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Evaluation of single- and multi-metric benthic macroinvertebrate indicators of catchment disturbance over time at the Fort Benning Military Installation, Georgia, USA

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Abstract

Stream benthic macroinvertebrates are useful indicators of the impacts of disturbances on catchment and stream conditions because they integrate many catchment-scale ecological processes. We tested the ability of macroinvertebrate assemblages over a 3-year period to indicate the impacts of a range of disturbances resulting from military training at the Fort Benning Military Installation, Georgia. We studied seven small streams that drained catchments spanning disturbances that ranged from light infantry movements to heavy disturbances from tracked vehicle movements. The main disturbance to streams was influx of sediment associated with training and use of unpaved roads. We quantified disturbance level as the % of catchment occurring as bare ground on slopes >3% and as unpaved road cover. Disturbance level values ranged from about 3 to 15%. Nonmetric multidimensional scaling ordinations revealed macroinvertebrate assemblages were associated with catchment disturbance. Irrespective of season, several richness measures (e.g., number of Ephemeroptera, Plecoptera, and Trichoptera taxa and richness of Chironomidae) negatively corresponded with catchment disturbance, however except for chironomid richness all measures showed high variation among seasons and annually. Compositional and functional feeding group measures also showed high seasonal and annual variation, with only the % of macroinvertebrates clinging to benthic habitats (=% clingers) corresponding with disturbance. Both tolerance metrics tested, the Florida index and North Carolina biotic index, showed little seasonal and annual variation, however only the Florida index related to disturbance. A regional multimetric, the Georgia stream condition index, consistently corresponded with catchment disturbance and showed the least temporal variability. Our results further suggest a threshold at 8–10% of the catchment as bare ground and unpaved road cover, a disturbance threshold similar to that reported for other land uses.

Keywords: Stream assessment; Military training; Disturbance; Macroinvertebrates; Metric; Seasonal and annual variability

1. Introduction

Streams are excellent systems to identify and test potential indicators of land use because they are

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intimately linked to their catchments, and thus integrate catchment-scale ecological processes and cumulative responses to disturbance. Benthic macroinvertebrates are a particularly useful indicator in this regard because they occur in a wide range of stream habitats, include a wide range of functional feeding groups, compose the bulk of animal diversity, show a wide sensitivity range, have sedentary life cycles allowing relatively easy quantification, and have relatively short life cycles (usually <2 years), thus exposing most species to the source of impairment for most of their life cycle (Rosenberg and Resh, 1993).

A major source of stream disturbance associated with catchment land use is increased sedimentation and concomitant decreased habitat availability, bed stability, and benthic organic matter in the channel (Chutter, 1969; Ryan, 1991; Quist et al., 2003; Maloney et al., 2005). Macroinvertebrate response to sedimentation ranges from altered behavior (e.g., emigration from drift) to mortality (reviewed by Newcombe and MacDonald (1991) and Waters (1995)). Increased sedimentation has also reportedly reduced macroinvertebrate density, biomass, and diversity (Lenat et al., 1981; Newcombe and MacDonald, 1991; Angradi, 1999), especially of sensitive taxa (Culp et al., 1986).

Response of macroinvertebrate assemblages to anthropogenic disturbance is often evaluated using ‘‘metrics’’, which describe biological conditions from structural and/or functional assemblage measures (Karr, 1991; Barbour et al., 1996, 1999). Whereas single metrics reflect only one aspect of the assemblage (e.g., number of Ephemeroptera taxa and Shannon's H') and may not indicate effects of multiple stressors, a multimetric analysis incorporates several single assemblage/habitat metrics that encompass multiple aspects of assemblages and thus may provide a more powerful means of assessment (Karr et al., 1986).

Military installations provide excellent landscapes to examine the influence of catchment-scale disturbance on streams because they contain a wide range of disturbance conditions on relatively homogenous soils and vegetation. Numerous areas of installations have been undisturbed for over 50 years and serve as contemporary sources of high quality habitat (Cohn, 1996), whereas other areas often within a few kilometers of undisturbed sites have been heavily disturbed (e.g., soil and vegetation disturbance) by military training for decades. Disturbance from training may reduce terrestrial vegetation, increase soil compaction, and reduce soil organic matter as well as alter terrestrial biodiversity (Severinghaus et al., 1981; Goran et al., 1983; Garten et al., 2003; Quist et al., 2003). Receiving streams in high military use catchments may be similarly disturbed, often by increased sedimentation associated with high amounts of bare ground resulting from training activity (Quist et al., 2003).

Macroinvertebrate assemblages vary greatly among seasons and years (Townsend et al., 1987; Resh and Rosenberg, 1989; Maul et al., 2004), which may affect the consistency and efficacy of metrics designed to indicate biotic integrity. Numerous studies have assessed seasonal, spatial, and site variation in biotic metrics (e.g., Linke et al., 1999; Li et al., 2001; Clarke et al., 2002). However, to our knowledge, there have been no comparisons between single metric and multimetric variability among seasons and years to identify metrics that are robust to temporal variation. Our objectives were to (1) evaluate the efficacy of single- and multi-metric benthic macroinvertebrate measures to indicate catchment-scale disturbance from military land use, and (2) assess the variability of both sets of metrics within and among sampling years.

