The Geomorphic Influence of Agricultural Land Use on Stream Hydraulics and Biological Function

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Abstract

Agricultural land use near streams frequently results in long-term disturbance to woody riparian vegetation and an alteration of reach scale geomorphic structure. Such disturbances often result in increased fine sediment input to the stream along with direct changes in channel structure. The study described here was designed to quantify stream geomorphic changes associated with agriculture and their influence on reach scale transient storage hydraulics and sediment biological function. Six small streams in the Appalachian Mountains of western North Carolina were selected to compare 3 reaches with active near-stream agriculture to 3 forested reference reaches. The study site categories differed significantly in many structural and hydraulic properties including slope, sinuosity, sediment size, and transient storage extent. However, differences cannot be attributed to land use alone. Distinct disparity in slope suggests that many of the categorical differences between stream types may also reflect valley scale structure. Despite these larger scale controls, the abundance of suspendable fines varied substantially among agricultural stream substrates, possibly due to varied land-use practices. Suspendable fine sediments and valley slope explained 91 % of variability in transient storage exchange, and abundance of inorganic fine sediments explained 77 % of variability in sediment microcosm nitrate production. This study supports conclusions that reach-scale influence of fine sediments occurred within the context of larger-scale valley structure, with implications on stream hydraulics and biogeochemistry.

Dedication

To Mom, Dad, and family for understanding.

To Horton, Megan, Scott, Annette, and Toby for inspiration.

To the VT Stream Team for acceptance and support.

To Art and Mary for experience and livelihood.

Acknowledgements

I would like to thank Maury Valett for his patience and guidance and Jack Webster for time above and beyond the call of duty. Jim Spotila and Panos Diplas contributed a great deal of input and reviews that were very helpful. The Virginia Tech Stream Team provided the most stimulating research environment imaginable. Financial support and/or facilities were provided by the Virginia Tech Stream Team, Coweeta Long Term Ecological Research Facility, and friendly land-owners of Macon County, North Carolina.

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Introduction

Understanding the geomorphic influence of land use on stream ecosystems requires a properly scaled context of disturbance mechanisms (White and Pickett 1985, Frissell et al. 1986, Allan et al. 1997). In the southern Appalachian Mountains, non-forested land use can be predicted by landscape slope and elevation (Wear and Bolstad 1998), such that agricultural influence is generally limited to valley floors. Agricultural practices may represent a press disturbance (sensu Bender et al. 1984) to riparian and floodplain vegetation, in the sense that stream-side woody vegetation is removed and growth is suppressed through tilling, mowing, or livestock activity (National Research Council 1992). As a result, the stream-riparian system exists in a human-maintained steady-state. Other mechanisms of agricultural disturbance may include channel redirection, floodplain tiling or ditching, and enhanced bank erosion by livestock activity (National Research Council 1992). In this paper, I explore how these potential geomorphic changes affect the hydraulics and sediment biogeochemistry of small streams.

Many agricultural practices have resulted in increased fine-grained (i.e. sands, silts and clay particles < 2 mm) sediments, hereafter referred to as "fines", in stream substrates. Fines are considered a major non-point source of pollution in rivers of the United States, and agricultural sources include runoff from tilled landscapes and bank erosion (Waters 1995, Wood and Armitage 1997). Land use at sites of the current study included pastures and hay fields, and the landscape was not regularly tilled. If excess fines were present, local sources would likely be enhanced bank erosion due to livestock activity and lack of vegetative support (National Research Council 1992). Fines can influence stream ecosystems by clogging sediment interstices (Brunke and Gonser 1997), and can subsequently change hydraulics (Schälchli 1992, Packman and MacKay 2003) and biological function (Mulholland et al. 1997, Valett et al. 1997, Boulton et al. 1998).

The interstitial space of stream bed sediments, or hyporheic zone (sensu Hynes 1983), is a potential location for slower hydraulic flow paths that contribute to stream transient storage (i.e. zones of a stream where water flows significantly slower than average channel velocity, Bencala and Walters 1983). The retention of water in these flow paths is strongly influenced by hydraulic conductivity of the stream substrate (Morrice et al. 1997). There is evidence that suspended fines introduced to gravel substrates can produce a layer of clogging just below the mobile surficial gravel, or pavement layer (Diplas 1994). This clogged layer appears to significantly limit the stream bed hydraulic conductivity and reduce exchange of water between surface water and interstices (Schälchli 1992, Packman and MacKay 2003). If agricultural practices represent a source of fines to stream substrates, then the influence of interstitial clogging on hydraulics may be evident in streams with a history of riparian agricultural land use.

Hydraulic flow paths through sediments control the transport of biologically important solutes between stream subsystems of different biogeochemical potential (Triska et al. 1989, Mulholland et al. 1997, Valett et al. 1997, Boulton et al. 1998). Oxygen transported from the surface water is critical to the subsurface habitats of aerobic microbial communities. If oxygen and organic matter are available, nitrogen (N) in organic matter can be transformed to biologically available inorganic forms through mineralization to ammonium (NH_4^+) and subsequent nitrification to nitrate (NO_3^-) (Triska et al. 1993). As the flow path returns to the surface water, these nutrients are available to benthic communities where growth and other metabolic processes are frequently limited by N availability (Valett et al. 1994). In addition to changing sediment habitat and biological structure, introduction of fines can potentially change biological processes through limitation of solute transport between surface and subsurface waters (Valett et al. 1996).

The objective of this study was to explore how agricultural changes to geomorphic structure of southern Appalachian stream systems may affect transient storage hydraulics and sediment biological function. Three forested reference streams and three agricultural streams were selected in the Blue Ridge Physiographic Province of the southern Appalachian Mountains. Study design was based on two-tiered hypotheses regarding the characteristics of agricultural streams relative to forested streams. First, I expected less transient storage in agricultural streams because the presence of more fine sediments should reduce complexity in flow paths. Second, I expected different sediment biogeochemistry in agricultural streams because less transient storage results in less exchange of critical solutes with the stream channel. To test these predictions, I compared characteristics of channel morphology, transient storage hydraulics, sediment organic matter, and sediment nitrate production among the 6 study reaches.

Methods

Site description

Study sites were located near the Coweeta Hydrologic Laboratory in southwest North Carolina, USA (Figure 1). All reaches were selected from first or second order headwater streams of the Little Tennessee River and shared common valley bedrock dominated by meta-sandstones, schist, and gneiss. Study streams were categorized by land use based on riparian vegetation. Agricultural streams were characterized by field or pasture development near the stream resulting in lack of significant riparian woody vegetation. Forested streams were characterized by unrestricted woody vegetation growth and lack of evident agricultural land use in recent history. Forested study reaches probably reflect the influence of past logging (Elliott et al. 1999). However, it is unlikely that the effects are currently as evident as those from decades of land use near agricultural streams (Wood and Armitage 1997). Base-flow discharge varied somewhat within each land use category, but streams were purposefully selected to avoid significant differences between categories (Table 1).

