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Effects of Land Use and Disturbance on Benthic Insects in Headwater Streams Draining Small Watersheds North of Charlotte, NC

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Abstract - Increasing development north of Charlotte, NC, threatens aquatic life in streams by reducing riparian zones and increasing runoff. Runoff, sedimentation from erosion, and poor construction practices are principal sources of pollution. We asked how land use and disturbance affected benthic insects. We visited nine streams from May to October 2001, collected data on insect diversity, chemistry, and physical habitat. We used a Geographic Information System to delineate watersheds and land use patterns. Watersheds were categorized based on land use, abiotic variables, and disturbance. Insect communities were more diverse in streams draining low disturbance watersheds than in streams draining highly developed watersheds. Sensitive taxa were found in streams with extensively forested watersheds, but were nonexistent in extensively developed watersheds. Disturbances occurring in streams caused declines in diversity, often eliminating sensitive taxa. Aquatic insect diversity is related to land use patterns and disturbances, and anthropogenic alteration of habitat has negative consequences to that diversity.

Introduction

Headwater streams in the Piedmont region near Charlotte, NC, are subject to high levels of disturbance from human activities. Many of these streams are only a few centimeters deep and less than one meter wide, and yet may have highly productive insect communities. Stream hydrology, biodiversity, and ecosystem function within these streams are in danger of being disrupted as land use in the surrounding watersheds changes. Disturbance to these streams results primarily from loss of riparian vegetation and increased sedimentation. These disturbances may cause declines in water quality and nutrient retention, and increases in erosion and runoff (Décamps 1993, Lamberti and Berg 1995, Newbold et al. 1983, Sponseller and Benfield 2001).

Changing land use patterns, including increases in impervious surfaces and construction near riparian zones, affect deposition of sediment, flow patterns (Oberlin et al. 1999), and stream communities (Décamps 1993, Thornton et al. 2000). Land use practices can strongly impact aquatic diversity well into the future; e.g., Harding et al. (1998) found that land use in the 1950s was the best predictor of present day diversity in streams. Urban runoff may cause decreased stream stability, and increased turbidity

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and sedimentation (Heimann and Roell 2000, Oberlin et al. 1999, Pitt et al. 1995, Winter and Duthie1998). Sedimentation disrupts filter feeding, clogs gills, alters substrate, and adversely affects species richness and biomass of a variety of taxa, including filter-feeding Trichoptera and Diptera and predaceous Plecoptera (Hogg and Norris 1991, Lamberti and Berg 1995, Lemly 1982, Lenat and Crawford 1994). Streambed characteristics and hydrology of small streams may change as development decreases riparian forests and increases sedimentation (Beschta 1996, Décamps 1993, Gore 1996, Swank et al. 1988). This may decrease flow, which can cause a drop in dissolved oxygen and an increase in temperature, eliminating taxa sensitive to those changes (Boulton and Suter 1986). Increased disturbance thus leads to decreased diversity in streams (Hogg and Norris 1991, Karr 1991, Lamberti and Berg 1995, Lemly 1982, Lenat and Crawford 1994, Schleiger 2000), and tolerant species may come to dominate the macroinvertebrates (Closs and Lake 1994).

Loss of biodiversity reduces the ability of stream ecosystems to perform numerous functions (Covich et al. 1999). Macroinvertebrates are influential in nutrient cycling, decomposition of detritus, energy flow, and sediment mixing (Covich et al. 1999, Wallace and Webster 1996). Food webs in streams surrounded by forested watersheds in eastern North America depend on leaf litter from riparian vegetation for energy (Cummins et al. 1973, Richardson 1990, Vannote et al. 1980, Wallace et al. 1997). Macroinvertebrates in headwater streams break down leaf litter and release nutrients and energy to downstream consumers (Cummins et al. 1973, Merritt et al. 1984, Vannote et al. 1980, Wallace and Webster 1996). Increased sedimentation causes a decline in leaf litter breakdown in streams, which is linked to declines in macroinvertebrate function (Cummins et al. 1973, Hogg and Norris 1991, Sponseller and Benfield 2001).