2. Methods

2.1. Study site

Our study was on the Fort Benning Military Installation (FBMI), in the Southeastern Plains ecoregion of central western Georgia, USA (Fig. 1). FBMI (area = 735 km^2) is primarily drained by Upatoi Creek and has a smooth to irregular plains land-surface form (Omernik, 1987). The climate is humid and mild with precipitation occurring year round (mean = 105 cm/y). Upland vegetation is mostly pine (*Pinus palustris*, *P. echinata*, and *P. taeda*) and mixed hardwoods (mostly *Quercus* spp.), whereas floodplain vegetation is primarily mesic hardwoods dominated by *Nyssa sylvatica*. Dominant soil series within study catchments were Troup (deep, excessively drained, moderately permeable loamy, kaolinitic, thermic Grossarenic Kandiudults), Lakeland (very deep,

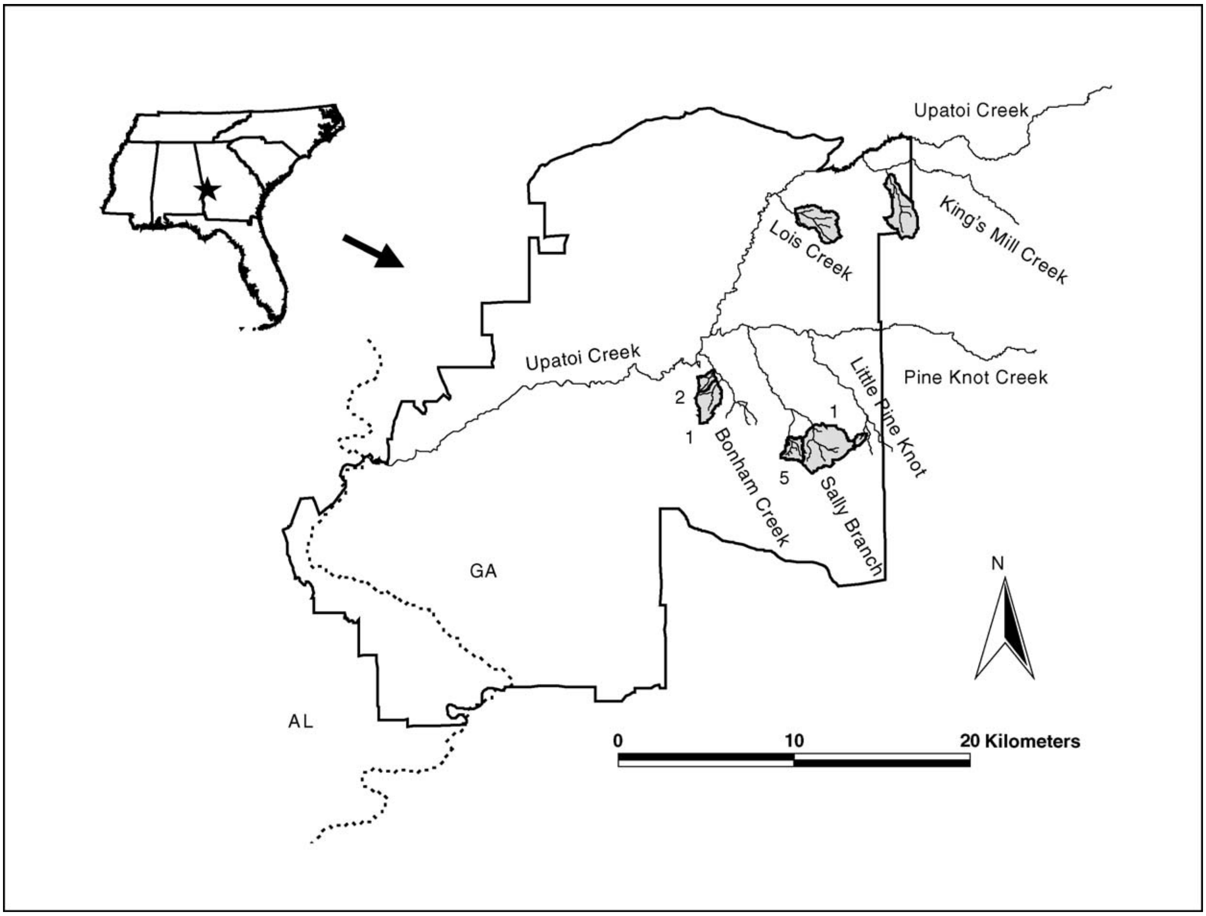

Fig. 1. Locations of study catchments (polygons) within Fort Benning Military Installation, GA. Dotted line in middle figure represents the Chattahoochee River, which separates Alabama (AL) and Georgia (GA). Numbers in the right figure identify watersheds on the same stream (e.g., 1 and 2 on the Bonham Creek represent Bonham Creek Tributaries 1 and 2, BC1 and BC2, respectively).

excessively drained, rapidly to very rapidly permeable, thermic coated Typic Quartzipsamments), Nankin (very deep, well drained, moderately slowly permeable, fine, kaolinitic, thermic Typic Kanhapludults) and Cowarts (very deep, well drained and moderately well drained, fine-loamy, kaolinitic, thermic Typic Kanhapludults) soils (Soil Survey Staff, 2004). Parent geology was mainly Cusseta Sand (Lawton, 1976). Streams channels are low gradient (slopes 1–2.5%), sinuous, and sandy, often with large amounts of entrained coarse woody debris (CWD) and leaf litter (Felley, 1992; Maloney et al., 2005).

The US military purchased most FBMI land between 1918 and 1942. Collectively, FBMI hosts a wide range of military training activities including dismounted infantry, tracked vehicle maneuvers (i.e., tanks), heavy weapons usage, and airborne training drop zones (USAIC, 2001; Dale et al., 2002). These strongly contrasting land uses often are spatially segregated in different training compartments, making it possible to select study catchments that varied in the type of military activity and associated disturbance.

We selected seven catchments that spanned the range of landscape disturbance at FBMI. Our low-disturbance streams drained catchments within compartments reserved largely for dismounted infantry training, whereas most high-disturbance streams were within compartments reserved for heavy-tracked vehicle training.

2.2. Land-use quantification

The most obvious disturbances from military land use at FBMI are the creation of bare ground from heavy-tracked vehicle training and creation, and repeated use of unpaved roads and trails by military and nonmilitary vehicles (Maloney et al., 2005). These two disturbance sources were similar on remotely sensed data (at the catchment scale), so we could not ascertain their separate influences on stream invertebrate assemblages. Therefore, we quantified disturbance as the amount of bare ground on slopes >3% and unpaved road and trail cover in each catchment (%BGRD) using geographic information system (GIS) data sets (i.e., roads: 10 m resolution, 1995 coverage; digital orthophotographs 1:5000, July 1999; digital elevation models, DEMs, 1:24,000, 10 m grid size, 1993; and Landsat imagery, 28.5 m resolution, July and December 1999). We processed GIS data sets to catchment boundaries using ArcView© software (Environmental Systems Research Institute, Inc., Redlands, CA, see also Maloney et al., 2005).