Though all study sites met the general categorical criteria above, there was notable structural variability among the streams, particularly in agricultural streams. Hog Lot Creek had a potential source of fines unavailable to the other agricultural streams. This study reach was located on the floodplain of the Little Tennessee River at an elevation ca. 4 m higher than the river. Therefore, the creek is likely cutting through deposition of a lower-gradient, 6^{th}-order river, and the alluvial organization of this stream may be subject to influence of the Little Tennessee flood regime. On the other hand, Skeenah Creek, a second agricultural site, had 3 structural characteristics that may have reduced fine sediment sources. First, rip-rap stones supported the banks at some areas more vulnerable to erosion. Second, riparian trees were more prevalent than at other agricultural sites. Third, the channel traversed a hay field, making it the only agricultural reach not subject to the potential influence of livestock activity on bank erosion.

Differences in land use were not evident among forested streams, but some artificial structures were present. The channel of Jones Creek included small, man-made sediment retention structures, presumably for the creation of deep plunge pools and fish habitat. Low-gradient forested streams were selected to provide baseline geomorphic-hydraulic conditions most similar to the agricultural streams.

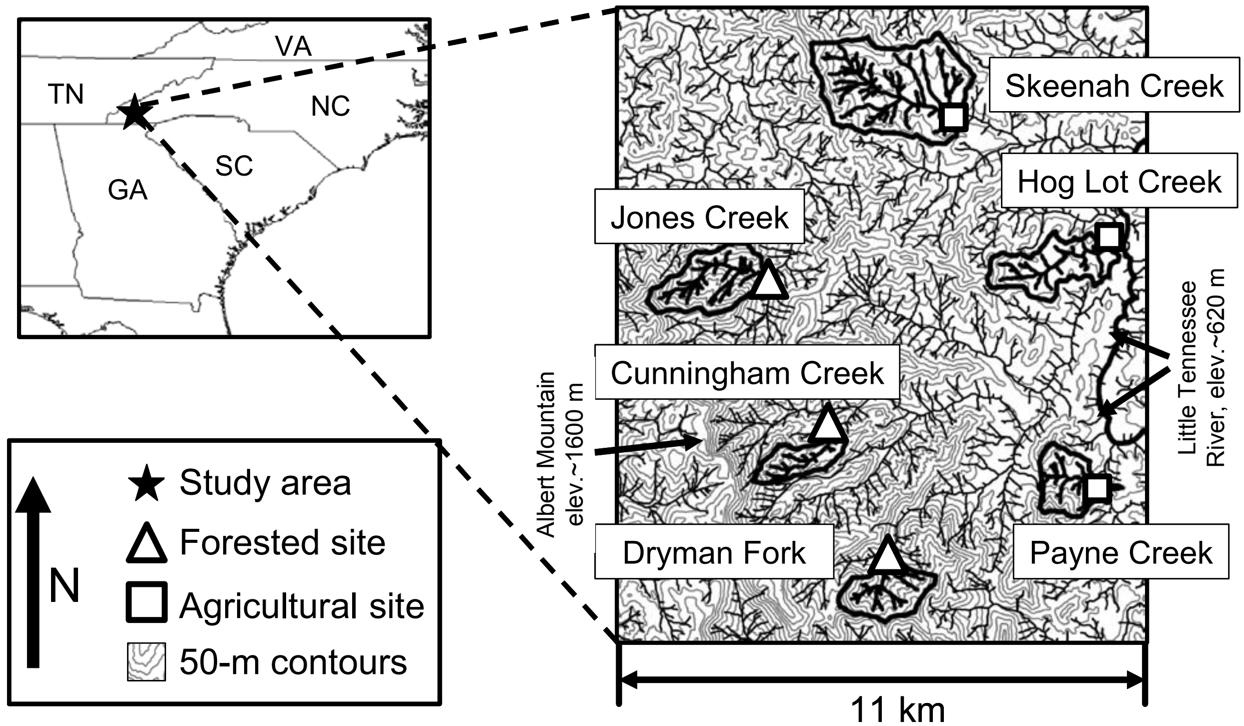

Figure 1. Study site locations. Cunningham Creek and Dryman Fork are located within the borders of the Coweeta Hydrologic Laboratory, Macon County, North Carolina.

Table 1. General characteristics of study reaches. Catchment areas were calculated from digital elevation maps. Discharge was determined from conservative solute injections and represents base-flow conditions at the time of the study (June-September 2003).

Land Use	Stream	Catchment area (ha)	Discharge (L s^{-1})	Reach length (m)	Reach slope (%)
Forested	Jones	239	31	194	4.5
	Dryman	162	49	200	4.3
	Cunningham	102	23	200	5.1
Agricultural	North Fork Skeenah	564	71	213	1.3
	Payne	151	20	195	1.6
	Hog Lot	226	55	327	0.9

Geomorphic structure

For each study reach, I visually identified the thalweg as the point in the wetted-channel carrying the most water. The thalweg path was surveyed three-dimensionally at a maximum 5-m resolution. Survey data were used to calculate slope and sinuosity of the study reaches. Reach slopes are presented as percent stream-bed elevation change per horizontal distance between the end points of the study reach. Sinuosity data are presented as the average distance that the thalweg was longer than the straight line distance at 10-m intervals (as percent longer). This metric quantifies thalweg sinuosity at the smallest scale possible from 5-m survey data.

The size of surficial stream bed sediment was characterized using pebble counts. Three particles were taken from each of 100 transects oriented perpendicular to flow and randomly selected along study reaches. Measurement was based on fit through square templates, sized by the Wentworth scale (Bunte and Abt 2001). At each transect, pebbles were chosen relative to thalweg location. One particle was sampled from the thalweg, and two others were sampled from the remainder of the wetted channel. Particles less than 5.6 mm were determined to be too small to collect by hand. When encountered, they were recorded as “fines” and included in distribution analysis to avoid bias toward larger size classes (Diplas and Fripp 1992). Size classes of rocks excessively embedded or large (>180 mm) were estimated using a meter stick. Cumulative particle size frequency distributions were generated from these data and the particle size larger than 75% of the sample by count (D_{75}) was interpolated log-linearly (Bunte and Abt 2001). Because of the wide range in sediment size among all 6 streams, the D_{75} was the only quartile measurable without extrapolation. In other words, in at least one of the streams, the D_{25} and D_{50} were smaller than the smallest size measurable by pebble count (< 5.6 mm).

Suspendable fines were quantified from 20 samples at 10 transects randomly selected along each study reach. At each transect, one sample was taken from the thalweg and the other taken from halfway to the farthest wetted edge. I inserted a circular stilling chamber (diameter = 25.3 cm) as far as possible into the stream bed and agitated the top 10 cm of substrate within the chamber to dislodge readily suspendable fine sediments. Water samples were taken immediately, and water depth was measured to determine stilling chamber volume. I filtered measured volumes of agitated samples through 0.7-μm pre-weighed glass fiber filters (Whatman GF/F) and subsequently dried the filters for at least 24 hours at 60°C. Dry mass was used to calculate suspendable fine concentrations in the water samples, and finally total suspendable fines within the stilling chamber water volume. Abundance of suspendable fines is presented as the mass of fines per bulk volume of stream substrate agitated. Bulk volume of substrate was calculated from the approximate depth of agitation and the diameter of the stilling chamber.