This study was done on Piedmont headwater streams of the Catawba and Rocky Rivers north of Charlotte, NC, where intense suburban development is occurring (Table 1). We wanted to know how aquatic insects are affected by changing land use patterns. Are some families eliminated from streams in watersheds subjected to development and disturbance? Are biodiversity patterns related to physical and chemical characteristics of streams? We measured several chemical, physical, and insect community response variables on nine streams from May to November 2001. We used land use characteristics determined from aerial photographs, topographic maps, habitat assessments, and observations of disturbance to categorize streams according to disturbance level. Types of disturbance included high, persistent disturbance, such as suburban development and long-term construction projects, and short-term, near-stream disturbances, such as sewer line installation, and drought. We then sought to determine if watershed disturbance level was related to in-stream variables.

Table 1. Classification of streams, disturbance type for each stream, substrate composition, land use within watersheds, and drainage area. In the disturbance column, Sewer line refers to construction of a sewer line next to or across the stream during the study. Parking lot refers to a large impervious surface at the head of the stream, Construction refers to a construction project occurring before and during the entire study, and Development refers to suburban development surrounding the stream. Values for cobble are not shown, but were typically small, and can be estimated by subtracting Silt, Sand, and Gravel from 100. Values in parentheses are standard errors.

Stream	Type/disturbance	Gravel (%)	Sand (%)	Silt (%)	Developed (%)	Forest (%)	Non-forest (%)	Area (ha)
CFCC	Low / none	12.4 (1.1)	27.0 (2.6)	42.0 (3.9)	3.2	56.5	40.3	64.1
DCEP	Low / none	3.0 (0.1)	42.6 (4.1)	54.2 (4.0)	7.4	57.1	35.5	104.6
Hopewell	Low / none	10.1 (1.6)	20.4 (1.3)	64.0 (4.9)	2.2	75.1	22.7	49.9
Erwin	Irregular / drought	13.4 (0.5)	46.0 (2.1)	35.8 (2.6)	5.0	83.1	11.9	72.1
Therese	Irregular / sewerline	48.4 (2.6)	26.0 (0.5)	24.0 (2.1)	27.9	40.2	31.8	199.2
Reeds	Irregular / sewerline	26.2 (1.3)	43.0 (1.8)	30.0 (5.5)	47.7	36.5	15.8	68.6
Baker	High / parking lot	24.6 (1.8)	40.0 (0.8)	18.6 (2.1)	44.0	25.7	30.3	39.1
Knobloch	High / construction	13.3 (1.3)	45.2 (2.1)	38.4 (3.4)	32.7	31.8	35.6	62.3
IB	High / development	4.3 (0.2)	25.3 (2.7)	67.6 (2.4)	41.9	18.7	39.4	20.9

Field site description and stream categorization

We studied nine headwater streams draining small watersheds (range of areas = 20–200 hectares, Table 1) in the Piedmont Region north of Charlotte, NC (Huntersville, Davidson, and Mooresville). We based our selection on stream size, flow, substrate composition, accessibility, suspected disturbance levels, and stream order. All streams were first order with bottom substrate composed of between 50 and 96% sand and silt (average = 76.6 ± 2.8%; Table 1). Stream widths ranged from 0.4 to 2.5 meters in the study reaches, and streams were between 2.5 and 21.5 cm deep (average = 5.9 ± 0.5 cm), with velocity between 0 and 1.0 m/s. All nine streams had measurable velocity in May and June, but by the end of the 2001 season all had velocity measurements close to zero.

Using ArcView GIS, 1998 aerial photographs, and digitized topographic maps, we delineated the drainage basins for each stream and then categorized the land use within each basin as forest, cleared, or developed. The latter category included mostly impervious surfaces and unvegetated land. Land use changes occurring after aerial photographs were taken were approximated.

We classified streams based on the percentage of land that was forested or developed, chemical and physical parameters, and actual disturbance events that occurred in the stream. Low disturbance streams (n = 3) drained heavily forested watersheds (> 55% forest) that did not suffer any disturbance during the study. Those three streams had < 8% developed area. High disturbance streams (n = 3) had little forested area within their watersheds (≤ 30%), 33% or more developed area (primarily residential), and were exposed to long term disturbances, such as construction projects and suburban development. There was very little agriculture in any watershed. Irregular disturbance streams (n = 3) had variable levels of forest and development; the percentage developed area in those watersheds overlapped with the two other watershed types (Table 1). During the course of the study some event, such as drought or construction, directly impacted these streams. Erwin Creek dried up in August and September, and in the other two (Reeds and Therese) installation of a sewer line parallel to or crossing the stream during July caused extreme sedimentation (Table 1).