2.3. Macroinvertebrate sampling

We quantified benthic macroinvertebrates in May (spring), September (summer), and January (winter) over a 3-year period (January 2000–September 2002), using four Hester–Dendy (HD) multiplate sampling units (Merritt and Cummins, 1996), with three multiplates per unit (total area = 0.33 m^2). We left HDs in situ for a 6- to 8-week colonization period. In addition, we also used two D-frame sweep net samples (250 μm mesh) to sample general benthic habitats (e.g., runs) in each study site, with net samples taken downstream and upstream of HD stations on each date. We field-preserved all samples in 95% EtOH, following elutriation of excess sediment. In the laboratory, we sorted the entire HD sample and subsampled sweep net samples (at least 200 organisms, see Vinson and Hawkins, 1996). We identified macroinvertebrates to the lowest taxonomic level possible (usually genus or morphospecies) using keys in Merritt and Cummins (1996), Wiggins (1996), and Epler (2001).

2.4. Quantification of habitat

We characterized stream habitat both at the catchment and stream-reach scale. We quantified catchment area as the drainage area upgradient from our furthest downstream sampling point using DEMs and ArcView. We measured stream discharge (incremental method, Gore, 1996) approximately every 2 months using a Marsh–McBirney (model 2000) flow meter. We quantified stream temperature continuously using HOBO® H8 temperature loggers (15–30 min intervals, Onset Computer Corporation, Bourne, MA) over the study in each stream. We calculated seasonal means for discharge and temperature. Stream site-specific current velocity and depth were based on means of three to four measures taken at each macroinvertebrate sampling location. We also visually estimated the relative abundance of instream CWD by classifying CWD over the streambed cover into four categories (0 = 0–25% of bed covered by CWD; 1 = 26–50%, 2 = 51–75%; 3 = >75%) to estimate the amount of local available woody habitat. Site-specific measures of current velocity, depth, and CWD relative abundance were averaged for each stream and then averaged by season.

2.5. Metrics

We tested a variety of single benthic macroinvertebrate metrics selected from standard USEPA rapid bioassessment protocols (Barbour et al., 1999), two regionally defined tolerance metrics, the Florida index (FLDEP, 2002) and the North Carolina biotic index (NCBI, NCDENR, 2003), and also a regional multimetric designed for Georgia streams (hereafter the Georgia stream condition index, GASCI, GADNR, 2002). In total, we tested 9 richness, 10 composition, 5 functional feeding group, and 2 tolerance metrics, and 1 multimetric index (Table 1).

For the Florida index, we separated taxa into three classes, with class 1 (sensitive) being assigned a value of 2, class 2 (moderately tolerant) assigned a value of 1, and class 3 (tolerant) a value of 0. The index is the sum of taxa in the respective classes, with lower and higher values indicating greater and lesser likelihood of stream impairment, respectively (FLDEP, 2002). NCBI is a tolerance index derived for streams in North Carolina. Taxa are assigned tolerance values accord-

Table 1
Definitions and predicted response of macroinvertebrate metrics used in the study

Measure	Metric	Definition	Predicted response
Richness	No. of Ephemeroptera taxa	No. of taxa in the order Ephemeroptera	Decrease
	No. of Plecoptera taxa	No. of taxa in the order Plecoptera	Decrease
	No. of Trichoptera taxa	No. of taxa in the order Trichoptera	Decrease
	No. of EPT taxa[a]	No. of taxa in the orders Ephemeroptera, Plecoptera, Trichoptera	Decrease
	No. of Chironomidae taxa[a]	No. of taxa in the family Chironomidae	Decrease
	No. of Orthocladiinae taxa	No. of taxa in the subfamily Orthocladiinae	Decrease
	No. of Tanytarsini taxa	No. of taxa in the tribe Tanytarsini	Decrease
	No. of taxa[a]	No. of aquatic insect taxa	Decrease
	No. of clinger taxa	No. of clinger habitat group	Decrease
Composition	Shannon's H'	Species diversity of assemblage	Decrease
	% Diptera[a]	% of assemblage as dipterans	Increase
	% Ephemeroptera	% of assemblage as mayflies	Decrease
	% Plecoptera	% of assemblage as stoneflies	Decrease
	% Trichoptera	% of assemblage as caddisflies	Decrease
	% Hydropsychidae of Trichoptera	% of total caddisflies as Hydropsychidae	Increase
	% Oligochaeta	% of assemblage as aquatic worms	Variable
	% Orthocladiinae of Chironomidae	% of chironomids as Orthocladiinae	Increase
	% Dominant of total[a]	Dominance of most abundant taxa	Increase
	% Clingers	% of clinger habitat group	Decrease
	% Tanytarsini of Chironomidae	% of chironomids in the tribe Tanytarsini	Decrease
Feeding group	% Predators	% of FFG as predators	Variable
	% Scrapers	% of FFG as scrapers	Decrease
	% Shredders	% of FFG as shredders	Decrease
	% Filterers[a]	% of FFG as collector—filterers	Decrease
	% Collector—gatherers	% of FFG as collector—gatherers	Variable
Tolerance	Florida index[a]	Weighted sum of intolerant taxa	Decrease
	NCBI	North Carolina biotic index	Decrease
Multimetric	GASCI	Georgia stream condition index	Decrease

Each metric's predicted response to disturbance came from published literature (Cummins et al., 1989; Kerans and Karr, 1994; Barbour et al., 1996, 1999). EPT: Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies); GASCI: Georgia stream condition index, FFG: functional feeding group.

[a] Single metrics used in GASCI calculation. See text for information about GASCI.

ing to tolerance level, based on a 0–10 scale, where 0 represents intolerant taxa and 10 represents highly tolerant taxa (NCDENR, 2003). NCBI is calculated as

$$\mathrm{NCBI} = \left(\frac{\mathrm{sum}(\mathrm{TV}_i)(n_i)}{N}\right) \quad (1)$$

where TV_i is the tolerance value of taxa i, n_i the abundance value of taxa i, and N is the sum of abundance values for all taxa in the sample (NCDENR, 2003). NCBI scores range from 0 to 10, where 0 and 10 indicate the highest and lowest water quality, respectively. In addition, we used a correction factor for non-summer samples for the Coastal Plains ecoregions (NCDENR, 2003).