Hydraulics

Chloride (Cl) introduced as sodium chloride (NaCl) was used as a conservative hydrological tracer. Tracer additions were conducted during base-flow conditions from June-September of 2003. A concentrated solution of Cl was added to the channel at a constant rate until downstream channel concentrations reached steady-state as indicated by constant conductivity with time. Chloride can be measured as electrical conductivity due to the linear relationship between Cl concentration and conductivity. Downstream conductivity was recorded every 2 minutes using automated sondes (Hydrolab Minisonde 4a, Loveland, Colorado, USA). Sondes were placed approximately 200 m downstream from the tracer release point in 5 of the 6 streams. Due to co-occurrence with another study, the sonde was placed approximately 327 m from the release point in Hog Lot Creek (Table 1). The resulting solute breakthrough curves were used to parameterize discharge (Q), cross-sectional channel area (A), transient storage exchange rate (α), and transient storage cross-sectional area (A_S) based on methods described in Harvey and Wagner (2000). I used a computer program to visually compare numerical solutions of a one dimensional transport model with solute breakthrough curves. I characterized Q and A by best visual fit. I then used OTIS-P (Runkel 1998) to parameterize α and A_S. OTIS-P provides a statistical algorithm to match model output to empirical data with the best sum-of-squares fit. Normalized transient storage (i.e., A_S/A) was subsequently calculated for each stream.

Based on the modeled hydraulic characteristics, the Damkohler number (DaI) for each study reach was calculated (Wagner and Harvey 1997). Wagner and Harvey reported that DaI between 0.5 and 5 indicate the least uncertainty in modeled transient storage parameters relative to the average velocity of channel flow. All but one of the study reaches were in this range. Hog Lot Creek was slightly out of the range (DaI = 5.7), but the modeled A_S of this reach was so limited that a small additional amount of uncertainty is unlikely to change conclusions about these streams.

The channel friction factor is a dimensionless metric describing the roughness required to limit velocity of a stream flow with given slope and depth. This metric technically applies only under uniform flow; a condition unlikely met in the study reaches. Despite this fact, channel friction factor may provide a useful comparative metric for stream roughness as applied by Harvey and Wagner (2000). The friction factor was calculated as $8gdSv^{-2}$, where g is acceleration due to gravity, d is average depth, S is energy gradient (approximated by bed slope), and v is average velocity or Q/A.

Biological structure and function

The potential transformations to and from NO_3^- in stream sediments were assessed by measuring NO_3^- change in microcosms. Using a trowel, I collected 4 replicate sediment samples from non-depositional locations, at least 20 m apart, in each of the 6 study reaches. Samples were taken within a 6-hr interval and transported on ice for processing 8-10 hours after sampling. Each sediment sample was stirred and two 100-cm^3 sub-samples were independently added to 250-mL Erlenmeyer flasks. Particles too large to fit through the neck of the flask were excluded. One flask was used as a microcosm to assess NO_3^- dynamics and the other flask was used to analyze fine sediment quality and quantity (see below). To each microcosm, I added 120 mL of filtered water collected from the stream corresponding to the sediment. Microcosms were incubated in the dark at 18°C while agitating at 70 rpm on an orbital shaker table. I took initial water samples after 20 minutes of agitation and final samples after 12 hours of incubation. All samples were immediately filtered using 0.7-µm glass fiber filters (Whatman GF/F) and frozen until analyzed for NO_3-N concentration using ion chromatography. After the incubation, microcosm sediments were dried for at least 24 hours at 60 °C and weighed to determine sediment dry mass. Net NO_3^- change over the incubation period is presented as mass nitrate-nitrogen (NO_3-N) produced per dry mass of microcosm sediment.

Quantity and quality of suspendable fines in stream sediments used for microcosms were assessed from the second 100-cm^3 sub-sample. Sediment samples were agitated in a known water volume to suspend the fines. Then, measured suspension samples were filtered through ashed and pre-weighed 0.7-µm filter (Whatman GF/F). Filters were dried for at least 24 hours at 60 °C and weighed to determine dry mass of fines. Filters were then ashed at 550 °C for at least 1 hour, re-wetted, re-dried, and re-weighed to determine organic matter content from ash-free dry mass (AFDM). Quality of fines is presented as percent mass OM per dry mass of fines. Overall sediment quality is presented as the mass suspendable organic fines and inorganic fines per dry mass of sediment (as percentages). Dry mass of sediment quality sub-samples was not available, so mass was estimated by averaging the microcosm sub-sample and a third 100-cm^3 sub-sample (coming from the corresponding stream sample).

Data analysis

Data were first statistically compared between forested and agricultural stream categories. Characteristics that significantly differed between land-use types were considered categorically different or distinctly representative of study streams within each category. Individual reach averages were calculated where within-stream replications were available. Each stream was considered a replicate for its respective type ($n = 3$), and t-tests were used to test for significant differences between land-use categories ($p < 0.05$). Before analysis, percentages were arcsine-square root transformed (Ott and Longnecker 2001). D_{75} data were natural-log transformed before analysis because sediments were log-normally distributed (Bunte and Abt 2001). Variability around means is presented as standard error and is reverse-transformed as appropriate. Asymmetric errors from reverse-transforms are not reported in the text but are represented in figure error bars.

Data that did not reflect categorical differences were considered to represent a gradient in conditions among all 6 streams. I used various regression analyses (generally $n = 6$) to test for significance ($p < 0.05$) in relationships among data reflecting a gradient.

Results

Forested vs. agricultural streams

Many of the structural characteristics of the study sites differed between land use categories. Among the reaches, slope varied from 0.9 to 5.1 % (Table 2). The average slope of 4.7 % in forested sites was significantly greater ($p < 0.001$, $n = 3$) than the average slope of 1.2 % in agricultural sites (Figure 2a). Sinuosity varied from 0.4 to 3.7 % and sediment size (i.e., D_{75}) varied from 13 mm to 86 mm among sites (Table 2). On average, sinuosity (2.9 %) and D_{75} (80 mm) in forested streams were significantly greater ($p = 0.044$ and $p = 0.028$, respectively) than in agricultural streams (1.0 % and 23 mm, Figure 2b, c). While there was a wide range of suspendable fines (27 to 144 mg cm^{-3}) and forested streams tended to have less fines than agricultural streams (34 ± 4 mg cm^{-3} vs. 90 ± 29 mg cm^{-3}, Figure 1d), average values were not significantly different ($p = 0.132$, Figure 2d). In part, this reflected extensive variability within the agricultural streams (45 to 144 mg cm^{-3}, Table 2).

As intended in site selection, Q and A were not significantly different between stream types ($p = 0.453$ and $p = 0.695$, respectively, Figure 3a, b). However, Q varied from 20 to 70 L s^{-1} and A varied from 0.10 to 0.33 m^2 among sites (Table 3).

While there was no pattern in measured channel hydrodynamics, there were significant differences in transient storage parameters. The A_S and A_S/A values for the study reaches varied from 0.01 to 0.19 m^2 and 0.08 to 1.1, respectively (Table 3). Average values of absolute (A_S = 0.14 ± 0.03) and normalized (A_S/A = 0.75 ± 0.17) transient storage areas in forested reaches were significantly larger ($p = 0.01$ and $p = 0.02$, respectively) than those of agricultural reaches (A_S = 0.02 ± 0.01, A_S/A = 0.09 ± 0.03, Figure 3c). The exchange coefficient (α) varied between 1.3×10^{-4} and 5.2×10^{-4} s^{-1} (Table 3), and mean rate for forested streams ($\alpha = 2.0 \times 10^{-4} \pm 0.4 \times 10^{-4}$ s^{-1}) was not significantly different ($p=0.268$) from mean rate for agricultural reaches (α = $3.5 \times 10^{-4} \pm 1.0 \times 10^{-4}$ s^{-1}, Figure 3d).