Methods

Streams were visited five times over the course of seven months from spring through late fall to one of two 100 meter long stream reaches (sites). We alternated sites along each stream so that each site was visited every other time. For habitat characteristics, we assessed the area surrounding each stream by estimating the percentage of riparian vegetation, the degree of erosion along both banks, and the percentages of substrate types.

We measured pH (Orion pH Meter Model 250A), dissolved oxygen, temperature, conductivity (YSI Model 85 combined oxygen, conductivity, salinity, and temperature system), and alkalinity (LaMotte test kit). We measured depth, width, and flow rate (Global Flow Probe), and collected suspended sediment samples for later analysis in the lab using a depth-integrated suspended sediment sampler (Beschta 1996), which works well even in shallow streams. A known volume of approximately 100 ml was vacuum-filtered in the laboratory through preweighed 1.2 ìm fiberglass filters. Filters plus sediment were oven-dried at 105 °C to determine sediment mass.

We took three insect samples on each date by disturbing a 0.5 m^2 area upstream from a D-frame net with 500-μm mesh size for 1 minute. Samples were taken primarily from areas with riffles and leafy debris. Most streams had at least part of each site with small riffles and leaf packs, but if those habitats were not present samples were taken from sandy substrate. We emptied the net into a tray, visually searched the net for remaining insects, and preserved all material in 75% ethanol. We sorted insects, identified them to family using Brigham et al. (1982), McCafferty (1998), and Merritt and Cummins (1996), and counted them. Number of families (family richness), total insect abundance, EPT (Ephemeroptera, Plecoptera, and Trichoptera) family richness and abundance were calculated for each sample (NCDENR 1997).

We used a multivariate analysis of variance (MANOVA) profile analysis for repeated measures (von Ende 2001) to test effects of stream type on the biotic variables of family richness, EPT abundance, and total abundance of insects, and the abiotic variables of suspended sediment, dissolved oxygen, alkalinity, and pH. Variables used in profile analysis were tested for normality and transformed as appropriate. Insect and EPT abundance were log-transformed. We also used t-tests to compare insect abundance and number of families in those watersheds with a high percentage of developed land with those with less than 10% developed land. This analysis used only the percentage of developed land in the watershed as the criteria for grouping streams, and resulted in irregular disturbance streams being split into the two groups because they had highly variable amounts of development within their watersheds (Table 1).

Results

Chemical and physical variables

Alkalinity, pH, and dissolved oxygen showed significant effects of either stream type or stream type by time interaction (Table 2). Alkalinity exhibited a strong disturbance level main effect (Table 2); irregular disturbance streams had lower alkalinity than high disturbance streams. Low disturbance streams had consistent alkalinity levels throughout the study period, but other stream types were more variable over time (Fig. 1a). Although there was a significant stream type by time interaction for pH, all pH values were between 6.4 and 7.4 (Table 2, Figure 1b). The stream by time interaction for DO (Table 2) is related to lower DO levels occurring in July for irregular stream types (Figure 1c). Suspended sediment levels were not significantly affected by disturbance level, but there were large, variable spikes in June and July for irregular disturbance streams (Fig. 1d).

Table 2. Results of main effects and main effects by time interactions in the Profile Analysis (Time effects not shown). Degrees of freedom for all MANOVAs were 8, 6.

Variable	Source	λ	P
Alkalinity	Disturbance level	0.0047	0.005
	Disturbance x time	0.16	0.47
pH	Disturbance level	0.26	0.68
	Disturbance x time	0.02	0.04
Dissolved oxygen	Disturbance level	0.041	0.10
	Disturbance x time	0.013	0.023
Log suspended sediment	Disturbance level	0.31	0.76
	Disturbance x time	0.33	0.78
Log insect abundance	Disturbance level	0.013	0.023
	Disturbance x time	0.011	0.017
Log EPT abundance	Disturbance level	0.016	0.032
	Disturbance x time	0.028	0.063
Number of families	Disturbance level	0.0086	0.013
	Disturbance x time	0.039	0.097

