Physical and ecological response to disturbance by gravel mining in a large alluvial river

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Abstract: The role of sediment transport during high flows for restoring fish habitat was demonstrated following an experimental gravel removal from Fraser River, British Columbia, Canada. Dry bar scalping 69 000 m^3 of river sediment left a topographically simple removal area with a loose surface of gravel and sand. Two subsequent, below-average floods yielded no gravel replenishment but restored substrate grain size and some topographical complexity at the habitat scale. A third, above-average flood replenished 31% of the removal volume. High-elevation bar area, which provides fish habitat at high flows, remained 25% smaller after the three floods. Effects of mining on the fish community could not be confirmed. Benthic invertebrates recolonized the removal site immediately after mining, and differences in community composition compared with three reference sites disappeared during the first flood. Results suggest that physical changes due to this mining operation fell within the range to which local aquatic populations are accustomed during flooding, because the ecological response was modest and short-lived. Despite an extensive sampling program, inherent variability in the biological data reduced statistical power to detect an effect. Monitoring programs to support adaptive management of river fisheries will require substantial investment and planning to yield definitive results.

Résumé : Après une extraction expérimentale de gravier dans le Fraser, la Colombie-Britannique, Canada, nous avons démontré le rôle du transport des sédiments pendant les forts débits dans la restauration des habitats des poissons. Le prélèvement par décapage de 69 000 m^3 de sédiments sur les barres sèches de la rivière a laissé une zone d'extraction à topographie simple avec une surface lâche de gravier et de sable. Deux crues subséquentes, de débit inférieur à la moyenne, n'ont pas rapporté de gravier, mais elles ont restauré la taille des particules du substrat et rétabli une partie de la complexité topographique à l'échelle de l'habitat. Une troisième crue, plus importante que la moyenne, a rétabli 31 % du volume retiré. La zone des hauts-fonds qui représente l'habitat des poissons pendant les forts débits est demeurée 25 % plus petite après les trois crues. Il n'a pas été possible de déterminer l'effet de l'extraction du gravier sur les communautés de poissons. Les invertébrés benthiques ont recolonisé le site d'extraction immédiatement après l'opération minière et les différences de composition de communauté observées en comparaison avec trois sites témoins sont disparues lors de la première crue. Nos résultats laissent croire que les changements physiques causés par cette extraction minière se situent dans la gamme des conditions auxquelles les populations aquatiques locales sont habituées parce que la réaction écologique a été modeste et de courte durée. Malgré un important programme d'échantillonnage, la variabilité inhérente aux données biologiques a réduit notre capacité statistique à détecter des effets. Les programmes de surveillance qui appuient la gestion adaptative des pêches de rivière vont exiger un investissement et une planification importants afin de produire des résultats définitifs.

[Traduit par la Rédaction]

Introduction

The distribution of sediment along stream channels determines the form of the channel, as well as the character of habitats available to aquatic organisms. In steep gradient systems, cobbles and boulders are major structural elements that define habitat boundaries (Halwas and Church 2002), while gravel and smaller-sized sediments are transported downstream. As gradient drops and the flow becomes less powerful, gravel is deposited and accumulates to form bars. The tendency for sediment to accumulate as gravel bars and islands in moderate and low-gradient channels creates outstanding habitat for various fish species and aquatic organisms (Thorp 1992; Johnson and Jennings 1998; Beechie et al. 2005).

River-run sediment is also highly desirable for construction purposes. Alluvial gravel is particularly sought after because of its high quality, often simple removal, and the fact that land-based aggregate is, with population growth, increasingly pre-empted for other uses (Kondolf 1994, 1998). Depending on channel characteristics and jurisdictional regulations, material is either removed by in-stream dredging (e.g., Harvey and Lisle 1998), extracted from off-channel floodplain deposits (e.g., Kondolf 1998), or scalped from dry bar surfaces within the channel during low flow (this study). Volumes extracted from many rivers have greatly exceeded the natural rate of recruitment, and in some cases, severe environmental damage has been reported (e.g., Macdonald 1988; Rinaldi et al. 2005; Rovira et al. 2005).

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Studies characterizing the physical impacts of gravel mining from rivers in the United States (e.g., Collins and Dunne 1990; Kondolf 1994; James 1999) and Europe (e.g., Sear and Archer 1998; Surian 1999) are relatively common. Far fewer studies have examined ecological impacts, despite growing concern that mining damages aquatic habitat. Attempts are made to minimize direct effects, such as the loss of benthic organisms (e.g., Griffith and Andrews 1981) or turbidity causing physiological stress to sensitive fish species (e.g., Berg and Northcote 1985; Shaw and Richardson 2001), through regulations restricting the timing and method of extraction (e.g., Boyd 1975; Meador and Layher 1998).

Indirect ecological effects due to gravel mining, those transmitted through habitat modifications, are likely to have the greatest impact on river ecosystems. But such effects are difficult to detect and characterize. Previous studies examining ecological effects have been carried out at sites with a prolonged history of gravel mining (e.g., Brown et al. 1998). There remains a major gap in our knowledge of the impacts to pristine aquatic habitat and the response of organisms. Gravel mining directly alters channel morphology (Collins and Dunne 1990; Kondolf 1997), thereby affecting flow velocity, water depth, and substrate texture, all of which influence the distribution and abundance of aquatic organisms. Species with specific habitat requirements may disappear from a system where substantial habitat modifications have occurred (Ricciardi and Rasmussen 1999). Other species with greater tolerance to habitat change may persist; however, recurrent habitat alteration will inevitably impact species composition and the productivity of river ecosystems (Benke 1990; Richter et al. 1997).

The objective of our study was to examine the effects of a single, experimental gravel removal on the physical habitat and invertebrate and fish communities in the lower Fraser River, British Columbia. A secondary goal of our study was to evaluate sampling requirements for effect detection in a large river system. Fraser River is unregulated and has a predictable annual hydrograph with snowmelt flooding in late spring that delivers substantial gravel annually to the lower river. Our hypothesis was that habitat alterations and the ecological response due to gravel mining are mediated by this annual flow event.

Materials and methods

Study area

Fraser River drains 232 000 km^2 of south and central British Columbia, Canada. The mainstem river is unregulated, and annual flooding due to snowmelt occurs in spring. At high flows, a large amount of sediment is mobilized and transported from the steep, upper basin, and a sharp decline in gradient in the lower 170 km forces deposition of much of this sediment load. Coarse sediment (gravel, cobble) is deposited within a 50 km reach between Laidlaw and Sumas Mountain (Fig. 1), referred to as the gravel reach, whereas fine sediment (sand, silt, clay) is transported further downstream (McLean et al. 1999). Sediment deposition in the gravel reach creates a wandering channel pattern (Desloges and Church 1989), with gravel bars and islands dividing the flow into multiple channels that shift with bar growth and bank erosion. Average peak flood discharge for the gravel reach (measured at Hope, Water Survey of Canada Stn. 08MF005) is 8766 m^3·s^{-1}, and mean annual flow is 3410 m^3·s^{-1}.

Because of annual gravel deposition, the Fraser River gravel reach has been exploited as a local source of high-quality gravel for many decades. At least 5 million m^3 have been mined since 1964 (averaging 117 000 m^3·year^{-1}; Weatherly and Church 1999), the majority of which was removed by dry bar scalping at low flow in winter. To place this volume in context, annual gravel influx averages 250 000 m^3·year^{-1} to the gravel reach (Ham 2005), while substantially larger volumes of sediment, on the order of 1 million m^3·year^{-1}, are redistributed by natural erosion and deposition processes during spring flooding (Ham and Church 2003). A removal rate of less than 50% the natural influx rate is low relative to most rivers where mining occurs (Collins and Dunne 1990; Rinaldi et al. 2005), and sediment transport processes in the gravel reach are mostly intact.

The Fraser River gravel reach supports 28 native fish species, including endangered white sturgeon (*Acipenser transmontanus*). Its residency in the gravel reach has been a major force behind habitat protection and sustainable management of the reach. The family Salmonidae dominates the faunal assemblage of the gravel reach with 11 species, and the Fraser River exceeds all rivers worldwide in terms of salmonid stock abundance (Northcote and Larkin 1989). Millions of pink salmon (*Oncorhynchus gorbuscha*) spawn within the gravel reach biennially, and large numbers of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) use the reach for rearing.