The GASCI incorporates seven macroinvertebrate metrics (taxa richness, EPT richness, Chironomidae richness, % dominant taxa, % Diptera, Florida index, % filterers) and one habitat metric (calculated by summation of assessment scores of 10 habitat characteristics, including channel sinuosity, bank stability, riparian vegetation features, see GADNR, 2002). Each metric was assigned a score of 1, 3, or 5 depending on predefined ranges for each metric for the summer and winter seasons. For example, taxa richness has the following pre-defined ranges and scores: >30 taxa given a score of 5, 16–30 taxa given a score of 3, and <16 taxa given a score of 1. Each metric has predefined ranges with associated scores and the overall GASCI score is the summation of individual metric scores for each stream.

2.6. Data analysis

We used nonmetric multidimensional scaling ordinations (NMS, McCune and Grace, 2002) to examine seasonal macroinvertebrate assemblage similarity within and among streams. Nonmetric multidimensional scaling is an indirect gradient analysis technique that uses pairwise dissimilarity matrices to estimate site (stream) position in species space (Jongman et al., 1995), and is a more robust ordination method than principal components analysis or detrended correspondence analysis (Minchin, 1987). Axes scores from NMS can be related to environmental variables to reveal ecological patterns (Hawkins et al., 1997). Rare taxa provide redundant information for ordinations, and the final stress of an NMS ordination increases with sample size (Marchant, 1999; McCune and Grace, 2002), so we excluded taxa occurring in <10% of samples prior to ordinations to reduce these biases. We averaged macroinvertebrate abundance data within a site by season, square-root transformed the data, and then performed NMS ordinations using PC-ORD (MjM Software Design, Gleneden Beach, Oregon). We then regressed stream-specific NMS scores with independent variables to determine which habitat or land use variable was related to macroinvertebrate assemblages.

We used correlation analysis on season-average stream metric values to assess the degree to which macroinvertebrate metrics were related to catchment disturbance (as %BGRD). We transformed all indicator variables (counts: square root, percentages: arcsine square root) as necessary prior to analyses to satisfy normality.

We calculated 95% confidence limits for the three least-disturbed streams (BC2, KM1, LC; Fig. 1), as a measure of low-disturbance conditions, to identify potential disturbance thresholds. We chose this statistic because it is commonly used to display variation within a data set (Zar, 1999). We chose the three least-disturbed streams because (1) each stream showed <5% BGRD, (2) an obvious break in disturbance levels occurred between the third (KM1, 4.68% BGRD) and fourth (SB1, 8.38%) least-disturbed catchment, and (3) these streams showed higher amounts of and more stable benthic habitat than other study streams (see Maloney et al., 2005). Our repeated sampling design (2–3 years, three seasons per stream) allowed us to further assess the variability of each metric both among seasons and years. For seasonal variation (i.e., variability within 1 year over different seasons) we calculated and compared coefficient of variation (CV) for each year for each stream, using season values as replicates ($n = 3$). For annual variation, we calculated and compared season-specific CVs for each stream using annual values as replicates ($n = 2$–3 depending on stream).

3. Results

Study catchments were small (range = 0.33–5.43 km^2) and showed a wide range of landscape disturbance (%BGRD, 3.15–14.66%, Table 2). Average stream discharge and current velocity ranged from <0.001 to 0.045 m^3/s and 0.028 to 0.289 m/s, respectively. Average stream width and water depth ranged 0.75–2.44 and 0.02–0.19 m, respectively (Table 2). Site-specific CWD cover ranged from 0.65 (<25% of the streambed) to 2.58 (51–75% cover). Maximum and average temperatures were highest in summer (28.7, 22.3 °C, respectively), followed by spring (24.5, 16.1 °C) and winter (18.62, 8.4 °C).

Nonmetric multidimensional scaling ordinations successfully distinguished variation in catchment disturbance among study streams, but also suggested an influence of channel and seasonal variables on assemblages (Fig. 2). Axis 1 accounted for most of the variation in assemblages ($R^2 = 0.46$), followed by axis 3 ($R^2 = 0.23$), and axis 2 ($R^2 = 0.14$). When axes 1 and 3 were regressed against land use and habitat variables axis 1 was best explained by catchment disturbance (as %BRGD) ($R^2_{adj} = 0.76, P < 0.001$), whereas axis 3 corresponded to season-average streamwater temperature and relative abundance of CWD ($R^2_{adj} = 0.54$, $P = 0.0003$). These relationships suggest that assemblage similarity associated with axis 1 was driven by land use (Table 3), whereas assemblage similarity associated with axis 3 was driven by habitat and season.

Correlation analysis revealed that macroinvertebrate richness measures were the best simple metrics