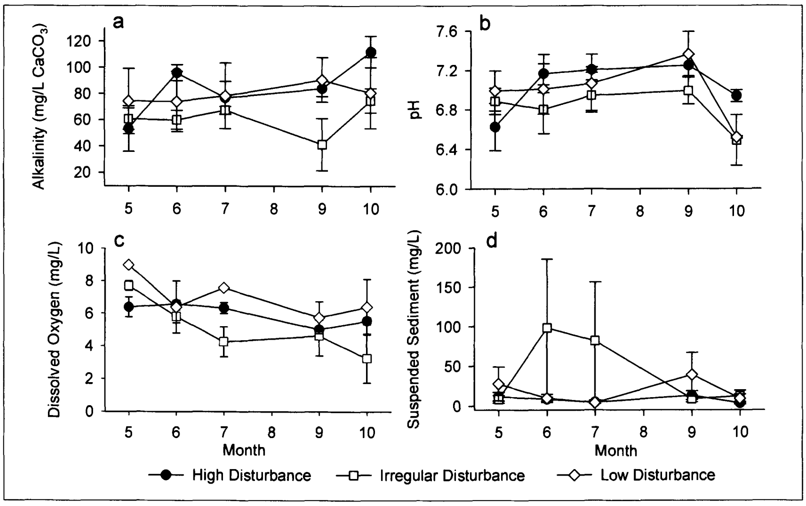

Figure1. Alkalinity (a), pH (b), disolved oxygen (c), and suspended sediment (d) over time for each disturbance type. Monthly means are averaged over three samples and three streams. Error bars represent 1 standard error above or below the mean.

Biota

There was a significant interaction between disturbance type and time on log-transformed abundance of insects. Low disturbance streams showed an increase in abundance, irregular disturbance streams started out similar to low disturbance streams and declined over time, and high disturbance streams had low abundance throughout the study (Fig. 2a, Table 2). Abundance was significantly higher in streams that had less than 10% developed land in their watershed than in streams that had > 25% developed land in their watershed (Fig. 3a; t-test: t = 8.5,

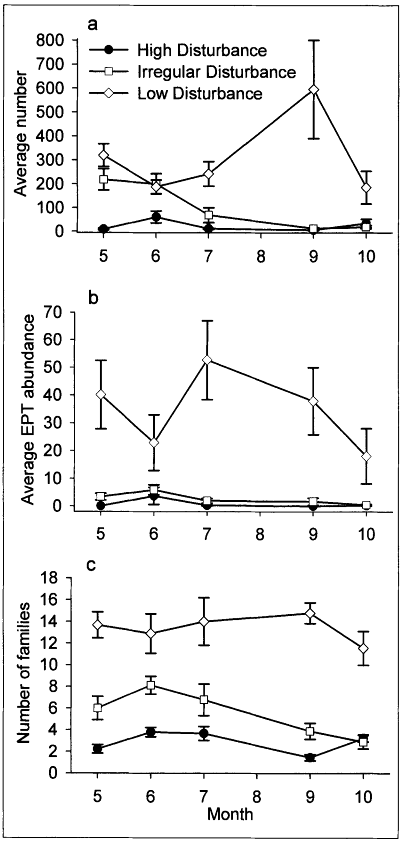

Figure 2. Insect abundance (a), abundance of EPT (Ephemeroptera [mayflies], Plecoptera [stoneflies], and Trichoptera [caddisflies]) individuals (b), and number of families (c) over time for each disturbance type. Monthly means are averaged over three samples and three streams. Error bars represent 1 standard error above or below the mean.

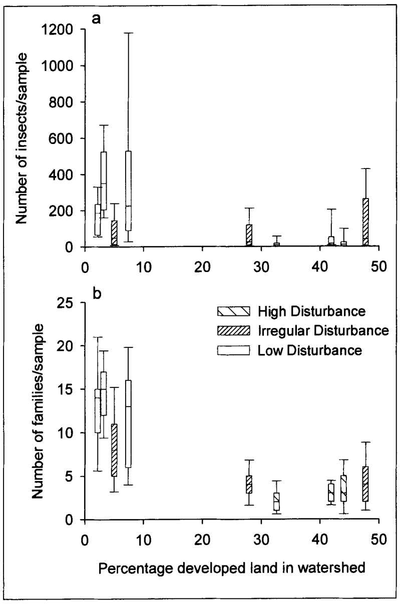

Figure 3. Insect abundance(a) and family richness (b) as related to percentage developed land. Box plots show median (thin line within boxes), the 25th and 75th percentiles (ends of boxes), and the 5th and 95th percentiles (ends of whiskers).

df = 133, P < 0.0001). Although highly variable, samples from low disturbance streams always had some insects, while high disturbance stream samples often had no insects. One irregular disturbance stream had < 10% developed land, and the other two were included in the high developed land category (Table 1, Fig. 3a). This analysis indicates that the percentage of developed land in the watershed is one factor that affects macroinvertebrate abundance. The trend of decreasing abundance of insects in irregular disturbance streams over time (Figure 2a) indicates that other factors also affect abundance.