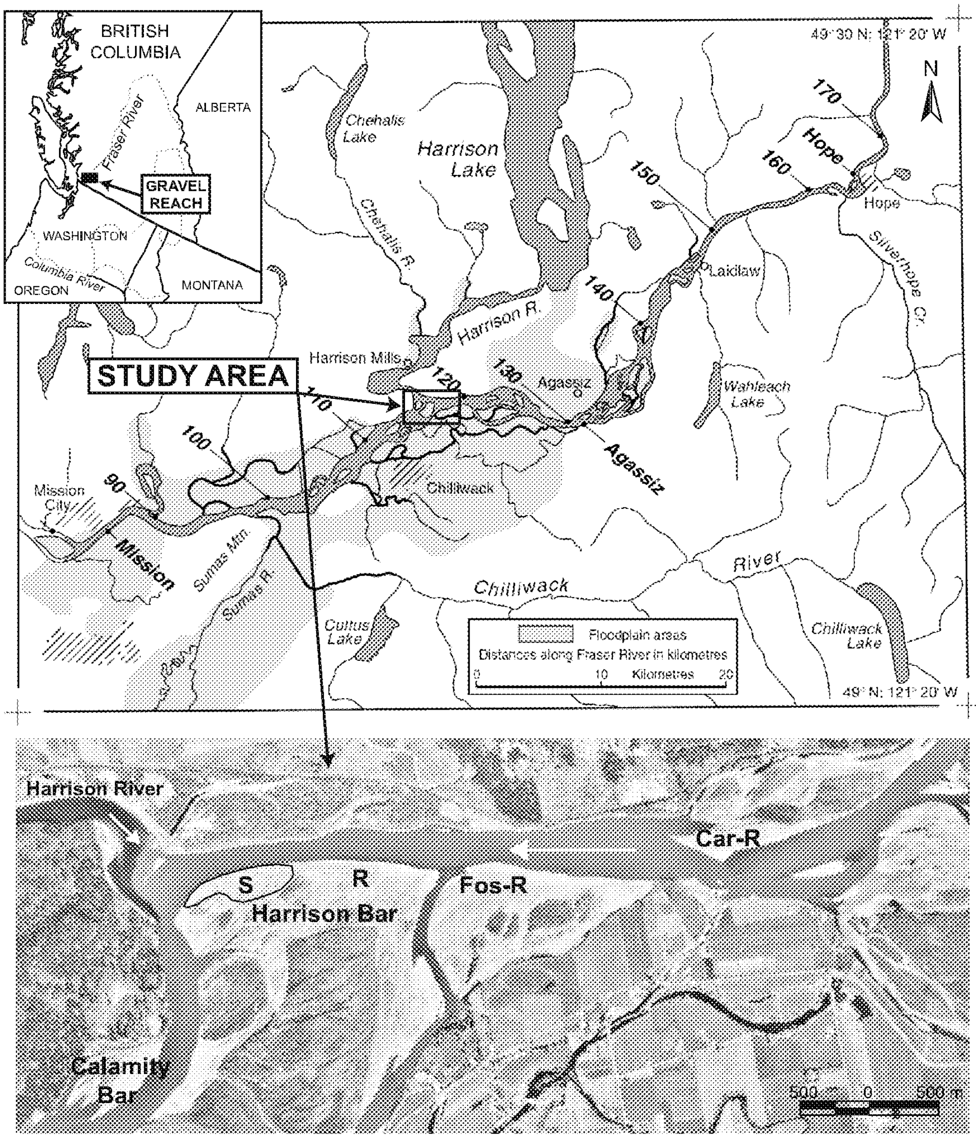
The lower Fraser River valley is also home to 2 million people, and with this concentration of people and investment, there is concern that annual gravel deposition is creating a flood risk. Gravel mining from within the main channel is proposed by river management agencies as a strategy to reduce flood risk, but concern over the potential impacts to fish habitat forced a moratorium on commercial mining from 1998 to 2004 to allow scientific studies to proceed. During the moratorium, one gravel removal (this study) was authorized to assess mining impacts on fish habitat and aquatic organisms.

Gravel mining

Gravel was removed by scalping 69 070 m^3 of dry sediment from lower Harrison Bar (Har-S) in early March 2000. The affected area represented 2% by volume and 15% by surface area of the nonvegetated Harrison Bar (Rice et al. 2008). The contractor followed normal industrial methods in accordance with Fisheries and Oceans Canada regulations. After completion, the site was graded to a 2% slope from the inner bar towards the main channel to ensure positive drainage and no fish stranding.

Upper Harrison Bar (Har-R), along with the lower halves of Carey Bar (Car-R) and Foster Bar (Fos-R), were designated reference sites (Fig. 1). The upstream proximity of reference sites to Har-S meant that they were unaffected by possible changes due to mining, but shared physical characteristics with respect to channel morphology, sediment transport regime, and substrate texture. Carey Bar has no prior history of gravel mining, but a site on Foster Bar located

Fig. 1. Location map of the Fraser River (British Columbia, Canada) gravel reach showing the study area, gravel mining site on Harrison Bar (S), and three upstream reference sites (Har-R, Fos-R, Car-R). Numbers indicate river kilometres measured from the mouth. Photograph taken 27 March 1999.

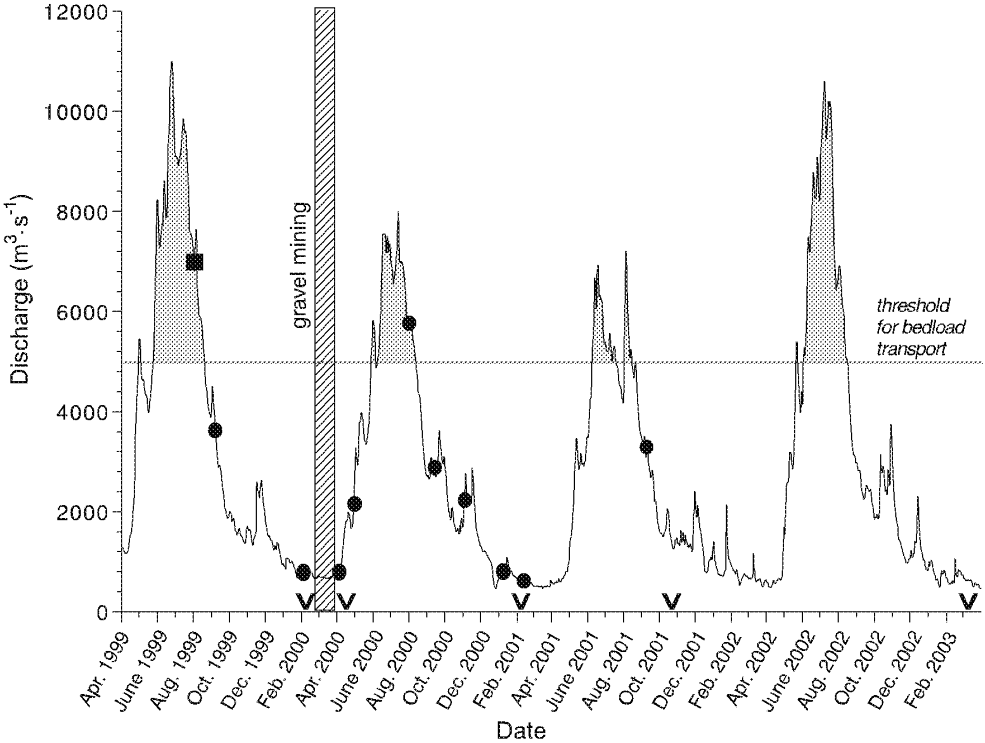


1 km upstream of Fos-R was mined in 1995. Herein, the term scalping is used interchangeably with mining and is defined as the removal by front-end loader of dry sediment from high-elevation areas of gravel bars.

Sampling schedule and design

Sampling began in August 1999 (Fig. 2) as part of a larger study examining the ecology of lower Fraser River. The experimental removal was not then anticipated and preremoval sampling effort was unequal among reference sites. Mining at Har-S occurred in March 2000 at low flow and sampling after mining extended over 18 months, during which time spring flooding occurred twice. It was only during these annual flood events that any gravel replenishment and habitat recovery at Har-S could take place. Fish sampling at Har-S and the reference sites occurred three times before (August and September 1999, February 2000) and eight times after (April, May, August, September, and November 2000; January, February, and October 2001) mining. Invertebrate sampling occurred twice before (September 1999 and February 2000) and the same eight times after mining. The sampling schedule was designed, within the

Fig. 2. Sampling and topographic survey dates of our study in relation to river discharge measured at Hope, British Columbia (square, fish sampling only; circles, fish and invertebrate sampling; **v**, topographic survey). Substantial bedload gravel transport occurs at >5000 $m^3 \cdot s^{-1}$. The date that gravel mining commenced is indicated.



constraints of an imposed planning timeline, to coincide with the timing of key life cycle stages of juvenile fish and invertebrates.

Sampling followed a modified BACI design (before–after control–impact; Stewart-Oaten et al. 1986) with three reference sites rather than a single control site. Including three reference sites leads to an asymmetrical analysis of variance (A-ANOVA; Underwood 1992, 1994, 1997), in which sources of environmental variance are assessed from observations at the multiple reference sites. This statistical design was specifically developed to assess the effects of major anthropogenic treatments in naturally variable systems, which are not often replicated.

A-ANOVA requires multiple reference sites for spatial replication and multiple sampling episodes before and after treatment for temporal replication. Only the reference condition is replicated; hence, the asymmetry. In our study, the difference between Har-S and reference sites prior to mining provided an estimate of the variability in possible outcomes after mining had the removal not occurred, thus making it possible to ascertain what a significant change at Har-S might be. A significant effect was defined as a detectable difference (negative or positive) in the change of measured parameters at Har-S from before to after mining compared with changes from before to after at the reference sites. Thus, a statistical interaction in the difference between Har-S and reference sites from before to after mining was required for the effect of gravel mining to be significant. This modified BACI design allowed for natural differences between the reference sites and Har-S and for changes during the before and after periods that influenced all sites in the same way. The practical mechanics of A-ANOVA are detailed in Underwood (1993) and described briefly herein to facilitate the reporting and interpretation of results for our study.

A series of questions are specified (Fig. 3), which are answered by up to five standard ANOVAs designed to determine if a detectable effect due to gravel mining at Har-S had occurred. Together, the ANOVAs systematically isolate the variance contributed by Har-S, before and after mining, from the total variance in the observations. SYSTAT (version 9.0, SPSS Inc., Chicago, Illinois) was used for the analyses. A-ANOVA was then calculated by subtractions and additions of the component sums of squares. We chose a critical value of $p = 0.05$ as a compromise between inflating the risk of a type I error by performing multiple analyses on the same data set and wanting to ensure that any real effect was detected. Power was estimated following Underwood (1993) for each analysis that failed to detect a significant impact.

