of fish populations must also be recognized. Limited gravel in boulder-dominated channels of northern Fennoscandia results in populations limited by spawning habitat to a much greater degree than populations in gravel-rich alluvial streams of coastal British Columbia. Streams in northern Fennoscandia are therefore necessarily more sensitive to loss of spawning habitat. This highlights the importance of understanding the limiting habitat associations of the target species, and correctly identifying and targeting limiting habitats during restoration planning (Kondolf 2000b; Rosenfeld and Hatfield 2006). This may be challenging. While spawning habitat limitation can be more easily identified (contrast Fig. 4a vs. c), our understanding of substrate effects on capacity to rear juvenile salmonids is incomplete. For instance, it remains unclear whether reaches with similar gradient and discharge but different substrate size (e.g., Fig. 4a vs. c) support different densities of juvenile salmonid, highlighting fundamental gaps in our understanding of the relationship between habitat and fish production.

Conclusions

The contrast between restoration priorities in coastal British Columbia and northern Fennoscandia demonstrates how restoration must take place within the context of regional geomorphology—in particular local sediment supplies, and how they are affected by landuse. Contrasting landuse impacts have pushed stream channels in opposite directions (aggradation versus degradation) away from the center of a phase-space defined by sediment transport and supply; effective restoration must reverse these trajectories. Placing historic conditions and land-use impacts within an explicit mechanistic framework defined by sediment supply and transport (Fig. 1, 3b) can help guide appropriate strategies for habitat restoration.

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