Organic content of suspendable fine sediments differed between streams of different land use. Percent organic matter of suspendable fines in sediments used for microcosm experiments varied from 17 to 45 % (Table 4). Forested streams had a significantly greater ($p = 0.016$)

percent organic matter in fines (average 41%) than agricultural streams (average 20 %, Figure 4a). As a fraction of total sediment mass, however, organic and inorganic fines did not differ among land-use categories ($p = 0.137$ and $p = 0.391$, respectively). Organic fines per total sediment varied from 1.5 to 3.4 % (Table 4) and averaged 3.1 and 2.1 % in forested and agricultural streams, respectively (Figure 4c). Inorganic fines per total sediment varied from 4.5 to 14.0 % (Table 4) and averaged 6.5 and 9.2 % in forested and agricultural streams, respectively (Figure 4d).

Stream sediments incubated with ambient stream water produced NO_3^- over the course of 12 hours. Rates of net NO_3^- production ranged from 17 to 51 ng N per g total sediment (Table 4). The net production tended to be higher in sediments from forested streams (47 ± 3 ng N g^{-1}) than agricultural streams (31 ± 8 ng N g^{-1}), but the difference was not statistically significant ($p = 0.105$, Figure 4b).

Table 2. Geomorphic characteristics of study reaches. Where multiple measurements were available per stream, data are presented as the mean plus or minus standard error.

Land Use	Stream	Reach slope (%)	Sinuosity n~20-30 (%)	D_{75} (mm)	Suspendable fines n~20 (mg cm^{-3})
Forested	Jones	4.5	2.6 ± 1.0	84	36 ± 5
	Dryman	4.3	2.4 ± 0.6	86	27 ± 5
	Cunningham	5.1	3.7 ± 1.0	70	39 ± 6
Agricultural	North Fork Skeenah	1.3	1.9 ± 0.8	44	45 ± 6
	Payne	1.6	0.4 ± 0.1	21	80 ± 18
	Hog Lot	0.9	0.9 ± 0.2	13	144 ± 33

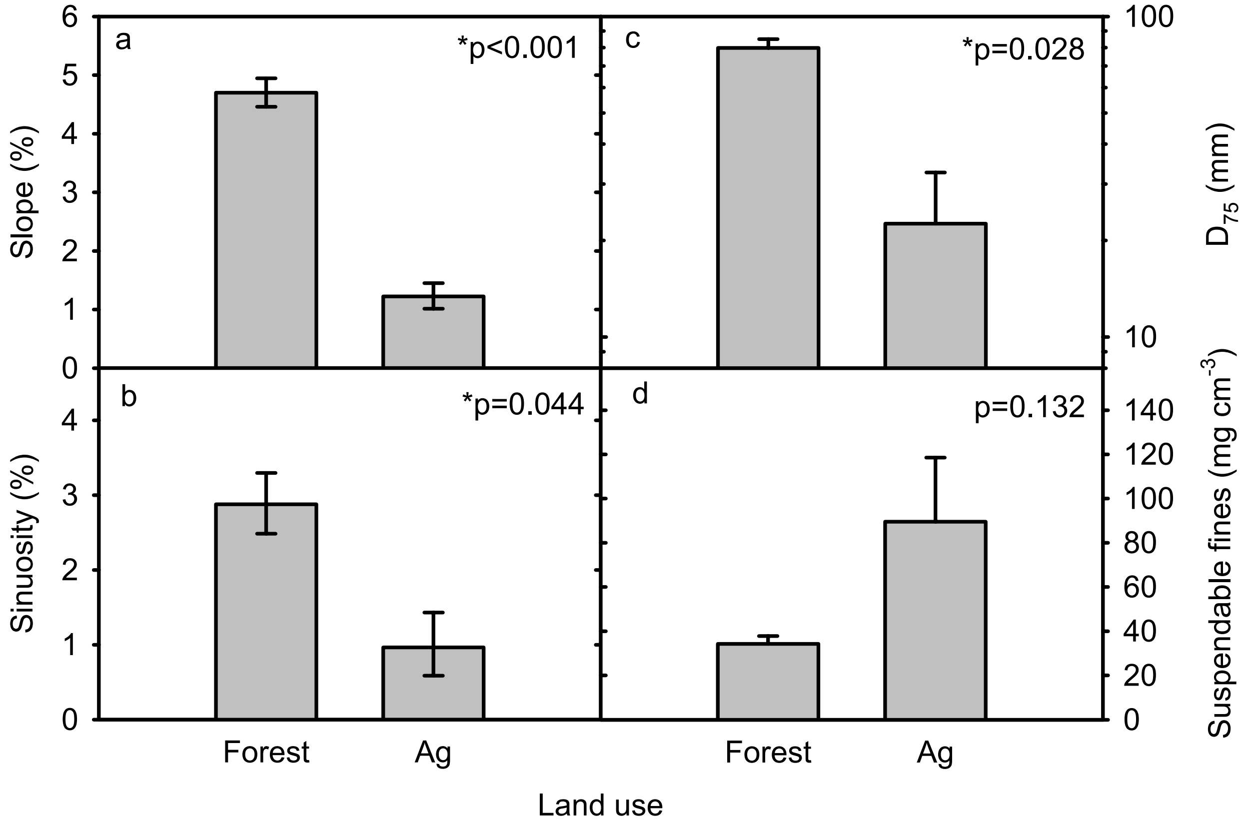

Figure 2. Geomorphic structural characteristics of forested vs. agricultural streams. Data reported are averages of (a) slope, (b) sinuosity, (c) D_{75}, and (d) suspendable fines from 3 streams of each land use. Error bars represent standard errors, reverse transformed where applicable. Percentages were arcsine-square root transformed (error bars asymmetric) and sediment size was log transformed before statistical analysis. P-values are from 2-tailed t-tests, and are marked with an asterisk where significant with greater than 95% confidence.

Table 3. Hydrologic characteristics of study reaches.