If a significant temporal interaction is detected among reference sites after mining (Fig. 3, 1-Yes), the test in step 2 for a different temporal pattern at Har-S is less sensitive (fewer degrees of freedom in the denominator). This condition indicates large natural variation among reference sites over time, and an impact may need to be large to be detect-

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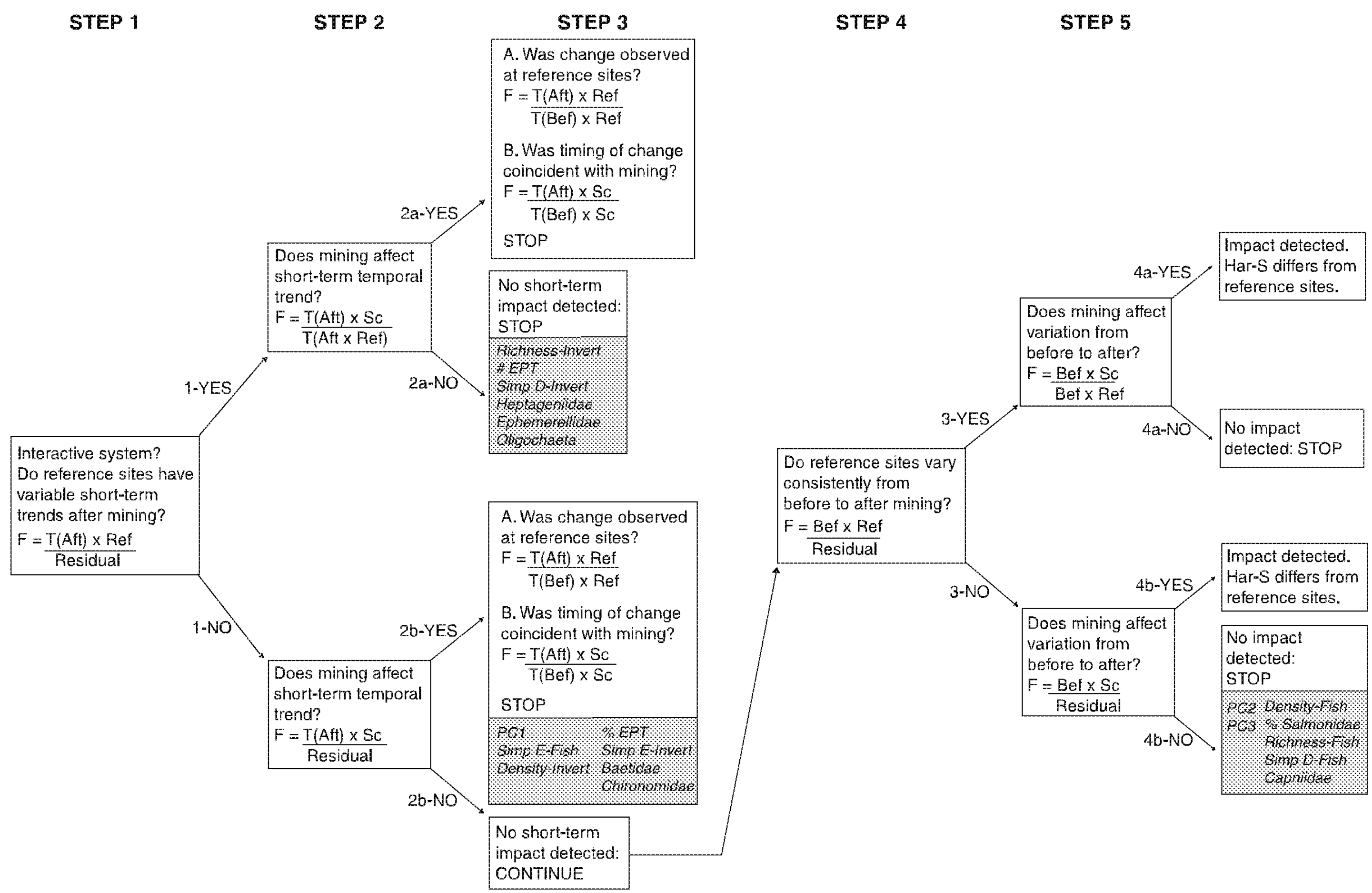
Fig. 3. Sequence of questions and statistical tests for asymmetrical analysis of variance (A-ANOVA) to determine if effects of mining at Har-S were significant (Underwood 1993). The question in each box is answered by a standard ANOVA; for example, the *F* value in step 1 equals the mean-square estimate of the interaction among reference sites after mining divided by the mean-square estimate of the residual (T, time; Aft, after mining; Bef, before mining; Ref, reference sites; Sc, scalping at Har-S; EPT, Ephemeroptera, Plecoptera, and Tricoptera; Simp D, Simpson's diversity; Simp E, Simpson's evenness; PC, principal component). Shaded boxes indicate the endpoints of statistical tests for the parameters examined in our study.



able (Underwood 1993). The most rigorous test for impact is available when the temporal interaction among reference sites is nonsignificant after mining (1-No) and an interaction between Har-S and the reference sites is not detected (2b-No). A detectable impact then produces an interaction in the difference between Har-S and the reference sites before mining compared with after mining (steps 4 and 5).

A short-term interaction between Har-S and reference sites (2a-Yes or 2b-Yes) implies that the temporal trend at Har-S falls outside that found at the reference sites. Accordingly, there must be no change in the interaction from before to after mining among the reference sites (step 3A), and the change in this temporal interaction must be coincident with mining (step 3B). Indeterminate results are produced when variance is large relative to the number of pretreatment sampling episodes. In such cases, we then examined the data graphically, depicted as normal-transformed variables to reflect the scale on which statistical analyses are based, for causal inference.

Juvenile fish

Juvenile fish were collected using a beach seine net (12.5 m × 2 m, 6 mm mesh) to compare the assemblage of species between sites over time. All fish were identified to species, measured (mm), weighed (g), and then promptly released. Each seine haul constituted a sample, and seine hauls were carried out within all habitat units present at each site based on the classification for gravel-bed rivers of Church et al. (2000). This classification recognizes seven habitat types associated with gravel bars: bar head, bar edge, bar tail, eddy pool, open nook, channel nook, and bay. In the gravel reach, these habitats occur at a scale of 10–100 m in perimeter. Habitat-specific sampling effort varied between sites and dates based on habitat unit presence, despite intentions to sample from all habitats on each date. Only bar edge habitat was sampled at all sites on all dates; it is the dominant habitat in the gravel reach and is defined as shallow-sloping (<5°) gravel bar edge oriented parallel to the flow and subject to constant and consistent flow forces of moderate velocity ($<50\ cm \cdot s^{-1}$).

We examined five fish community metrics separately using A-ANOVA at two spatial scales: the bar-scale (seines from all habitat types pooled) and habitat-scale (bar edge seines only). Analyzing data at both spatial scales allowed us to examine to what physical scale the ecological response best corresponded and to accommodate the dilemma that bar-scale analysis pools habitat-specific variability, whereas habitat-scale analysis reduces sample size. The following metrics were included after transformation to meet assumptions of normality and homogeneity of variance: log density ($number \cdot 10\ m^{-2}$), % salmonids (arcsine-transformed), species richness, Simpson's diversity, and Simpson's evenness (no transformation).

Because the experimental gravel removal was not anticipated when sampling began, data collection was incomplete for ANOVA requirements at some reference sites. Following Underwood (1997), "dummy values" were substituted for missing data (1% of bar-scale cases, 5% of habitat-scale cases) by using the mean of the other reference sites on that date. The residual degrees of freedom were adjusted to compensate for missing values.

Benthic invertebrates

Three replicate invertebrate samples were collected using a Surber net (500 µm mesh, 0.09 m^2) at each site within habitats with flow (riffle, bar head, bar edge, bar tail). Sampling effort varied between months because habitat availability changed as water levels fluctuated. Samples were field-preserved in 4% formalin and wet-sieved (250 µm mesh) in the laboratory for sorting and identification. No subsampling occurred. Mayflies, stoneflies, and caddisflies were identified to genus; dipterans to either family or subfamily (Chironomidae); beetles and true bugs to family; oligochaetes, leeches, crustaceans, and mites to class; and nematodes to phylum.

We examined six invertebrate community metrics separately using A-ANOVA both at the bar (all habitats pooled) and habitat scale (bar edge only). The following metrics were included after transformation to meet assumptions of normality and homogeneity of variance: log density ($number \cdot m^{-2}$), % EPT (Ephemeroptera, Plecoptera, and Tricoptera, arcsine-transformed), total and EPT richness, Simpson's diversity, and log Simpson's evenness. We replaced missing data with dummy values following Underwood (1997) for three cases of missing data (1.5% of habitat-scale cases) at reference sites before mining. The residual degrees of freedom were adjusted accordingly.

Densities of common taxonomic families (each representing >1% of invertebrates collected) were compared between sites before and after mining using A-ANOVA for insight into recolonization of a mined gravel bar. Six families met the 1% criterion: Baetidae, Heptageniidae, Ephemerellidae, Capniidae, Chironomidae, and Oligochaeta. Together, they represented 96% of invertebrates collected in our study. Densities were log-transformed prior to analysis to meet assumptions of normality and homogeneity of variance.

Habitat characteristics

Habitat characteristics were measured at all fish sampling sites. Water velocity and depth measurements were taken at nine points within the sampled area using a wading rod and Marsh–McBirney electromagnetic velocity meter. Surface sediment was visually classified for embeddedness and percent representation by major grain-size classes. The slope angle of the bank was calculated as the sine function of maximum sample depth divided by sample width.

Principal components analysis (PCA) was used to summarize total variation in the characteristics of bar edge habitat units and reduce the number of variables to an orthogonal, linear subset representing the dominant physical gradients. These PC axes were then used to examine habitat differences between Har-S and the reference sites before and after mining by considering the relation among all physical factors simultaneously. The following variables were included after transformation to meet assumptions of normality and homogeneity of variance: $\log_{10}$ bank angle, mean depth, maximum depth, mean velocity, maximum velocity, and the arcsine-transformed proportions of cobble, gravel, and sand. A-ANOVA was applied to each of the first three PC axes to determine if the physical characteristics of bar edge units changed as a result of gravel mining.

Sedimentology

Surface sediment samples were collected from the inner bar and water edge of Har-S and Har-R once before (February 2000) and three times after mining (April and September 2000, September 2001). Sampling followed either the Wolman or photographic technique (Church et al. 1987) to measure sediment size and sand coverage. Wolman samples consisted of 400 independently sampled stones and the size-frequency curve was plotted to determine median grain size (D_{50}) and the size of the coarse (D_{95}) sediment present. The photographic method was used only in September 2001 based on a calibration data set from the gravel reach (Rice et al. 2008), from which size percentile metrics were derived.

Single-factor ANOVA was used to compare surface sediment over time between samples collected before (February 2000) and on two dates after gravel mining (September 2000, 2001). Separate analyses were run for inner bar and water edge samples. Three parameters were examined after transformation to meet assumptions of normality and homogeneity of variance: arcsine-transformed proportion of sand and untransformed D_{50} and D_{95}. The critical value was adjusted by the Bonferroni method because multiple significance tests were performed on the same data (p = 0.05 divided by four contrasts = 0.0125).

No sampling occurred downstream of the removal area to examine sand deposition as a result of mining. Fine sediment is highly transient in the gravel reach, and considering an average 5.5 million tonnes of sand are transported through the reach each year (McLean et al. 1999), a change in sand content on downstream gravel bars would be undetectable.