Low disturbance streams always had significantly more EPT individuals than both irregular and high disturbance streams (Fig. 2b). There was

Table 3. Number of individuals per family found in the study streams. We captured > 10 individuals from 46 families; numbers from 37 of those families are shown.

Order	Family	Low	Irregular	High
Plecoptera	Nemouridae	51	12	0
	Chloroperlidae	22	9	0
	Perlidae	23	7	0
	Perlodidae	60	0	0
	Leuctridae	47	0	0
	Capniidae	41	0	0
Ephemeroptera	Baetidae	435	67	0
	Heptageniidae	206	6	0
	Leptophlebiidae	113	0	0
	Ephemeridae	82	0	0
	Ephemerellidae	10	0	0
Trichoptera	Hydropsychidae	418	24	34
	Polycentropodidae	13	0	1
Diptera	Chironomidae	9590	3242	810
	Tipulidae	563	68	190
	Syrphidae	2	36	9
	Culicidae	7	26	3
	Dixidae	44	7	3
	Psychodidae	25	9	2
	Simuliidae	558	953	1
	Empididae	34	25	1
	Tabanidae	73	7	0
Diptera	Ceratopogonidae	70	5	0
	Ephydridae	157	3	0
	Ptychopteridae	74	2	0
Megaloptera	Corydalidae	44	26	0
	Sialidae	32	0	0
Coleoptera	Elmidae	126	44	13
	Dytiscidae	16	12	6
	Dryopidae	19	4	1
	Ptilodactylidae	633	7	0
Odonata	Calopterygidae	55	2	9
	Coenagrionidae	9	12	6
	Cordulegastridae	36	25	4
	Aeshnidae	8	6	0
	Gomphidae	24	5	0

only a main effect of disturbance type, and no interaction with time (Table 2). Irregular disturbance streams had more EPT individuals than high disturbance, although no stoneflies or mayflies were collected in high disturbance streams, thus EPT taxa were exclusively caddisflies (Table 3). Sialidae (Megaloptera) and three families each of Ephemeroptera and Plecoptera were found only in low disturbance streams (Table 3). Samples from low disturbance streams had high diversity of Plecoptera, with two to five families in each sample (Fig. 4, Table 3).

We found a significant disturbance effect on family richness (Table 2). On average, there were more insect families in low disturbance streams than in irregular disturbance streams. The latter had a higher average number of families than high disturbance streams for most of the study, although it dropped steadily after disturbances occurred in June and July (Fig. 2c). The number of families was significantly greater in streams that had < 10% developed land in their watershed than in streams that had > 25% developed land (Fig. 3b; t-test: $t = 13.90$, $df = 133$, $P < 0.0001$). As with abundance, despite the variability in irregular disturbance streams, the percentage of developed land in a watershed is one factor that may affect insect diversity (Fig. 3b).

Discussion

Changing land use patterns may affect several water chemistry parameters (Prowse 1987), and changes in water chemistry may negatively affect stream insect biota, resulting in decreased stream biodiversity (Lillie and Isenring 1996, Winter and Duthie 1998). Our results indicate that alkalinity and dissolved oxygen change in streams subject to increased development or disturbance. Other chemical parameters not measured likely also changed, and some of the variability among aquatic insect communities is probably associated with changes in water