Land Use	Stream	Q ($L\ s^{-1}$)	A (m^2)	A_S (m^2)	A_S/A	α ($x10^{-4}\ s^{-1}$)
Forested	Jones	31	0.18	0.19	1.06	2.8
	Dryman	49	0.22	0.10	0.47	2.0
	Cunningham	23	0.20	0.14	0.71	1.3
Agricultural	North Fork Skeenah	71	0.25	0.04	0.14	5.2
	Payne	20	0.10	0.01	0.08	3.6
	Hog Lot	55	0.33	0.02	0.06	1.7

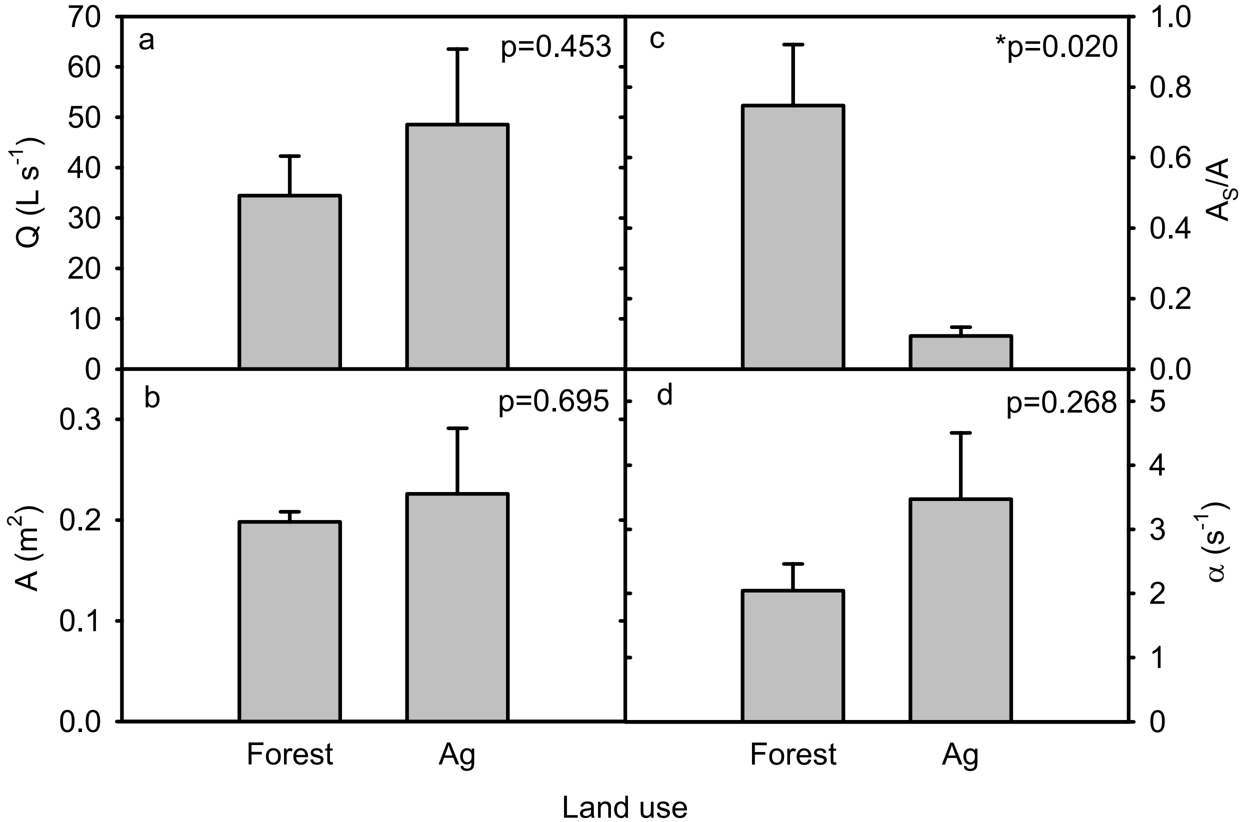

Figure 3. Hydrologic characteristics of forested vs. agricultural streams. Data reported are reverse model parameterizations of reach (a) discharge (Q), (b) cross-sectional channel area (A), (c) normalized transient storage area (A_S/A), and (d) channel - transient storage exchange rate (α) from 3 streams of each land use. Model estimations are based on breakthrough curves of downstream conservative tracer concentrations. Error bars represent standard errors. P-values are from 2-tailed t-tests, and are marked with an asterisk where significant with greater than 95% confidence.

Table 4. Biogeochemical characteristics of study reach sediments. Data are presented as the mean plus or minus standard error.

Land Use	Stream	Percent OM in fines n=4 (%)	Percent suspendable fine OM n=4 (%)	Percent suspendable fine IM n=4 (%)	Nitrate production n=4 ($ng\ g^{-1}$)
Forested	Jones	29 ± 4	2.9 ± 0.9	9.6 ± 5.6	42 ± 14
	Dryman	36 ± 1	3.0 ± 0.5	5.3 ± 1.1	51 ± 3
	Cunningham	45 ± 4	3.4 ± 0.6	4.5 ± 1.4	49 ± 6
Agricultural	North Fork Skeenah	17 ± 2	1.5 ± 0.2	7.4 ± 0.4	32 ± 8
	Payne	22 ± 1	1.7 ± 0.3	6.2 ± 1.4	43 ± 10
	Hog Lot	19 ± 2	3.1 ± 0.7	14.0 ± 3.9	17 ± 14

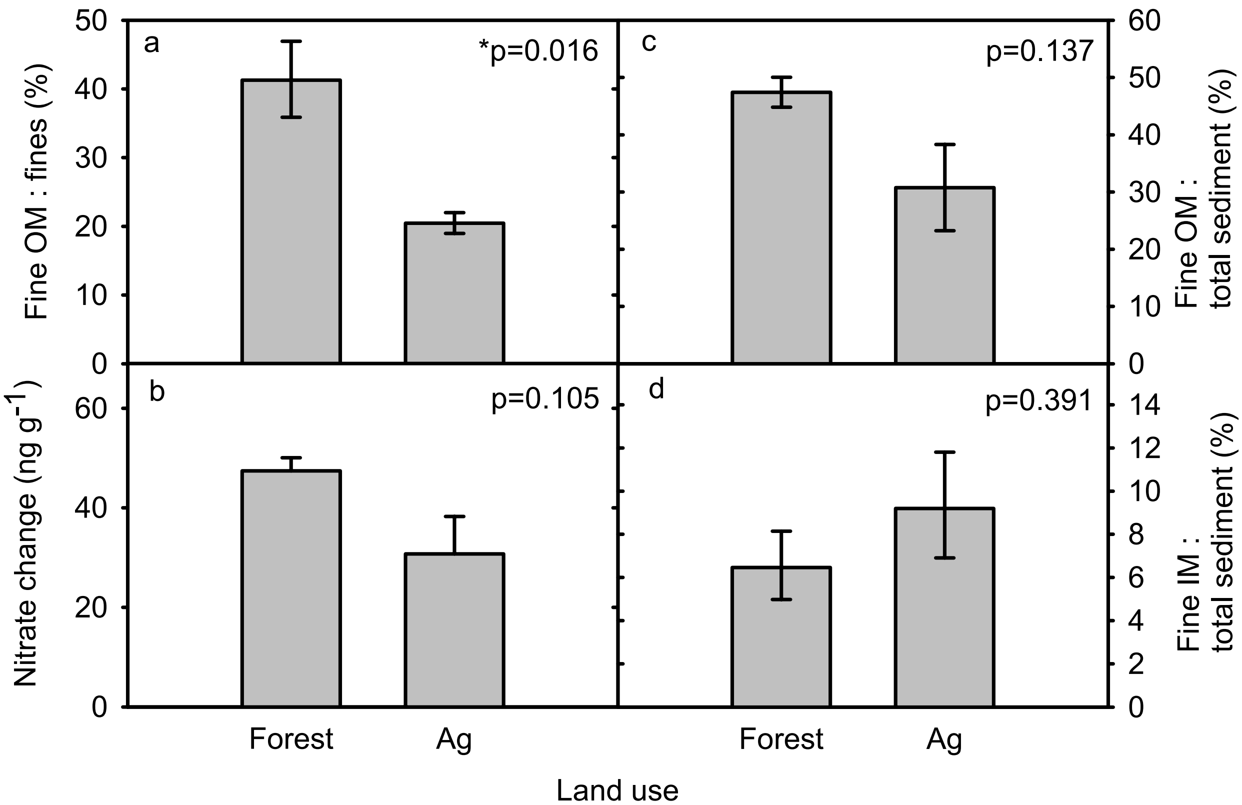

Figure 4. Biological characteristics of sediment in forested vs. agricultural streams. Data reported are stream averages of (a) percent organic matter in fines, (b) dissolved nitrate change in microcosm per mass sediment, (c) percent organic fines per total sediment, and (d) percent inorganic fines per total sediment from 3 streams of each land use. Error bars represent standard errors, reverse transformed where applicable. Percentages were arcsine-square root transformed (error bars asymmetric). P-values are from 2-tailed t-tests, and are marked with an asterisk where significant with greater than 95% confidence.