Table 2
Study stream and catchment characteristics in order of %BGRD

Stream	Abbreviation	%BGRD	Drainage area (km^2)	Season	Discharge (m^3/s)	Site-specific				Temperature (°C)		
						Current (m/s)	Depth (m)	Width (m)	CWD	Mean	Min	Max
Bonham Creek (Tributary 2)	BC2	3.15	0.75	Spring	0.003	0.074	0.11	0.96	0.65	17.41	7.83	23.63
				Summer	0.001	0.028	0.06	0.75	1.04	22.89	17.14	31.12
				Winter	0.008	0.171	0.14	1.18	1.17	8.64	2.03	16.00
Lois Creek	LC	3.67	3.32	Spring	0.040	0.289	0.19	1.34	1.13	15.64	9.00	26.30
				Summer	0.008	0.128	0.10	1.15	1.54	23.20	18.28	26.73
				Winter	0.019	0.189	0.15	1.64	1.77	8.32	2.46	26.70
King's Mill Creek (Tributary 1)	KM1	4.63	3.69	Spring	0.044	0.139	0.19	2.13	0.80	16.57	8.23	23.63
				Summer	0.014	0.097	0.15	2.07	1.47	22.38	17.14	25.95
				Winter	0.028	0.130	0.17	2.24	1.45	8.84	2.03	26.73
Sally Branch (Tributary 1)	SB1	8.38	5.43	Spring	0.045	0.243	0.09	1.90	0.79	15.82	8.63	29.90
				Summer	0.007	0.146	0.06	1.55	0.79	22.91	17.90	33.17
				Winter	0.025	0.222	0.17	2.44	1.33	6.91	0.29	14.85
Bonham Creek (Tributary 1)	BC1	10.46	2.10	Spring	0.008	0.110	0.17	1.27	1.20	15.19	8.63	21.71
				Summer	0.005	0.103	0.13	1.17	1.63	21.87	18.28	29.90
				Winter	0.012	0.116	0.17	1.52	2.58	9.03	2.89	15.62
Little Pine Knot	LPK	11.26	0.33	Spring	0.003	0.118	0.06	1.04	0.70	17.22	9.82	21.71
				Summer	0.002	0.111	0.05	0.83	0.83	21.42	17.52	28.70
				Winter	0.003	0.137	0.08	1.03	1.01	11.21	5.81	17.14
Sally Branch (Tributary 5)	SB5	14.66	1.27	Spring	0.014	0.147	0.06	0.95	0.94	15.09	6.20	24.80
				Summer	<0.001	ND	0.02	0.79	1.00	22.53	19.04	25.17
				Winter	0.002	0.076	0.07	1.14	1.08	5.62	−1.06	13.32

%BGRD: the proportion of bare ground on slopes >3% and unpaved road cover in a catchment, CWD: coarse woody debris measured as the planar coverage of stream bottom (see Section 2), Min: minimum, Max: maximum, ND: no data. Site-specific indicates mean values for site locations in a stream.

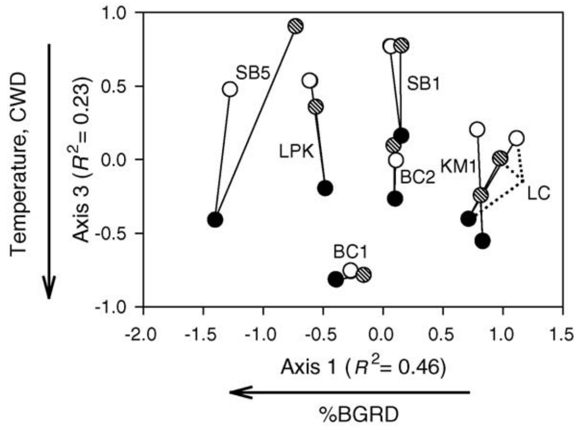

Fig. 2. Results of nonmetric multidimensional scaling (NMS) ordination. Symbols represent stream-specific macroinvertebrate scores, and lines connecting symbols show seasonal changes in scores for each stream. Open circles: winter, shaded circles: spring, and solid circles: summer. R^2 values represent the proportion of variation in the macroinvertebrate assemblage similarity accounted for by each axis. Arrows on axes indicate direction of relationships between habitat variables and NMS scores (see text for values). Axis scores are raw values, stress level = 11.8 for the three-dimension solution, with a final instability of 0.00001 after 91 iterations. CWD: coarse woody debris.

indicating disturbance from land use. The number of clinger taxa consistently related to catchment disturbance (as %BGRD, Table 3). Total number of EPT taxa ranged from 2 to 16 per stream per season and was negatively related to %BGRD in all seasons (Fig. 3, Table 3). At %BGRD levels >10 EPT richness fell below the 95% confidence limit for the three least-disturbed streams (Fig. 3). Modeled thresholds levels (%BGRD where correlation intersected the lower 95% confidence limit for the three least-disturbed streams) for EPT richness were 6.51, 8.46, and 5.67% BGRD for spring, summer, and winter, respectively. The number of Ephemeroptera taxa consistently correlated with %BGRD as did the number of Trichoptera taxa during spring and winter, whereas the number of Plecoptera taxa (range from 0 to 6 per season) corresponded with %BGRD only during spring (Table 3). The number of Chironomidae taxa was strongly inversely correlated with catchment disturbance in all seasons and consistently showed values below the 95% confidence limit of the three least-disturbed streams for catchments with BGRD values >10%, modeled threshold levels were 9.55, 5.28, and 7.84% BGRD for spring, summer, and winter, respectively (Table 3, Fig. 3). The number of Tanytarsini taxa, a tribe of Chironomidae, was consistently negatively related to %BGRD.

Composition and feeding measures typically showed no relationship with %BGRD (Table 3). Only %clingers consistently indicated catchment disturbance, being negatively related to %BGRD in all seasons (Table 3). Tolerance metrics showed mixed success as indicators of catchment disturbance. The Florida index scores were negatively related to %BGRD in all seasons (Fig. 3). At %BGRD levels >10 the Florida index fell consistently below the 95% confidence limit for the three least-disturbed streams, modeled thresholds were 6.27, 9.90, and 6.10% BGRD for spring, summer, and winter, respectively (Fig. 3). The NCBI showed no relationship to %BGRD in spring and summer and only a weak relationship in winter (Table 3). Regardless of season, the GASCI was negatively correlated with %BGRD (Table 3). At BGRD >8% GASCI scores fell below the 95% confidence limit for the three least-disturbed streams, modeled threshold levels were 4.84 and 5.36% BGRD for summer and winter, respectively (Fig. 4).

Variability analysis revealed that macroinvertebrate composition and functional feeding group metrics were more variable annually (mean CV = 52.0 and 43.4%, respectively, Fig. 5) and seasonally (38.6 and 37.1%, respectively) than richness metrics (25.0 and 20.9%, respectively) and tolerance metrics (7.6 and 7.9%, respectively, Fig. 5, see Appendix A). The GASCI multimetric index showed lower seasonal and annual variability than the other metrics (mean CV = 3.7 and 6.3%, respectively, Fig. 5).