Bar topography

Har-S was surveyed in February 2000 and immediately after scalping in March 2000 to determine the volume of gravel removed. The survey was repeated in February 2001, October 2001, and March 2003 to quantify bar-scale sediment recruitment to Har-S after each of three flood events and to measure habitat-scale topographic change. The extent of surveys after mining did not exactly match; thus, we examined the largest area common to all surveys and refer to it as Lower Harrison Bar. This area excluded the outer corner of Har-S but included a larger area of the inner bar to ensure that bar-scale changes in topography were captured.

Volumetric change between each survey of Lower Harrison Bar was estimated using the TOPOGRID (5 m grid spacing) and CUTFILL commands in Arc/Info Workstation (version 8.3, Environmental Systems Research Institute, Redlands, California). Habitat-scale topographic change was examined by creating hypsometric curves to relate bar surface area and elevation based on the TOPOGRID surfaces. Bar elevation was then related to river discharge by regression based on stage readings from a gauge at the mouth of Harrison River and commensurate discharge data at Hope to determine the amount of bar area exposed at high flows. This question was of interest because the lowering of bar surface elevation by scalping may reduce the availability of shallow, nearshore habitat for fish during flooding.

Potential effects of the removal on channel gradient and upstream–downstream changes to sediment supply were not evaluated in this study because they are considered to be negligible. Islam (2008), using the advanced morphodynamic simulation model MIKE21C, calculated that mining as much as 500 000 m^3 of sediment from Harrison Bar would induce a drop in water level, locally, of about 35 mm at the highest probable flood stage. This would affect local river gradient (400 $mm{\cdot}km^{-1}$) by less than 10% and have only a small influence on sediment transfer along the river, which would soon be neutralized by renewed deposition on the bar. In comparison, the experimental gravel removal under study was nearly an order of magnitude smaller (69 000 m^3). Water levels and sediment transfer at Harrison Bar are dominated by the hydraulic effect of the sharp channel bend opposite the Harrison River confluence (Fig. 1). Any gravel removal from the bar that does not cause channel realignment is apt to have water level and sedimentation effects that are practically impossible to measure.

Results

Juvenile fish

We report only on bar-scale analyses of fish data because A-ANOVA results were similar at the bar and habitat scales, but the former had higher power to detect an effect when all habitat types were pooled (242 total seines versus 124 seines in bar edge units). A total of 12 094 fish representing 24 species were captured by beach seine at all sites during our study. The number of beach seines differed each month (inset box, Fig. 4) because of varying habitat unit presence; fish sampling could not be conducted at flows > 5700 $m^3{\cdot}s^{-1}$.

Fish density varied among sites and seasonally, with highest density between April and September and lowest density in winter months (Fig. 4*a*). In all months after mining except February and August 2001, density at Har-S was equal to or greater than the average density at reference sites (Fig. 4*a*), and no significant effect due to scalping was detected (Table 1).

Species richness was low in winter at all sites compared with spring and summer (Fig. 4*b*). At Har-S, richness was higher than or within the range of values at reference sites in all months except August 1999 before mining and September 2000 and August 2001 after removal (Fig. 4*b*). No effect due to bar scalping could be confirmed, and statistical power was moderate (Table 1).

The proportion of Salmonidae at Har-S was lower than that at reference sites in most months of the study, both before and in the first year after scalping (Fig. 4*c*). The exception was May 2000 when Chinook salmon abundance at Har-S was high. One year after scalping in 2001, the proportion of salmonid species at Har-S was similar to that at reference sites, and no effect due to scalping was detected (Table 1).

Simpson's diversity was lower at Har-S than at reference sites in summer 1999 before scalping and remained lower immediately after scalping in April and May 2000 (Fig. 4*d*). In all periods after August 2000, Har-S samples had diversity similar to that at reference sites, and no effect due to bar scalping was detected (Table 1).

Simpson's evenness was higher at Har-S in August 1999, 2000, and 2001 compared with reference sites, but varied considerably in the intervening periods (Fig. 4*e*). A signifi-

Fig. 4. Average (± standard error) fish metric values at Har-S and reference sites before and after mining (diamonds, Har-S; circles, Car-R; triangles, Fos-R; squares, Har-R). The date that gravel mining commenced is indicated with a vertical broken line. Lines joining symbols connect sampling episodes and are not meant to represent a trend in the intersampling period. The number of beach seines in each month is indicated in the box.

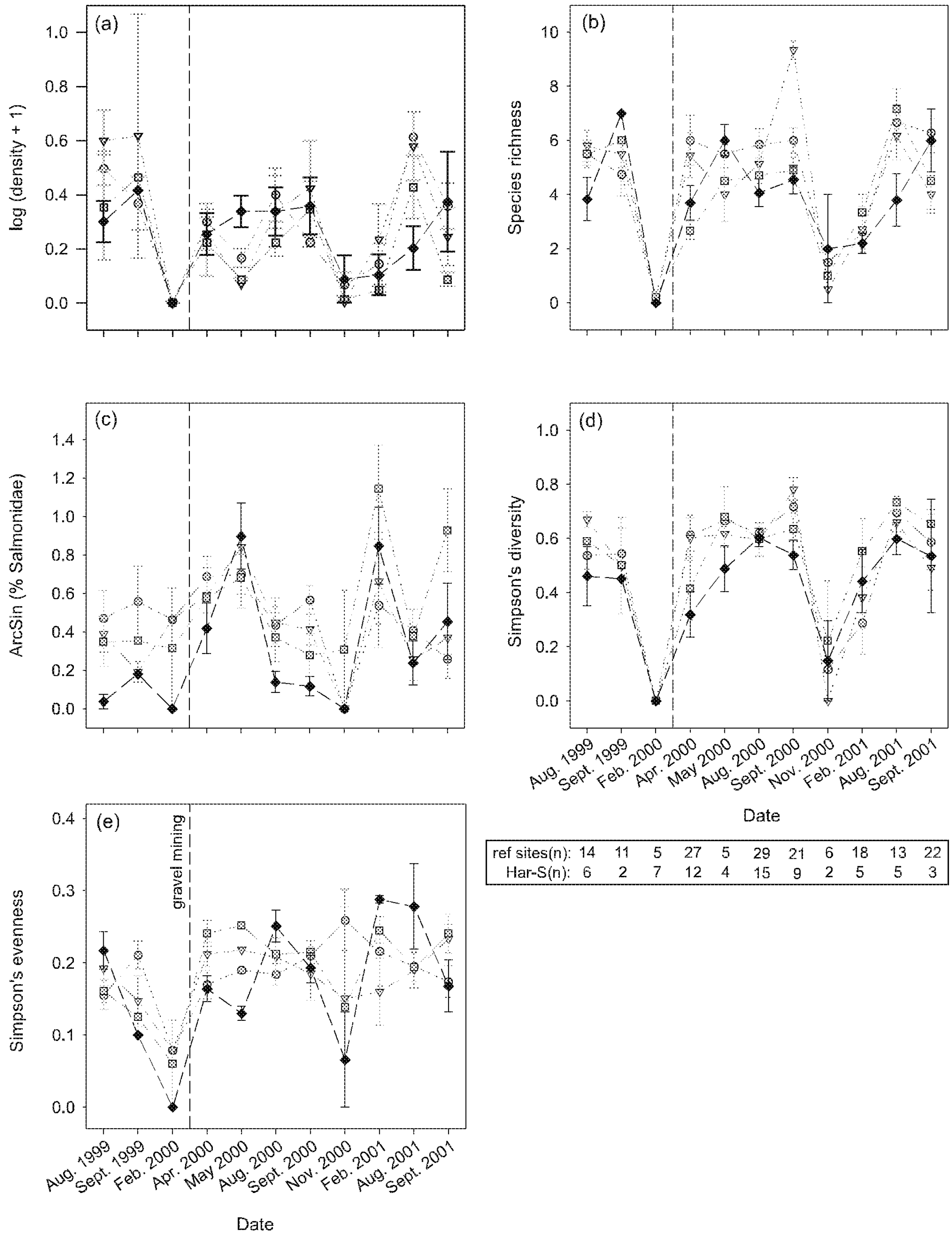


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Table 1. Asymmetrical analysis of variance (A-ANOVA) results examining gravel mining impacts at Har-S on fish community metrics (all habitats combined).

Variable	Step 1: Do reference sites have variable short-term trends after mining?	Step 2: Does mining affect short-term temporal trend?	Step 3A: Was change observed at reference sites?	Step 3B: Was timing of change coincident with mining?	Step 4: Do reference sites vary consistently from before to after mining?	Step 5: Does mining affect variation from before to after?	Conclusion	p value	Power
Density	No	No	→	→	No	No	No effect detected	0.37	0.18
	No	No	→	→	No	No	No effect detected	0.68	0.37
	No	No	→	→	No	No	No effect detected	0.27	0.08
	No	No	→	→	No	No	No effect detected	0.49	0.26
	No	Yes	Yes	No	—	—	Inadequate degrees of freedom to confirm an effect due to mining	<0.001	—

Note: Refer to Fig. 3 for flowchart showing steps and details of A-ANOVA.

cant temporal interaction between Har-S and reference sites after mining was detected, but the analysis had inadequate power to attribute mining as the cause (Table 1). Graphical examination was not informative in this regard.

Benthic invertebrates

We report only on habitat-scale analyses of invertebrate data because A-ANOVA results were identical at the bar and habitat scales, but the latter had higher power to detect an impact. Invertebrate density varied seasonally at all sites, and February samples contained more than four times the density of animals in August and September (Fig. 5*a*). Year-to-year variability was evident as well. Mean density at Har-S was similar to that at reference sites before mining but lower in May and August 2000 when samples were collected within the removal boundary and from sediment directly disturbed by scalping. A-ANOVA detected a significant temporal interaction among reference sites after mining (Table 2) but lacked statistical power to attribute mining as the cause. The short-term difference detected by A-ANOVA was more likely higher density at Har-S in January 2001 compared with reference sites (Fig. 5). On all dates after August 2000, density at Har-S was higher than the average of reference sites (Fig. 5*a*).