Comparisons among streams

Suspendable fine sediment characteristics varied among the study streams with implications for both hydrologic and biogeochemical features. Within each land-use category, α appeared to be negatively correlated with suspendable fines, but this relationship was distinctly different between categories (Figure 5). When slope was added as a regressor along with suspendable fines, they together explained 96 % of the variability in transient storage exchange rates (multiple regression, $n = 6$, $p = 0.007$). Streams with more suspendable fines had lower α, and streams with lower slopes had higher α.

Rates of NO_3^- production in sediment microcosms were not related to suspendable fine organic matter as a percent of total sediment mass ($n = 6$, $p = 0.839$, Figure 6a). At the same time, there was a significant negative relationship ($n = 6$, $p = 0.022$) between inorganic suspendable fines per total sediment and NO_3^- production. The abundance of inorganic fines explained 77% of the variability in net NO_3^- production in the microcosms (Figure 6b).

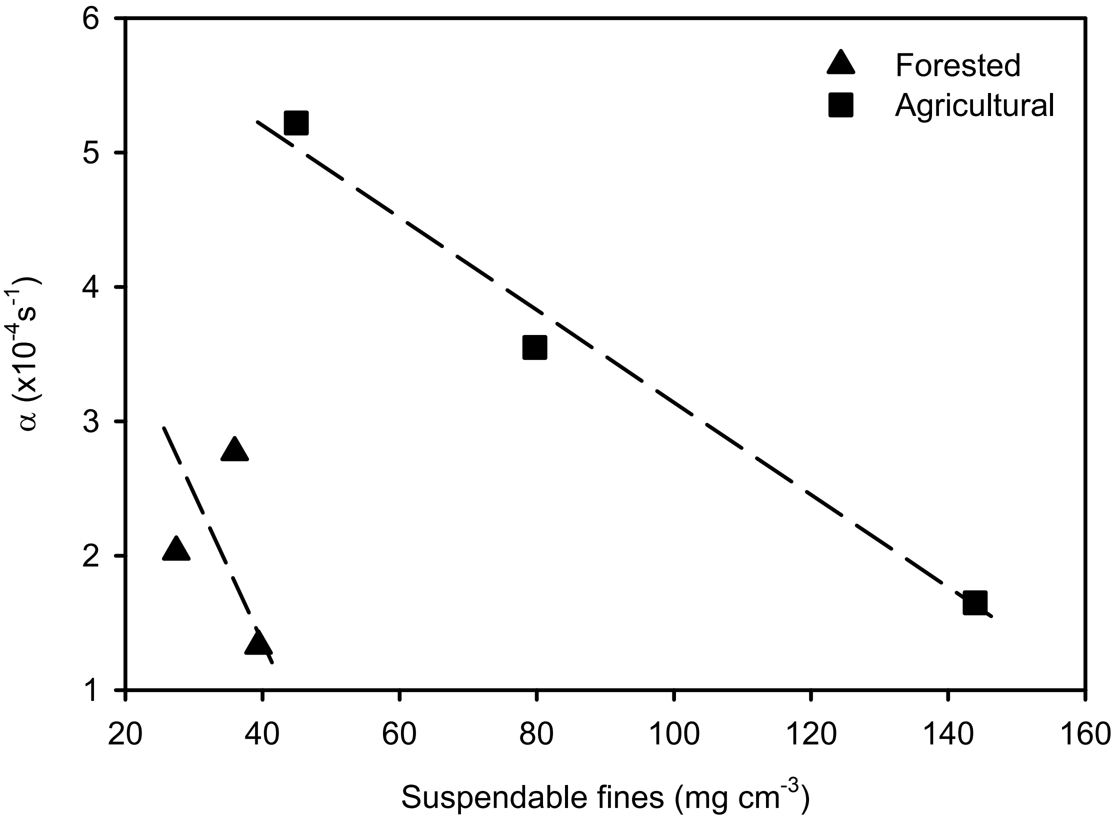

Figure 5. Transient storage exchange rates compared to suspendable fines. A multiple linear regression with two terms, suspendable fines and slope, was significant and described 95% of the variability in transient storage exchange rates (p=0.007).

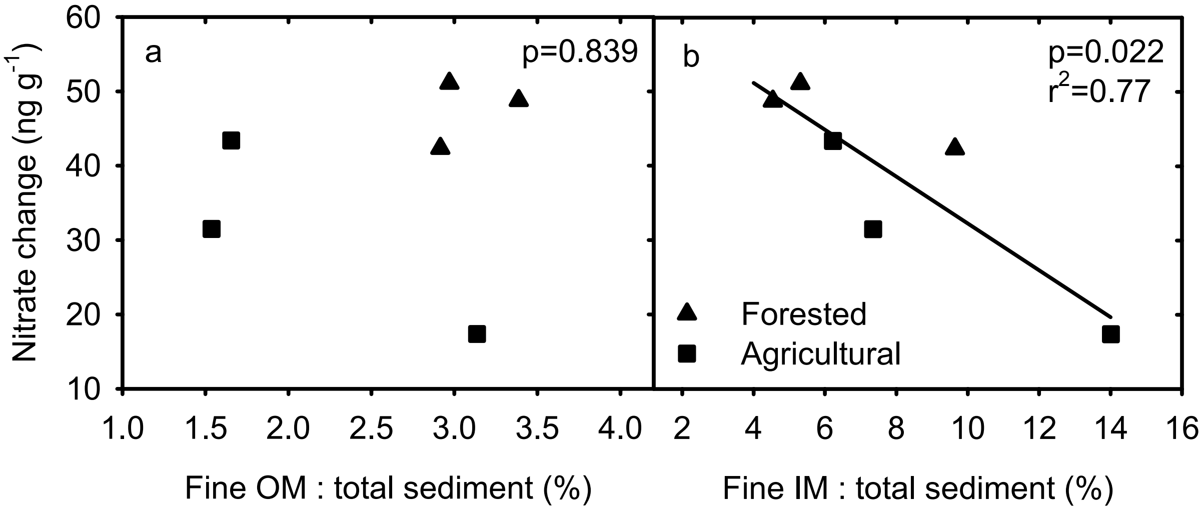

Figure 6. Nitrate change in microcosms vs. sediment quality. Sediment quality is characterized by (a) suspendable organic fines per total sediment and (b) suspendable inorganic fines per total sediment. Nitrate change is expressed in mass nitrate-nitrogen per mass total sediment.