4. Discussion

A useful ecological indicator of disturbance should be easily measured, sensitive, anticipatory, and integrative across key environmental gradients (Cairns et al., 1993; Dale and Beyeler, 2001). Land managers also require indicators that have low variation among seasons and/or years. Results of our study suggest that benthic macroinvertebrate assemblages are useful indicators of a wide range of catchment disturbance, as measured by %BGRD, and its impact on receiving

Table 3
Pearson correlation coefficients between benthic macroinvertebrate metrics and the proportion of catchment disturbance as bare ground and unpaved road cover (%BGRD)

Type	Metric	Spring	Summer	Winter
Richness	No. of Ephemeroptera taxa	−0.81**	−0.82**	−0.88**
	No. of Plecoptera taxa	−0.74**	–	–
	No. of Trichoptera taxa	−0.81**	–	−0.87**
	No. of EPT taxa	−0.88**	−0.72*	−0.93**
	No. of Chironomidae taxa	−0.76**	−0.83**	−0.84**
	No. of Orthocladiinae taxa	–	–	–
	No. of Tanytarsini taxa	−0.85**	−0.77**	−0.90**
	No. of taxa	−0.72*	–	−0.84**
	No. of clinger taxa	−0.91**	−0.73*	−0.96**
Composition	Shannon's H'	–	–	–
	% Diptera	–	–	–
	% Ephemeroptera	–	–	−0.77**
	% Plecoptera	–	–	–
	% Trichoptera	−0.69*	–	−0.70*
	% Hydropsychidae of Trichoptera	–	0.78**	–
	% Oligochaeta	–	–	–
	% Orthocladiinae of Chironomidae	–	–	0.71*
	% Dominant of total	–	0.96**	–
	% Clingers	−0.77**	−0.69*	−0.79**
	% Tanytarsini of Chironomidae	–	–	−0.69*
Feeding group	% Predators	–	–	–
	% Scrapers	–	−0.89**	–
	% Shredders	–	–	–
	% Filterers	–	–	–
	% Collector—gatherers	–	–	–
Tolerance	Florida index	−0.97**	−0.88**	−0.95**
	NCBI	–	–	0.71*
Multimetric	GASCI	NA	−0.96**	−0.95**

Metric abbreviations defined in Table 1. NA: metric not applicable in this season. '–' Nonsignificant ($P > 0.10$).
* $P < 0.10$.
** $P < 0.05$.

streams. Our results also suggest that, except for Chironomidae richness, all single metrics displayed high seasonal and annual variation, and thus were less useful in discriminating streams of contrasting disturbance than the comparatively less temporally variable Florida index and the multimetric GASCI. Our data also suggest the presence of a disturbance threshold between 8 and 10% of the catchment as bare ground and unpaved road cover, where several metrics fell below the 95% confidence limit for the three least-disturbed streams. However, this threshold is potentially high, as some taxa likely were negatively affected at much lower %BGRD, as evidenced by the modeled threshold levels ranging from 4.8 to 9.9% BGRD (Figs. 3 and 4). Interestingly, although catchment disturbance from military training is different than that from urbanization (i.e., impervious surface), this threshold is within the range of disturbance thresholds identified for urbanized impacts on streams (8–20%, Arnold and Gibbons, 1996; Paul and Meyer, 2001; Wang et al., 2001).

The main disturbance in our catchments was removal of vegetation, concomitant disruption of soil surface, and general use of unpaved roads, each of which likely increased erosion and subsequent sedimentation of stream channels. Results of our NMS ordinations suggested that macroinvertebrate assemblages, as a whole, were affected by catchment disturbance, as indicated by the high separation of site scores along axis 1, the axis that was highly associated

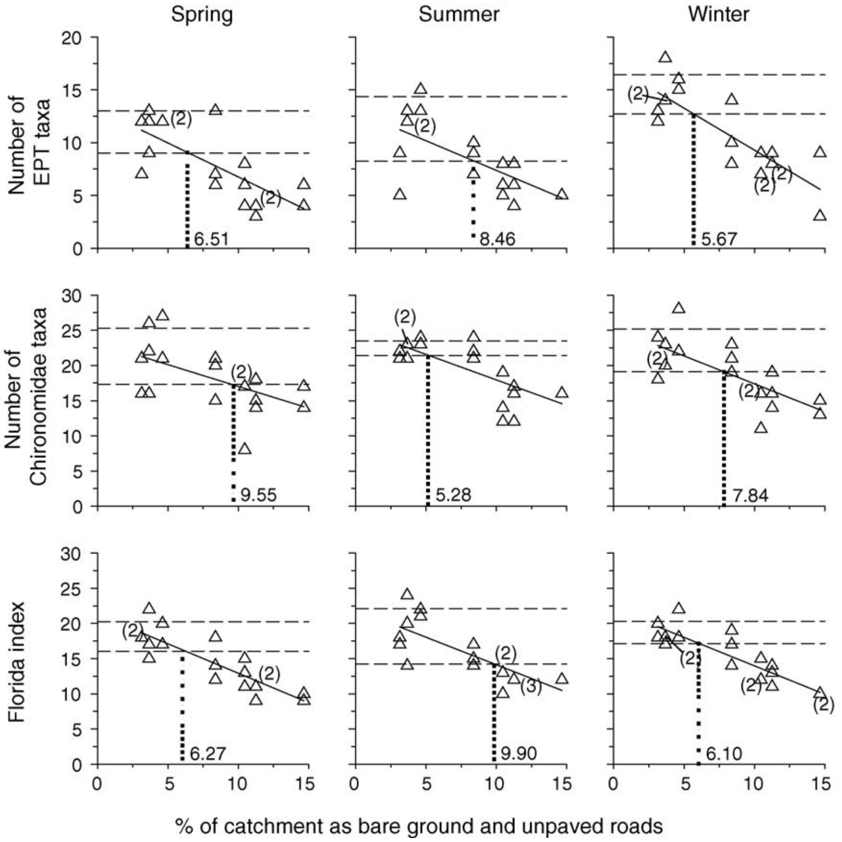

Fig. 3. Relationships between %BGRD (% of catchment as bare ground on slopes >3% and unpaved road cover) and EPT richness, Chironomidae richness, and Florida index by season. Solid lines represent trends using means (all trends significant at $P = 0.05$ see Table 3 for r and P values), dashed lines represent 95% upper and lower confidence limits of the three least disturbed streams in the data set (BC2, KM1, K13), dotted lines indicate %BGRD where modeled relationship passes lower 95% confidence limits of least disturbed streams. Points represent individual stream values over several years. Numbers in parentheses indicate overlapping points.