The proportion of EPT was highest in samples from Har-S before scalping, and values remained higher than at reference sites immediately after scalping in April 2000 (Fig. 5*b*). The proportion of EPT at Har-S in all subsequent months was within the range observed at reference sites, and differences between sites were small (Fig. 5*b*). A-ANOVA detected a significant change at Har-S (Table 2), which graphical examination suggested was the positive difference in April 2000.

Both total richness and the number of EPT taxa followed a seasonal cycle similar to density, being highest in winter samples collected between November and February (Figs. 5*c*, 5*d*). Har-S had higher values than the average at reference sites both before and one year after scalping. The lower number of EPT taxa at Har-S in May and August 2000 samples was not statistically significant, and no effect due to scalping was detected for either metric (Table 2).

Simpson's diversity was highest at Har-S prior to scalping but low relative to reference sites in April 2000 when a high proportion of *Ameletus* sp. was collected (Fig. 5*e*). Between May and November 2000, diversity at Har-S was higher than the average of reference sites (Fig. 5*e*) but was lowest in January 2001 when Chironomidae and Baetidae dominated Har-S samples. These differences between Har-S and reference sites were not significant (Table 2).

Simpson's evenness was highest in months immediately after scalping at most sites, including Har-S, and lowest in winter months (Fig. 5*f*). The numerical dominance of Orthocladiinae contributed to low evenness values in February of both years at all sites. A-ANOVA revealed a short-term change at Har-S (Table 2) that likely corresponded with January 2001 samples having notably lower evenness than all reference sites (Fig. 5*f*).

Baetidae abundance at Har-S was approximately equal to or higher than the average at reference sites in all months after mining (Fig. 6*a*). Whereas abundance declined between November 2000 and February 2001 at reference sites, it in-

Fig. 5. Average (± standard error) invertebrate metric values at Har-S and reference sites before and after mining (diamonds, Har-S; circles, Car-R; triangles, Fos-R; squares, Har-R). The date that gravel mining commenced is indicated with a vertical broken line. Lines joining symbols connect successive sampling episodes and are not meant to represent a trend in the intersampling period. EPT indicates Ephemeroptera, Plecoptera, and Tricoptera.

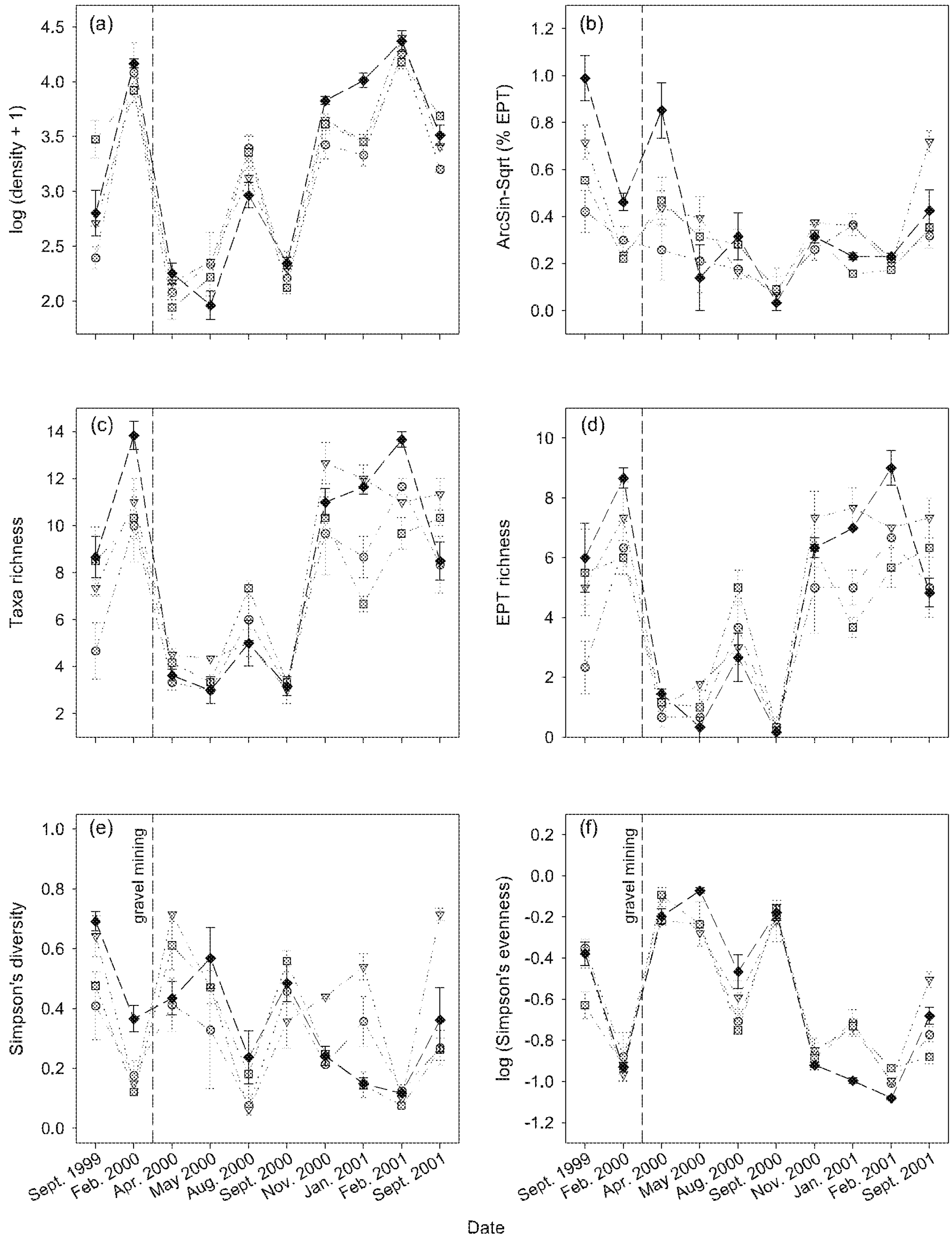

Table 2. Asymmetrical analysis of variance (A-ANOVA) results examining gravel mining impacts at Har-S on invertebrate community metrics (bar edge habitat only).

Variable	Step 1: Do reference sites have variable short-term trends after mining?	Step 2: Does mining affect short-term temporal trend?	Step 3A: Was change observed at reference sites?	Step 3B: Was timing of change coincident with mining?	Step 4: Do reference sites vary consistently from before to after mining?	Step 5: Does mining affect variation from before to after?	Conclusion	*p* value	Power
Density	No	Yes	No	No	—	—	Inadequate degrees of freedom to confirm an effect due to mining	<0.001	—
% EPT*	No	Yes	No	No	—	—	Inadequate degrees of freedom to confirm an effect due to mining	<0.001	—
Taxon richness	Yes	No	—	—	—	—	No short-term effect detected	0.39	0.54
EPT richness	Yes	No	—	—	—	—	No short-term effect detected	0.21	0.67
Simpson's diversity	Yes	No	—	—	—	—	No short-term effect detected	0.35	0.62
Simpson's evenness	No	Yes	No	No	—	—	Inadequate degrees of freedom to confirm an effect due to mining	<0.001	—

Note: Refer to Fig. 3 for flowchart showing steps and details of A-ANOVA.
*EPT: Ephemeroptera, Plecoptera, Tricoptera.

creased at Har-S. Notably higher abundance at Har-S compared with reference sites in January 2001 (Fig. 6*a*) likely explains the statistically significant A-ANOVA results (Table 3).

Chironomids (mostly Orthocladiinae) were the most abundant taxon in most samples on all dates. A significant short-term interaction between Har-S and the reference sites is detected (Table 3), but only in January 2001 did abundance at Har-S fall outside, and above, values observed at reference sites (Fig. 6*b*).

Capniidae is the only taxonomic group for which the temporal trend was consistent among reference sites after mining, and no short-term interaction between Har-S and the reference sites was found (Table 3). This allowed for more rigorous impact assessment and no significant effect due to mining was detected. Capniidae abundance was highest in winter months at all sites (Fig. 6*c*).

Patterns of abundance were similar for Heptageniidae and Ephemerellidae families (Figs. 6*d*, 6*e*). Whereas Har-S had higher relative abundance in the summer prior to mining, the families were uncommon at both Har-S and reference sites in spring and summer after removal. Abundance was variable among sites in the winter following mining, but Har-S was generally similar to or higher than the average of reference sites during this period. No significant short-term effect at Har-S was detected for either taxon (Table 3).

Oligochaeta (mostly Naididae and Tubificidae) abundance was the most variable among sites of all families examined (Fig. 6*f*). On most dates after mining, abundance at Har-S was similar to or exceeded values at reference sites, and power to detect an impact was high (Table 3).

Habitat characteristics

Bar edge habitat dominated both Har-S and Har-R prior to mining, and individual units were up to 500 m in length. Increased topographic complexity as a result of flooding in the 3 years after scalping reduced the length of individual bar edge habitat units and increased the variety of habitat types overall.

PCA applied to bar edge habitat characteristics at Har-S and the three reference sites accounted for 90.5% of the total variation in the first three PC axes (Table 4). PC1 explained 44.3% of the variation and represented a hydraulic gradient of increasing water depth, velocity, and bank angle. PC2 and PC3 represented gradients of coarse and fine sediment, respectively. There was a seasonal shift along PC1 at Har-S relative to reference sites from shallow and lower velocity conditions in summer months to deeper and faster-flowing water in winter (Fig. 7). The shift was observed over three summers of sampling, and May 2000 PC1 scores for Har-S fell outside the values for reference sites. A-ANOVA found a significant short-term change in this hydraulic gradient at Har-S (Table 5), and graphical examination supports mining as the cause (Fig. 7). PC2 and PC3 values were similar among sites on all dates before and after scalping.

Sedimentology

Surface sediment texture (D_{50}, D_{95}) prior to mining was similar at Har-S and Har-R (Fig. 8) and became finer from the water edge toward the inner bar. Average sand cover

Fig. 6. Average (± standard error) density of common invertebrate taxa at Har-S and reference sites before and after mining (diamonds, Har-S; circles, Car-R; triangles, Fos-R; squares, Har-R). The date that gravel mining commenced is indicated with a vertical broken line. Lines joining symbols connect sampling episodes and are not meant to represent a trend in the intersampling period.