Discussion

Forested vs. agricultural streams

The agricultural and forested study reaches had significantly different geomorphic structure, as indicated by slope, sinuosity, and sediment size. The difference in reach slope, in particular, suggests that these reaches were subject to different valley geomorphic structure as well as different land-use histories. While sediment retention structures may influence the localized slope of channel units (Frissell 1986), it is unlikely that retention structures in these small streams were large enough to differentiate 200- to 300-m reach slope from valley slope. A significant difference in valley slope suggests that some of the variability in reach structure is due to valley structure rather than agricultural reach alteration. The mechanisms of valley scale controls could include differences in coupling with hill-slope sediment sources (colluvium) and flow regime erosional/depositional thresholds (Church 2002).

Slope was probably considered in historical land use decisions. Forest clearings in the study area can be predicted by low topographic elevation and gradient, meaning that cleared land is found mostly in low-elevation alluvial stream valleys (Wear and Bolstad 1998). During my site selection, it was impractical, if not impossible, to locate historically forested or agricultural reaches with similar slopes. It is likely that, for this eastern mountainous region, land use and slope are nearly inseparable as independent variables.

Agricultural practices are known to introduce fine sediments to streams (Waters 1995, Wood and Armitage 1997), but there was relatively high variability in the amount of suspendable fine sediments collected from the 3 agricultural streams. Variability among the agricultural sites resulted in statistical similarity in suspendable fines between land use categories. Introduction of fine sediment may be a specific mechanism of land use influence that is evident despite significant differences in valley structure. If true, the abundance of suspendable fines suggests that the three agricultural streams vary in the degree to which they are influenced by agricultural practices.

Substrate particle size and distribution determines hydraulic conductivity and subsequent transient storage hydraulics, particularly in hyporheic zones (Morrice et al. 1997). The results of this study are consistent with this relationship. Forested reaches were characterized by larger sediments and greater extent of transient storage (i.e. A_S). The categorical difference in A_S and A_S/A also suggests that valley geomorphic structure and flow regime played some role in determining this reach-scale characteristic. The transient storage exchange coefficient (α) was more variable across agricultural streams than among forested streams, and across all streams, α was related to both slope and abundance of suspendable fines. This relationship may be further evidence of land use influence overlying the control of valley structure.

With evident differences in land use, hydraulics, and channel structure among study reaches, it was somewhat surprising not to find more evident differences in sediment biological characteristics. The data suggest more of a gradient among study sites than a categorical separation in these characteristics. While the percent organic matter was significantly different relative to total fines, it was not different relative to the entire sediment sample. Nitrate production in microcosms containing these sediments was likely biological (Triska et al. 1993). Hence, the mineralization-nitrification pathway appears to have dominated over nitrate removal during the 12-hr incubations. The trend toward lower production in agricultural sediments may be explained by a trend toward fewer organic fines or more inorganic fines. However, the lack of significant categorical differences in sediment biological structure and function does not strongly support either explanation.

Comparisons among streams

Comparisons and regression analyses among all 6 streams may reveal meaningful patterns in characteristics that do not reflect threshold differences between the land-use types. Despite categorical differences in every other geomorphic characteristic reported, suspendable fines were highly variable across agricultural streams and therefore not significantly different from forested streams. A similar pattern occurred in the transient storage exchange rate (α). It is logical that fines clogging bed interstices would reduce flow rates represented by α, and this phenomena has been demonstrated by Schälchli (1992) and Packman and MacKay (2003). While there seemed to be a negative relationship between these variables *within* land-use categories, it was evident that slope differentiated transient storage *between* agricultural and forested study reaches. Because slope is considered a descriptor of valley structure, the full model describing α may illustrate the additive effects of a gradient in fines and a threshold in geomorphic regime. The model also depicted a negative relationship between slope and α suggesting that the lower gradient streams had higher exchange rates. This is consistent with summaries of mountain and mountain valley streams reported by Harvey and Wagner (2000).

Using data from 50 tracer studies in the United States, Harvey and Wagner (2000) also reported a positive relationship between stream friction factor and normalized transient storage cross-sectional area (A_S/A). Two of the agricultural streams, Payne Creek and Hog Lot Creek, did not have transient storage areas within the range typical of other streams (Figure 7). This may be explained by the relatively large amount of suspendable fines in the beds of these streams. These fines may affect transient storage hydraulics, specifically by clogging sub-surface hyporheic storage without affecting the overall friction established by surface roughness of the bed. It may also be relevant that the one agricultural stream that did fit within the reported range, Skeenah Creek, had features that may reduce sediment inputs including bank stabilization from rip-rap, vegetation, and lack of livestock activity.

The biological function of the sediments, as indicated by NO_3^- production, was inversely related to the quantity of suspendable fines, particularly inorganic fines. It was surprising that the amount of inorganic fines explained variability in microcosm nitrate production while the amount of organic fines did not. The lack of a relationship with organic fines suggests their availability did not limit nitrate production, though the lability of organic nitrogen in fines and availability of nitrogen in other forms are unknown. On the other hand, inorganic fines may have limited the extent of dissolved oxygen circulation to mineralizers and nitrifiers in the sediment. This may further relate to microzones of anoxia, which would inhibit nitrification and potentially promote denitrification, the biological reduction of NO_3-N to N_2 gas, further reducing the net production of NO_3^-.