with %BGRD. A likely environmental driver in separation among benthic assemblages among streams was a reduction of available in-stream habitat (CWD) and decreased bed stability in high-disturbed streams (Maloney et al., 2005). Amounts of CWD (and associated snags) and degree of bed stability have been shown to affect available macroinvertebrate habitat in sandy-bottomed streams (Benke et al., 1984; Wallace and Benke, 1984; Benke and Wallace, 1990). Moreover, the NMS analysis revealed a seasonal influence on macroinvertebrate assemblages, with summer NMS scores being lower (i.e., assemblages more dissimilar) than respective spring or winter scores in most streams. Summer assemblages were possibly influenced by physical stress associated with low flows and/or high temperatures, as this season had the lowest average discharge, site-specific flow, depth, and width, and highest average temperature of all seasons (Table 2). Strong seasonality in benthic macroinvertebrates have been reported from other sandy-bottomed streams (Benke et al., 1984; Lenat, 1993) possibly in response to hydrologic stress (Felley, 1992, but see Boulton et al., 1992; Hutchens et al., 1998).

Except for Chironomidae richness, our data suggest that use of single metrics did not adequately indicate catchment disturbance at FBMI as a result of high seasonal and annual variation, low correlation with disturbance, or a combination of both high variation and low correspondence with disturbance. For example, EPT richness correlated well with

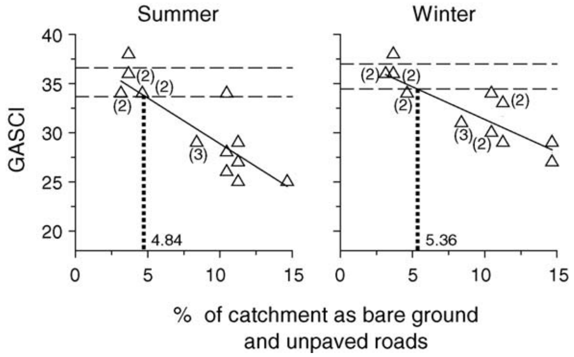

Fig. 4. Relationships between Georgia stream condition index (GASCI) values and %BGRD (% of catchment as bare ground on slopes >3% and unpaved road cover) for summer and winter. Solid lines represent trends using means (all trends significant at $P = 0.05$ see Table 3 for r and P values), dashed lines represent 95% upper and lower confidence limits of the three least disturbed streams in the data set (BC2, KM1, K13), dotted lines indicate %BGRD where modeled relationship passes lower 95% confidence limits of least disturbed streams. Points represent individual stream values over several years. Numbers in parentheses indicate overlapping points.

disturbance in all seasons and had sufficient number of taxa seasonally collected per stream (4–15); however it also showed high seasonal and annual variation. The number of EPT taxa is a widely used indicator of stream integrity (Plafkin et al., 1989; Klemm et al., 2002) and is incorporated within numerous

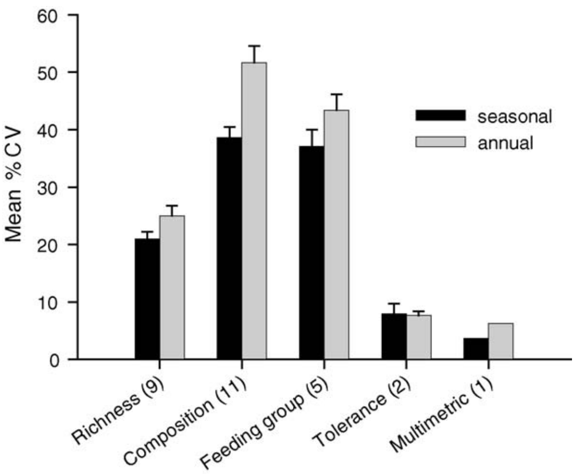

Fig. 5. Mean (+1 S.E.) coefficient of variation (CV) of the five categories of macroinvertebrate metrics among seasons (spring, summer, winter) and years (2000–2002) by category. Numbers in parentheses indicate the number of metrics in each category.

multimetric indices (Barbour et al., 1999; Royer et al., 2001; Ofenböck et al., 2004). Our data suggest its high variability may preclude its use as a stand-alone metric in low gradient, sandy-bottomed streams. Further, it is important to note that the separate use of Ephemeroptera, Plecoptera, and Trichoptera taxa as indicators was inadequate because of the low numbers of these taxa seasonally collected per stream (Ephemeroptera 0–4, Plecoptera 0–6, and Trichoptera 1–8, K.O. Maloney unpublished data) and their relatively high seasonal and annual variation, which together resulted in low detection ability. Low numbers of taxa in these aquatic insect orders has been reported elsewhere for sandy-bottomed streams (Barbour et al., 1996) and may generally constrain the separate use of these metrics in such streams. Moreover, composition and functional feeding group metrics were not reliable indicators of disturbance and generally had high seasonal variation as well as high annual variation. The only successful indicator within this group, the % of clinger taxa, consistently showed a negative relationship with disturbance likely in response to lower amounts of CWD in high-disturbance catchments (Maloney et al., 2005). These taxa require firm substrate such as CWD as habitat. The % of clinger taxa, however, showed high seasonal and annual variation suggesting an inconsistent temporal relationship with catchment disturbance. The high variation of composition and feeding group metrics has been reported elsewhere (Resh and Jackson, 1993; Fore et al., 1996) and may be a result of the inherent patchy nature of stream substrates (Pringle et al., 1988; Townsend, 1989) as well as the difficulty in accurately assigning species to specific feeding groups (Cummins and Klug, 1979; Merritt and Cummins, 1996).