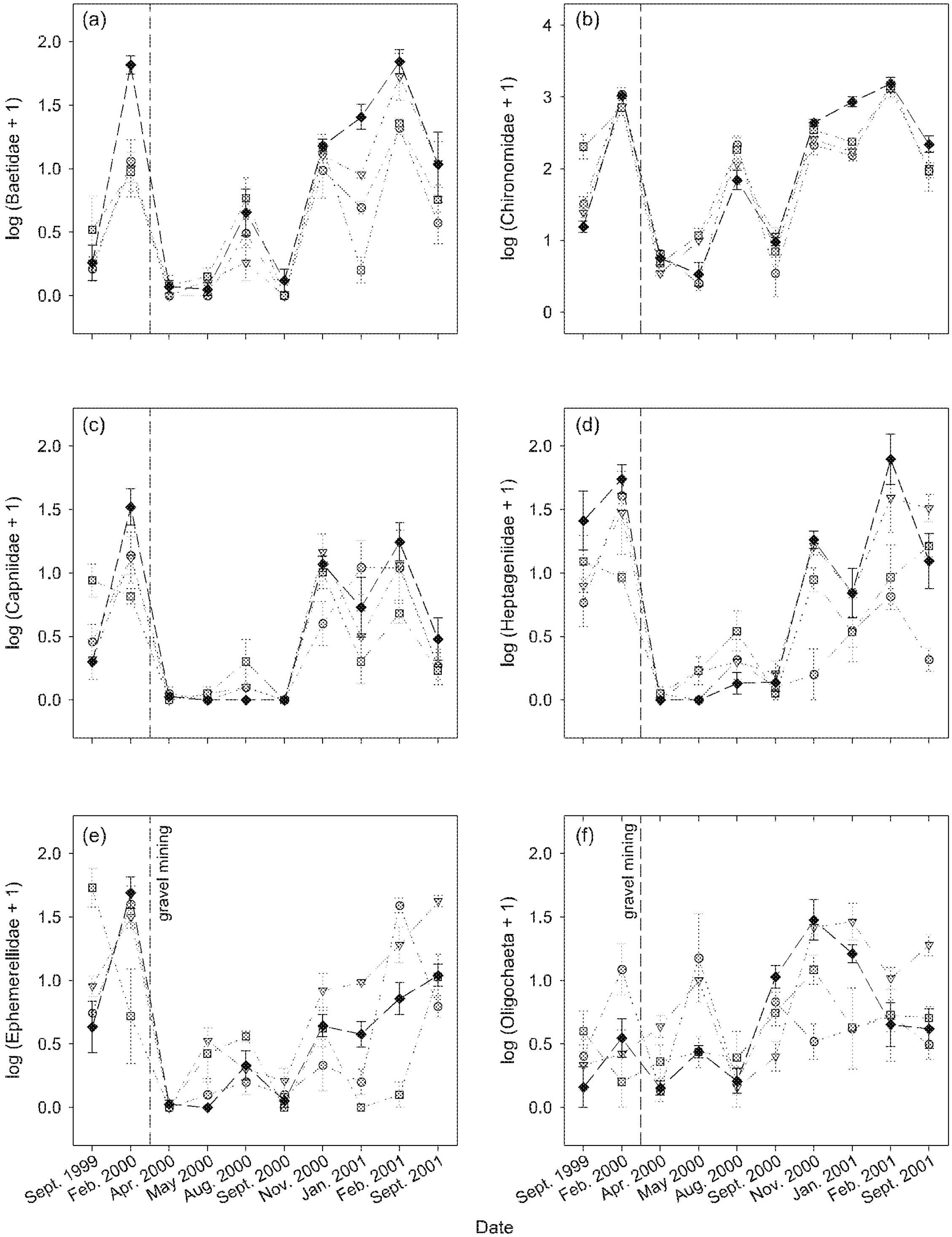

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Table 3. Asymmetrical analysis of variance (A-ANOVA) results examining gravel mining impacts at Har-S on common invertebrate family densities.

Variable	Step 1: Do reference sites have variable short-term trends after mining?	Step 2: Does mining affect short-term temporal trend?	Step 3A: Was change observed at reference sites?	Step 3B: Was timing of change coincident with mining?	Step 4: Do reference sites vary in difference from before to after mining?	Step 5: Does mining affect differences from before to after?	Conclusion	p value	Power
Baetidae	No	Yes	No	No	—	—	Inadequate degrees of freedom to confirm an effect due to mining	0.03	—
Chironomidae	No	Yes	No	No	—	—	Inadequate degrees of freedom to confirm an effect due to mining	<0.001	—
Capniidae	No	No	→	→	No	No	No effect detected	0.71	0.07
Heptageniidae	Yes	No	—	—	—	—	No short-term effect detected	0.29	0.79
Ephemerellidae	Yes	No	—	—	—	—	No short-term effect detected	0.98	0.15
Oligochaeta	Yes	No	—	—	—	—	No short-term effect detected	0.40	0.81

Note: Refer to Fig. 3 for flowchart showing steps and details of A-ANOVA.

Table 4. Factor loadings from principal components analysis (PCA) of bar edge habitat units.

Variable	PC1	PC2	PC3
Cobble	–0.63	0.71*	–0.26
Gravel	0.29	–0.88*	–0.35
Sand	0.55	0.08	0.78*
Bank angle	–0.81*	–0.31	0.44
Average depth	–0.82*	–0.27	0.42
Average velocity	–0.73*	–0.26	–0.27
Eigenvalue	2.66	1.53	1.24
% variation explained	44.3	25.6	20.6

*Correlated with PC axis.

was relatively high at both Har-S (11%) and Har-R (17%) but locally variable. Immediately after scalping, Har-S had a higher proportion of sand, average D_{95} decreased from 66 to 39 mm, and average D_{50} decreased from 25 to 13 mm. After two below-average floods, the D_{50} at Har-S in September 2001 was nearly identical to the size before removal both along the water edge and inner bar. Average D_{95} was less than that before scalping at the water edge, but a reduction in size over this period was observed at Har-R as well. Sand content in both areas was lower in September 2001 than before scalping.

Single-factor ANOVA comparing values at Har-S over time showed that the inner bar had significantly higher sand content before scalping compared with both sampling dates after scalping (Table 6). The gravel fractions were similar in size before and after scalping.

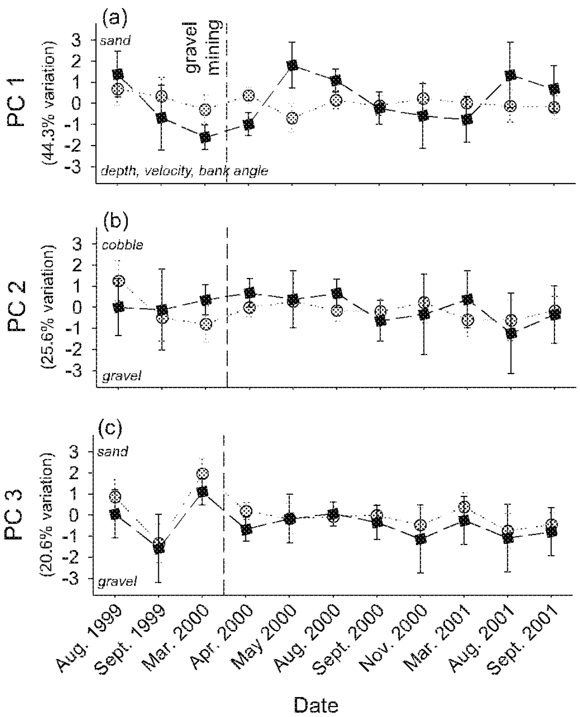
Bar topography

The topography of Lower Harrison Bar (the area commonly surveyed in all years) was simple prior to mining (Fig. 9*a*), and average and maximum surface elevations were 8.4 and 11.6 m, respectively (Table 7). Scalping removed 69 070 m^3 of sediment from within Har-S (62 232 m^3 from Lower Harrison Bar, the difference due to exclusion of the outer corner of Har-S) and left a low-gradient slope running from the inner bar to the water edge (Fig. 9*b*). The maximum vertical depth of extraction was nearly 2 m, and average surface elevation was reduced by approximately 1 m.

The modest 2000 and 2001 floods resulted in further net losses of 6635 and 1676 m^3 from Lower Harrison Bar, respectively (Table 8). There was, however, sediment exchange (erosion and deposition) over the bar in both years that filled the major area that had been reduced to <8 m elevation (Fig. 10) and increased topographic complexity at the habitat scale (Figs. 9*c* and 9*d*). A summer channel developed across the lower corner of the bar during flooding in 2000 (Fig. 9*c*) that had irregular geometry, high habitat diversity, and conveyed flow through October 2000 (discharge > 1500 $m^3 \cdot s^{-1}$). Sediment deposition by the 2001 flood cut off flow into the channel after September 2001 (discharge > 1800 $m^3 \cdot s^{-1}$), and in 2002 the channel carried flow through August (discharge > 2000 $m^3 \cdot s^{-1}$).

The large 2002 flood produced the most notable topographic change, depositing 27 630 m^3 of sediment. Comparing February 2000 and March 2003 surveys, there remained

Fig. 7. Mean factor scores (±95% confidence interval) for Har-S and reference sites derived from principal component analysis (PCA) of bar edge habitat characteristics (squares, Har-S; circles, reference sites). Variables most highly correlated with each axis are indicated in each panel. The date that gravel mining commenced is indicated with a vertical broken line. Lines joining symbols connect sampling episodes and are not meant to represent a trend in the intersampling period.



a net loss of 42 913 m^3 over Lower Harrison Bar (Table 8). With 62 232 m^3 removed from this same area, 31% was replenished by the 2002 flood to restore average bar elevation to within 10 cm of the surface before scalping (Table 7). Comparing these two surveys also reveals the extent to which topographic complexity increased across Lower Harrison Bar from before to after mining (Figs. 9*a*, 9*e*). Based on the relation between discharge (Q) and water surface elevation ($z = 0.0005Q + 6.55$, $r^2 = 0.98$), Lower Harrison Bar would have been submerged at a discharge of 10 100 $m^3 \cdot s^{-1}$ prior to mining compared with 10 900 $m^3 \cdot s^{-1}$ after the 2002 flood (maximum bar elevations of 11.6 and 12.0 m, respectively, Table 7).