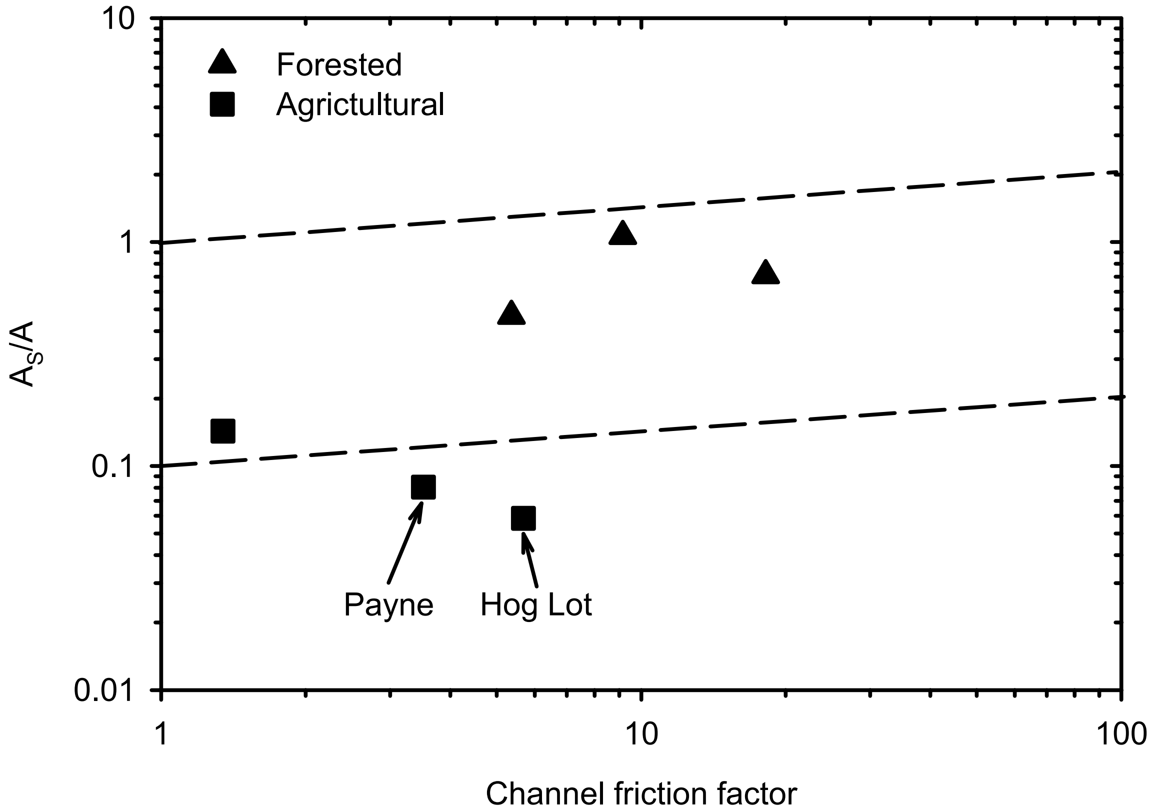

Figure 7. Normalized transient storage area (A_S/A) vs. channel friction factor. Dashed lines represent the range of U.S. stream data compiled by Harvey and Wagner (2000).

Conclusions

The agricultural and forested study sites were categorically different in many aspects of geomorphic structure and hydraulics. Furthermore, patterns among these differences are consistent with previous studies relating reach scale hydraulics to sediment organization. The data presented in this paper suggest that the forested and agricultural streams fall into different categories of geomorphic regime. The three forested streams all had significantly higher slope, more sinuosity, and larger sediments than the other streams. They have the structural characteristics and subsequent reach scale hydraulic properties in the range of mountain streams as generalized by Harvey and Wagner (2000). The three agricultural streams all had significantly lower slopes, less sinuosity, and smaller sediments. They fit well into Harvey and Wagner's generalization of mountain valley streams, but in some characteristics, two agricultural streams reflected the influence of excess fine sediments.

High variability in the abundance of suspendable fines in agricultural streams may explain non-categorical differences in hydraulics and sediment biogeochemistry. The variability in fines was likely due to differences in bank erosion mediation, livestock activity, or proximity to large reservoirs of river-deposited fines. From the results of this study, it is not possible to attribute abundance of fines directly to land-use practices. Regardless of the source, the consequences of these fine sediments may be seen in reach scale transient storage exchange (α), particularly in agricultural streams. Two of the agricultural streams of this study also had less extensive transient storage (A_S/A) than streams of similar friction factors, possibly due to fine sediments. The implications for biogeochemistry are evident in that inorganic fines may limit the net production of nitrate in stream sediment samples. It is challenging to directly test predictions of agricultural influence in geophysical regions where streams of different land use are almost invariably within different geomorphic regimes. Direct support of causality or coincidence in these potential mechanisms requires large scale manipulations of agricultural reaches or forested reference streams of similar valley scale structure.

The potential influence of agriculture was limited to riparian interactions because land use was topographically limited to near-stream areas. Therefore, the effects of agriculture were likely occurring within the larger-scale context of valley structure and flow regime. Structure and function of stream ecosystems are nested in a hierarchical array of multi-scale relationships integrating catchment geomorphic, hydrologic, and biologic characteristics (Schumm and Lichty 1965). Stream reach properties are hierarchically limited to finite possibilities by valley-scale controls (e.g. hillslope structure and valley gradient) and refined by processes within the reach (e.g. bank erosion and riparian interactions, Frissell et al. 1986). The data of this study support these nested effects of valley-scale structure and reach-scale fine-sediment influence.

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Vita

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EDUCATION

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIV. – Blacksburg, Virginia

MS Biology – June 2004

THE OHIO STATE UNIVERSITY – Columbus, Ohio

BS Electrical Engineering – December 1993

RESEARCH EXPERIENCE

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIV. – Blacksburg, Virginia

Graduate Research – August 2001 to June 2004

Thesis research investigated the geomorphic effects of agricultural land use on stream hydraulics and sediment biogeochemistry. Analytical skills gained through this study and other studies at Virginia Tech include:

- Quantification of geomorphic structure through surveys and sediment size analysis
- Tracer injections to quantify stream hydraulics and biogeochemistry
- Microcosm assays of stream sediment biogeochemical potential
- Development of models and conceptual frameworks for study of nutrient spiraling

WITTENBERG UNIVERSITY SPELEOLOGICAL SOCIETY – Springfield, Ohio

Volunteer Field Research Assistant – May 1995 to June 2001

Assisted in field work of cave and karst related research projects led by students and professors associated with the organization, including some aspects of the following:

- Population studies of stygophilic amphipods and troglobitic insects: Indiana, Ohio
- Geomorphology of solutional features and dating of sediment deposition: Kentucky
- Cave survey (cartography and spatial representation): Indiana, Kentucky

PRESENTATIONS

Payn, R. A., H. M. Valett, J. R. Webster. 2004. The geomorphic influence of agricultural land use on hydrology and biogeochemical function in small streams. North American Benthological Society Meeting. Vancouver, British Columbia, Canada.

Payn, R. A., H. M. Valett, J. R. Webster, and J. A. Spotila. 2003. Hyporheic function in forested vs. agricultural streams (poster). Geological Society of America. Seattle, Washington, USA.

Webster, J. R., R. A. Payn, E. N. J. Brookshire, S. R. Earl, O. S. Starry, H. M. Valett, and P. J. Mulholland. 2003. Estimation of ambient nutrient uptake from nutrient enrichment experiments. North American Benthological Society Meeting. Athens, Georgia, USA.

PROFESSIONAL EXPERIENCE

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIV. – Blacksburg, Virginia

Graduate Teaching Assistant: Biology Department – August 2001 to June 2004

Responsible for teaching lab sections for general biology. Work with department faculty and staff to produce and maintain on-line Internet teaching materials for general and honors biology courses. Also responsible for maintaining web servers and lab computers associated with exchange of the teaching materials.

UUNET-WORLDCOM (FORMERLY COMPUSERVE) – Columbus, Ohio

Senior Internet Product Engineer – January 1996 to June 2001

Responsible for product development, certification, and support. Products included Internet remote access solutions. Participated in a core team establishing a new engineering process and technical group within the company to design, implement, and support solutions that fall outside of normal product definitions. Led the technical design and implementation effort for a non-standard Internet solution for a major corporation.

LEXIS-NEXIS – Dayton, Ohio

Telecommunications Engineer – January 1994 to December 1995

Developed, implemented, and supported connectivity solutions for large customers. Development involved testing of potential solutions for connection of various local area network environments to a private wide area network. Implementations involved building and testing production solutions, travel to the customer site to install the equipment, and integration of communications software on the customers' computer systems. Support included extensive trouble shooting of problems related to all aspects of these solutions.

AFFILIATIONS AND HONORS

- North American Benthological Society (NABS)
- NABS Graduate Resources Committee
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