The number of Chironomidae taxa was a reliable indicator of disturbance and had relatively low seasonal and annual variation. We collected a total of 50 chironomid taxa (>25% of the total taxa collected), which likely vary greatly in trophic level, habitat preference, life cycle, and tolerance (Beck, 1954; Merritt and Cummins, 1996; Vuori and Joensuu, 1996; Barbour et al., 1999; Shaw and Richardson, 2001). Such features make Chironomidae a good candidate for assessing stream condition, especially where they are diverse and numerically dominant. Chironomids compose the bulk of macroinvertebrate richness in many streams in North America

(Barton, 1980; Benke et al., 1984; Jackson and Fisher, 1986; Bourassa and Morin, 1995), South America (Bojsen and Jacobsen, 2003; Miserendino, 2004), Europe (Aagaard et al., 1997; Solimini et al., 2001; Arscott et al., 2003) and Australia (Kay et al., 2001; Milner et al., 2001). As a cautionary note, however, use of subsets of Chironomidae was not as effective in indicating disturbance in our study. For example, the number of Tanytarsini taxa was negatively related to %BGRD in all seasons and also showed low seasonal and annual variation, however this metric was not robust because of low richness in our study (two to four taxa per stream per season).

Regionally defined tolerance metrics and multimetric indices showed mixed ability to indicate catchment disturbance. The NCBI was unrelated to catchment disturbance in spring and summer and only weakly related to disturbance in winter, whereas the Florida index successfully indicated catchment disturbance in all seasons. The Florida index also had relatively low seasonal and annual variation. However, the Florida index uses a presence/absence approach, which may not identify alterations to the assemblage compositional structure from disturbance. The GASCI incorporates the Florida index along with six other metrics (with two inclusive metrics, the number of EPT taxa and number of Chironomidae taxa being useful indicators) and a habitat assessment score into a single robust score, reducing the limitations of a presence/absence method. The GASCI indicated catchment disturbance for both the summer and winter and had relatively low seasonal and annual variation, which taken together suggest the GASCI was a successful indicator for our streams.

Resource managers must accurately and consistently assess potential impacts of land use on receiving streams. Our results suggest land managers at FBMI can use preexisting, ecoregion-based multimetric indices to ascertain the degree of stream impairment caused by training and related land uses. These indices also may be effective in other southeastern US streams where sediment is the main pollutant (including other USDoD lands, e.g., Fort Stewart, Fort Mitchell, Fort Polk; USDoD, 2004). Sediment was the main stressor in our streams, thus restoration or remediation should focus on reducing intrusion of eroded sediment from upland areas and unpaved roads. In particular, management strategies should be aimed at protecting channels from upland sediment sources, which may include implementation of improved road design, effective buffer strips, and revegetation of bare ground. Each of the above practices is currently in use at FBMI, and which also may apply to other sediment-disturbed streams in the southeast.

Our results not only provide further support for the highly variable nature of single metrics (e.g., Linke et al., 1999; Li et al., 2001; Clarke et al., 2002), but also expand on these earlier findings by documenting the high variation in single metrics not only among seasons, but also among years. Most states in the US have programs already in place that incorporate multimetric approaches to bioassessment (Barbour et al., 2000); however, some states still rely heavily on use of single metrics (Klemm et al., 2002). High seasonal and annual variation of single metrics shown in our study may, during times when such metrics are used alone, result in misidentification of impaired conditions and/or site misclassification. It is logical to infer, therefore, that ecoregion-based multimetrics indices, such as those developed within the US and Europe, may be the most accurate, and thus appropriate, indicators of stream integrity (Barbour et al., 1999; Vlek et al., 2004).

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Appendix A

Results of coefficient of variance (%CV) analysis. Abbreviations defined in Table 1

Type	Metric	Within years coefficient of variation			Among years coefficient of variation		
		Mean	Min	Max	Mean	Min	Max
Richness measures	No. of Ephemeroptera taxa	39.28	0.00	141.42	56.99	0.00	173.21
	No. of Plecoptera taxa	22.03	0.00	34.64	26.97	0.00	52.92
	No. of Trichoptera taxa	38.61	0.00	141.42	43.36	0.00	100.00
	No. of EPT taxa	22.68	0.00	70.71	25.98	7.69	50.94
	No. of Chironomidae taxa	15.11	3.01	37.12	11.69	4.55	23.18
	No. of Orthocladiinae taxa	16.48	0.00	32.73	18.79	9.12	30.93
	No. of Tanytarsini taxa	7.40	0.00	33.33	17.80	0.00	43.30
	No. of taxa	10.98	1.30	30.88	9.47	1.04	17.90
	No. of clinger taxa	16.02	4.56	38.57	14.09	0.00	28.64
Composition measures	Shannon H'	6.41	0.53	18.66	8.06	0.84	20.97
	% Diptera	17.67	3.28	52.43	21.18	2.20	42.32
	% Ephemeroptera	74.31	7.41	141.42	118.09	41.28	173.21
	% Plecoptera	48.03	10.21	114.08	74.53	31.67	117.85
	% Trichoptera	62.34	1.59	141.42	88.93	42.72	142.07
	% Hydropsychidae of Trichoptera	37.89	2.42	141.42	59.95	16.77	111.80
	% Oligochaeta	55.08	2.42	148.39	52.25	10.76	92.34
	% Orthocladiinae of Chironomidae	32.06	3.57	84.21	33.15	8.98	58.49
	% Dominant of total	27.64	1.06	57.76	27.12	12.02	46.10
	% Clingers	30.68	3.92	74.00	42.59	19.28	81.05
	% Tanytarsini of Chironomidae	32.94	8.56	62.81	42.66	11.34	103.77
Feeding group	% Predators	26.23	1.59	64.88	34.75	6.75	77.53
	% Scrapers	58.93	1.42	121.63	47.96	11.10	86.09
	% Shredders	45.38	6.56	110.70	65.53	20.27	110.34
	% Filterers	28.14	6.49	90.89	37.19	11.57	70.46
	% Collector—gatherers	26.74	2.71	70.41	31.54	7.72	62.93
Tolerance metrics	Florida index	10.47	0.00	26.03	8.64	0.00	18.52
	NCBI	5.34	0.27	9.57	6.66	0.42	17.75
Multimetric	GASCI	3.66	0.00	14.19	6.27	0.00	18.86

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