Bar scalping resulted in a major shift in the elevation profile of Lower Harrison Bar that was partially reversed by flooding (Fig. 10). For example, the proportion of bar with >9 m elevation declined from 24% before scalping to 0% immediately after scalping and 18% after three flood events (Table 7). Hence, there remained a net 25% loss of bar area with >9 m elevation after the 2002 flood. Despite no long-term reduction in maximum surface elevation, this remaining deficit in high bar area, which provides shallow-water habitat for fish during flood, was notable (Table 7).

Table 5. Asymmetrical analysis of variance (A-ANOVA) results examining gravel mining impacts on the physical characteristics of bar edge habitat units at Har-S.

Variable	Step 1: Do reference sites have variable short-term trends after mining?	Step 2: Does mining affect short-term temporal trend?	Step 3A: Was change observed at reference sites?	Step 3B: Was timing of change coincident with mining?	Step 4: Do reference sites vary consistently from before to after mining?	Step 5: Does mining affect variation from before to after?	Conclusion	*p* value	Power
Hydraulic gradient (PC1)	No	Yes	No	No	—	—	Inadequate degrees of freedom to confirm an effect due to mining	<0.001	—
Coarse sediment gradient (PC2)	No	No	→	→	No	No	No effect detected	0.72	0.004
Fine sediment gradient (PC3)	No	No	→	→	No	No	No effect detected	0.48	0.04

Note: Refer to Fig. 3 for flowchart showing steps and details of A-ANOVA.

Fig. 8. Surface sediment characteristics (mean ± standard error) in the scalped (black symbols) and reference (grey symbols) areas of Harrison Bar before and after gravel mining along the water edge (circles) and inner bar (squares). The date that gravel mining commenced is indicated with a vertical broken line. Lines joining symbols connect sampling episodes and are not meant to represent a trend in the intersampling period.

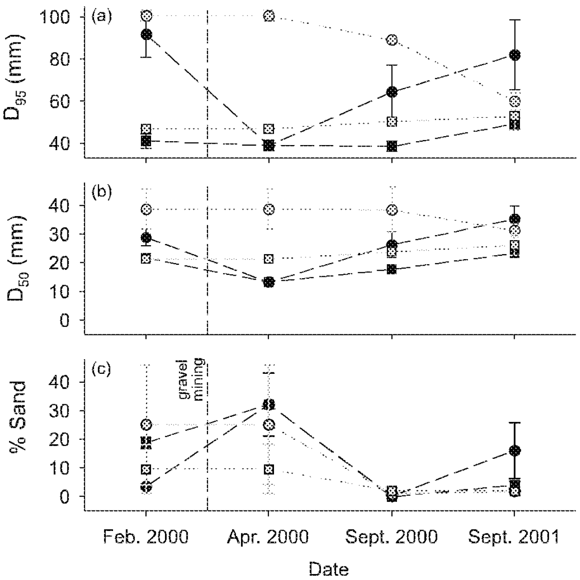


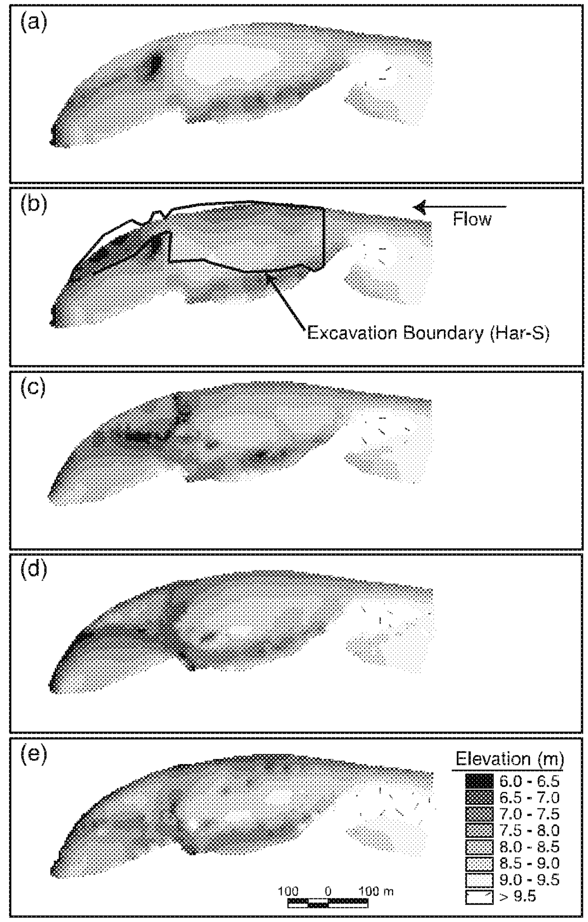
Table 6. Analysis of variance (ANOVA) results comparing surface sediment samples before and after gravel mining.

Parameter	df (residual)	MS (residual)	*F*	*p*
Water edge				
% sand	2 (3)	0.04 (0.05)	0.83	0.52
D_{50}	2 (3)	43.3 (57.8)	0.75	0.54
D_{95}	2 (3)	384.3 (724.9)	0.53	0.64
Inner bar				
% sand	2 (3)	0.1 (0.003)	33.31	0.009*
D_{50}	2 (3)	19.3 (11.5)	1.67	0.32
D_{95}	2 (3)	33.5 (40.2)	0.83	0.52

Note: D_{50}, median sediment size; D_{95}, coarse sediment size; df, degrees of freedom; MS, mean square.

*$p < 0.0125$, corrected by Bonferroni's method for multiple contrasts.

Fig. 9. The topography of Lower Harrison Bar before and on four dates after gravel mining: (*a*) Feb. 2000, (*b*) Mar. 2000, (*c*) Feb. 2001, (*d*) Oct. 2001, (*e*) Mar. 2003.



Discussion

Physical changes

Immediate physical changes to Harrison Bar as a result of gravel mining in March 2000 were substantial. Scalping removed 69 070 m^3 of sediment, and the pre-existing coarse and stable bar surface was replaced by an evenly graded area of loose gravel and sand. However, the dramatic change in sediment texture was short-lived, as flooding in 2000 transformed the loose and sandy substrate into a moderately coarse surface with negligible sand cover. Reduced sand cover over both the scalped and reference areas of Harrison Bar after flooding indicates that sand entrainment across the entire bar surface was high. These observations are consistent with the transient occurrence of sand in the gravel reach, and considering the 5.5 million tonnes of sand transported through the reach each year on average (McLean et al. 1999), sand transport from Har-S is believed not to have had a detectable or lasting impact on downstream habitats. Flooding in 2001 produced additional surface coarsening within the removal area, although the coarsest fraction (D_{95}) along the water edge remained smaller than that prior to mining.

Sedimentary changes at Har-S as a result of flooding occurred concurrently with volumetric and topographic changes. Modest flooding in 2000 and 2001 yielded no volumetric replenishment but resulted in minor rebuilding of high bar habitat and increased topographic complexity due to sediment exchange across the bar surface. In the gravel reach, topographic complexity begets habitat diversity, and the increased topographic complexity over Har-S after flooding in 2000 and 2001 resulted in higher habitat diversity at the site overall. Therefore some habitat-scale recov-

Table 7. Surface elevation characteristics of Lower Harrison Bar before and on multiple dates after gravel mining (area: 247 825 m^2).

		Elevation (m)			Elevation > 8 m*		Elevation > 9 m*	
Date	Period	Mean	Max.	Min.	Area (m^2)	%	Area (m^2)	%
Feb. 2000	Before scalp	8.4	11.6	5.7	175 725	71	58 925	24
Mar. 2000†	After scalp	7.2	9.7	5.5	9 775	4	<1 000	<1
Feb. 2001	After flood 1	8.1	10.9	6.1	135 900	55	35 300	14
Oct. 2001	After flood 2	8.1	11.9	5.8	136 950	55	38 250	15
Mar. 2003	After flood 3	8.3	12.0	5.6	141 250	57	44 750	18

Note: Lower Harrison Bar represents the area commonly included in all surveys after mining.

*The areas of bars with elevations >8 m and >9 m would remain exposed at discharges of 2960 and 4960 m^3·s^{-1}, respectively.

†Values for March 2000 are derived from within Har-S removal area rather than from Lower Harrison Bar.

Table 8. Volumetric (m^3, bulk volume) comparisons between surveys of Lower Harrison Bar.

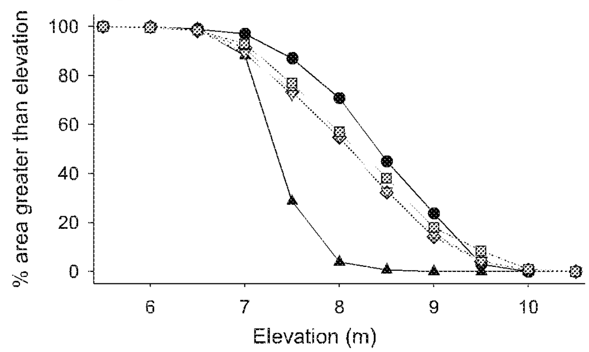
Survey contrasts	Erosion	Deposition	Net change
Feb. 2000 vs. Mar. 2000 (mining)	–63 881	+1 648*	–62 232†
Mar. 2000 vs. Feb. 2001 (2000 flood)	–47 476	+40 840	–6 635
Feb. 2001 vs. Oct. 2001 (2001 flood)	–28 414	+26 737	–1 676
Oct. 2001 vs. Mar. 2003 (2002 flood)	–23 348	+50 978	+27 630
Feb. 2000 vs. Mar. 2003	–81 317	+38 400	–42 913

Note: Lower Harrison Bar represents the area commonly included in all surveys after mining and excludes the downstream, outer corner of Har-S (see Fig. 9*b*).

*Minor deposition due to a sediment berm left by the contractor at the downstream end of Har-S.

†Discrepancy with reported volume of 69 070 m^3 due to exclusion of the downstream corner of Har-S in the survey comparison.

Fig. 10. Area–elevation relation of Lower Harrison Bar based on topographic surface modeling (circles, Feb. 2000; upright black triangles, Mar. 2000; diamonds, Feb. 2001; reverse grey triangles, Oct. 2001; squares, Mar. 2003).



ery occurred in these two low-flood years despite the fact that bar-scale recovery in sediment volume did not. In 2002, above-average flooding replenished 31% of the scalped volume and restored average bar surface elevation to within 10 cm of the average before mining. Maximum bar elevation exceeded the level before scalping by 35 cm. These findings demonstrate that vertical bar growth can proceed after gravel mining so long as an upstream supply of sediment is recruited to the site during high flow events.