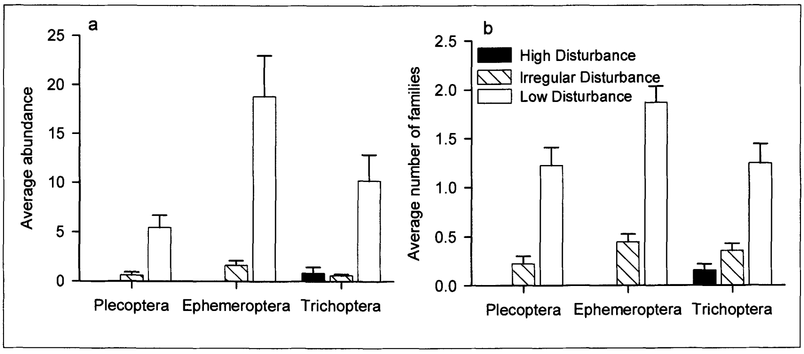

Figure 4. Abundance of EPT insects (a) and number of EPT families (b) by order and for each disturbance category. Error bars represent 1 standar error above or below the mean.

chemistry. Low dissolved oxygen eliminates sensitive taxa from streams (Closs and Lake 1994), and we saw decreases in abundance that correlated with decreases in dissolved oxygen in irregular disturbance streams. Dissolved oxygen levels were probably not low enough to cause elimination of sensitive taxa. However, these changes may have occurred as temperatures rose and stream velocity dropped, and the analysis indicates a disturbance effect on oxygen that is associated with, but not necessarily causative of, the effect on insect abundance.

Sedimentation and turbidity also increase as headwater forests are cleared (Lamberti and Berg 1995), and this decreases species richness, the proportion of pollution-sensitive species, overall insect biomass, and abundance (Beschta 1996, Kemp and Spotila 1997, Lamberti and Berg 1995, Lemly 1982, Oberlin et al. 1999, Schleiger 2000). Streams we categorized as high disturbance had 30% or more of their watershed in construction or impervious surface. Because we did not confine collection of suspended sediment to high flow periods, the relationship between sediment and disturbance level is not as evident as in other studies (Hachmoeller et al. 1991, Lemly 1982). The lack of relationship in our data may also reflect the low rainfall and runoff during the study period. However, the total number of insects, the number of insect families, and the abundance of pollution-sensitive EPT taxa were all lower in high disturbance streams than in low disturbance streams, and we found that abundance and diversity declined with an increase in the percentage of developed land in a watershed. Plecopterans in general have low tolerance values (Lenat 1993), and were rare in irregular disturbance streams and nonexistent in high disturbance streams. Several other families were found only in low disturbance streams or in low abundance in irregularly disturbed streams (Table 3). This tendency of low abundance of many taxa in disturbed watersheds with high levels of impervious surface appears to be a general occurrence (Hachmoeller et al. 1991, Lenat and Crawford 1994, Schleiger 2000, Walsh et al. 2001, Willson and Dorcas 2002). Disturbances that introduce sediment result in the death or drift of aquatic insects (Hochmoeller et al. 1991, Lenat and Crawford 1994). Our results may be associated with higher sediment loads, but more data on sediment discharge are needed from high flow periods to make conclusions.

Irregular disturbances that directly affected streams, such as drought or near-stream construction, caused declines in insect diversity and abundance, and dissolved oxygen. It is unknown whether these streams have the ability to recover from such disturbances. Although one irregular disturbance stream had the highest percentage of developed area (Reeds: 48% developed area, Table 1), early on it had high insect diversity (Figure 3b), indicating that the percentage of developed land is not the sole or best predictor of benthic insect diversity. A major disturbance occurring in or next to the stream had an overriding effect on diversity and abundance of insects. The installation of a sewer line directly disturbed two of the streams; the installation occurred in Reeds and Therese Creeks in late June and early July close to our study sites. The suspended sediment concentrations in the streams increased dramatically due to the direct pumping of muddy water into the streams as ditches were dug nearby. Not only was there no attempt to control erosion, we observed workers pumping mud from ditch digging directly into the stream. The effect of this in Reeds Creek was to reduce the total number of insects from an average of 314 individuals/sample in May and June to 54 individuals/sample in October. Other factors may have contributed to the decline, but our observations of the sediment pumped into the stream undoubtedly had an impact on the community.

Our research supports the link between urbanization, sedimentation, and declining aquatic biodiversity, and shows that development threatens small headwater streams. Streams with a high level of development and nearby construction had less diverse communities with lower abundance than streams with more heavily forested watersheds. High percentages of developed land within a watershed can help explain stream insect diversity, but direct disturbance overrides those effects. Since small headwater streams are particularly susceptible to development and disturbance, incorporation of erosion control methods, clean construction practices, and restoration and preservation of wide riparian forests should be considered to reduce runoff and preserve water quality of streams.

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