Despite modest sediment replenishment and vertical bar growth over Lower Harrison Bar, the proportion of area at elevations > 9 m after the 2002 flood remained 25% smaller than that before mining. The loss of high bar habitat was most significant for flows > 5000 m^3·s^{-1}, generally from May through August, when these areas represent nearshore rearing habitat for juvenile fish. Habitat availability naturally decreases in summer months as flooding inundates gravel bars and low-lying islands. The reduction in high elevation bar area as a consequence of mining would have further reduced available rearing habitat during a period when it is already limiting for fish in the gravel reach (Perkins 2007). Only by comparing the area–elevation relation and then relating it to the specific range of flows over which fish might be affected was this impact to fish habitat identified.

The extent to which the effect of this high-bar habitat loss transmitted to fish populations remains uncertain. Fish species may have alternate strategies to cope with seasonal flooding in Fraser River, especially given the river's highly predictable hydrograph. Several studies of northern floodplain rivers have documented lateral shifts in the distribution of fish during high flow events (Sommer et al. 2001; King et al. 2003; Schwartz and Herricks 2005), with side channels becoming increasingly important. Flood predictability and duration are believed to be important factors influencing seasonal side channel use for spawning and rearing and as refugia from flooding (Galat et al. 1998; King et al. 2003). In Fraser River side channels, gillnet and minnow trap sampling during spring flooding consistently yielded high catch rates (L.L. Rempel, unpublished data), but comparable data during flooding from main channel and bar top habitats are not available.

The overall physical transformation of Har-S by flooding highlights the critical role of sediment transport for maintaining fish habitat in the gravel reach and in gravel-bed rivers in general. Even in the absence of gravel mining, bars undergo changes in sediment texture, topography, and volume on an annual basis that create habitat at a local scale and cause lateral instability at the bar scale (Rice et al. 2008). Sediment transport also is important for maintaining

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high-quality habitat by episodically reworking and cleaning the substrate (Milhous 1982; Resh et al. 1988; Kondolf and Wilcock 1996). Such fluvial processes and the relatively dynamic presence of habitat units characterize the natural state of the Fraser River gravel reach to which local populations of aquatic organisms are likely accustomed and which may habituate them to modest imposed disturbances.

Response by aquatic organisms

More than 12 000 fish representing 24 species were captured by beach seine during this study. Chinook salmon were numerically dominant and most commonly found in the main channel occupying bar edge habitat as well as eddy pools and channel nooks. The extensive use of the Fraser River by juvenile Chinook salmon has been documented previously (Brown et al. 1989; Levings and Lauzier 1991), but its dominant abundance year round in the gravel reach was a novel finding. Large numbers of juvenile Chinook were collected in the former removal area of Harrison Bar soon after mining in May 2000, but Chinook density and percent Salmonidae were lower at Har-S in most subsequent months.

Fish density, along with several other metrics characterizing the fish community, showed no detectable impact at Har-S as a result of mining over the range of flows sampled. The statistical analyses were relatively sensitive because reference sites varied in a consistent manner over time. Only Simpson's evenness changed significantly at Har-S relative to reference sites, but high variance among all sites over time prevented the analysis from confirming that the change was coincident with scalping. More generally, high spatial and temporal variance reduced statistical power overall and confounded our attempt to detect the effect of gravel mining on the fish community at Harrison Bar. A replicated study design, wherein gravel mining occurred at multiple sites, would have been more powerful and possibly generated more definitive results. However, this design was not possible given regulatory restrictions and the moratorium on gravel mining in place.

Benthic invertebrates have been used to examine the ecological response to habitat disturbance in numerous previous studies (e.g., Gurtz and Wallace 1984; McCabe and Gotelli 2000). In our study, benthic invertebrates recolonized Har-S immediately after mining as water inundated the site with the onset of flooding. Samples collected in April 2000 had above average density and included a high proportion of mayfly, stonefly, and caddisfly nymphs. Several of these taxa (e.g., *Ameletus* sp.) are highly mobile and have good swimming ability (Mackay 1992). These behavioral tactics are practical for survival in the gravel reach, where the water edge shifts laterally across the surface of gravel bars during flooding. The rapid colonization of Har-S is consistent with previous work in the gravel reach by Rempel et al. (1999), which showed invertebrates migrate laterally across undisturbed gravel bars with the rise and fall of water levels. Just as *Ameletus* sp. was found almost exclusively in April 2000 samples in this study, it was collected by Rempel et al. (1999) only in April.

In two subsequent sampling episodes after April 2000, invertebrate density at Har-S was lower than that at reference sites. Taxon and EPT richness were lower at Har-S during this period as well, though differences were not statistically significant. These May and August 2000 samples were collected from within the scalped boundary, and it was during this period of high discharge that the bar surface underwent the most dramatic change in sediment texture. The rate of sediment transport across Lower Harrison Bar was probably higher because of the loose material left by scalping (US ACE 1982), and these conditions may have deterred settlement by some taxa or crushed them. But just as sediment texture generally recovered by September 2000, invertebrate samples collected from Har-S in September 2000 and all months thereafter had higher density than the average of all reference sites.

Taxon richness, the number of EPT taxa, and Simpson's diversity each showed variable trends after mining at the reference sites, and no short-term effect at Har-S was detected. Statistical power was relatively high for these analyses despite temporal variability among reference sites. Metrics for which a short-term change was detected (density, % EPT, Simpson's evenness) had more consistent, though still high variance among reference sites after mining relative to those metrics showing no detectable impact. High variance generally characterizes the natural condition for Fraser River, and Underwood (1993) asserts that a significant temporal interaction among reference sites after treatment (i.e., mining) indicates that an impact would have to be large to be ecologically important. Otherwise, it falls within the natural range of variability encountered by populations and therefore should be within the community's capacity to recover.

The fact that virtually all community metrics and taxon-specific densities at Har-S were similar to or higher than those at reference sites after August 2000 implies that the scale of disturbance by a single gravel removal of modest size at Harrison Bar was within the system's capacity to recover. Moreover, aquatic organisms appeared most sensitive to habitat-scale effects of mining because community and taxon-specific metrics recovered soon after the first flood, coincident with the recovery of sediment texture and topographic variability. These habitat-scale physical changes persisted only into the first flood after mining, whereas bar-scale changes in volume and overall topographic distribution remained through at least three freshets. The statistical appearance that fish metrics were best evaluated at the bar-scale is an operational sampling issue related to high variance, which does not upset this conclusion. Our hypothesis that the ecological response to mining is mediated by annual flooding is therefore supported.

This finding, however, can provide a basis for ecologically sound management of gravel mining only up to a point. The experimental removal at Harrison Bar was situated in a reach of persistent sediment aggradation, and the removal volume constituted only a small fraction (approximately 30%) of mean annual sediment recruitment to the gravel reach of Fraser River. We recommend that an essential element of any river gravel management plan is for removal volumes to remain modest in comparison with natural rates of sediment recruitment to ensure that sediment transport processes remain intact. Larger removals may require years of sediment recruitment for recovery, with the potential loss of important bar-scale habitat, particularly high-bar rearing habitat, for periods exceeding the generation time of most aquatic organisms. The removal of 30% of the average annual recruitment rate was coincidentally similar to Kondolf et al.'s (2002) recommendation for limiting removals to 50% of the annual rate of sediment recruitment to reduce impacts on salmonid spawning habitat in Washington rivers. Implementing this recommendation requires knowledge of basin-scale processes of sediment recruitment and storage and reach-scale patterns of sediment erosion and deposition. These factors influence the system's response to disturbance and capacity for recovery and should be regarded as fundamental factors in the maintenance and management of fish habitat.

Sampling strategy and statistical power

Statistical power is a well-established concept being applied increasingly in studies when results have important implications for resource management (Peterman 1990). Power analysis is particularly useful when planning a study to determine the necessary sampling effort for a desired level of power or to solve for the minimum detectable effect size based on a predetermined sampling effort (Osenberg et al. 1994). In both applications, knowledge of the system's natural variance is required. Variance estimates from our study are useful in this regard for designing future habitat and fishery monitoring programs in the gravel reach of Fraser River.

Determining the most effective sampling strategy (i.e., that returns the most discriminating results without excessive effort) will ultimately depend on the temporal and spatial structure of variance in the data. Large variability in time and space characterized our data, and four exploratory analyses were carried out to evaluate how changes to our sampling strategy might have improved statistical power. The invertebrate metric taxon richness was chosen, and analyses consisted of (*i*) simulating a larger effect size in April 2000 by greatly reducing taxon richness at Har-S; (*ii*) adding a fourth reference site to the analysis (Calamity Bar was included in the sampling program but data were excluded from primary analyses because it is downstream of Har-S); and (*iii*) eliminating several after-mining sampling episodes. The fourth simulation used a hypothetical data set of Underwood (1993) in which we randomly eliminated two of four before-impact sampling episodes to evaluate if the ability of A-ANOVA to detect change was compromised by our unequal sampling episodes before and after mining.

Collectively, these simulations indicated that when spatial variability (i.e., bar to bar) is high, the addition of another reference site does not improve resolution greatly. An additional reference site will, however, improve power when the effect size is very large. Also, the addition of one or two sampling episodes may not greatly increase resolution when there is high temporal variability. In such cases, it is more effective to increase sample replication at all sites to improve as much as possible the estimates of mean values, thereby improving the ability of the analysis to discriminate among them. Lastly, statistical power is virtually unaffected by an unbalanced sampling design compared with the effect of variance in the data set. Hence, our study was not fatally weakened by its unbalanced design. A greater number of sampling episodes prior to mining would have improved estimates of the natural variance, thereby increasing statistical power to detect an impact. Of course, such insights can only be drawn once knowledge of the system's natural variance has been gained. Because a replicated and balanced design is often not realistic for real world, anthropogenic treatments, Underwood's (1992, 1994, 1997) A-ANOVA presents an alternative statistical design for such cases. Our chosen analysis was as rigorous as the data allowed.

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