water MDPI

Forested Riparian Buffers Change the Taxonomic and Functional Composition of Stream Invertebrate Communities in Agricultural Catchments

Supplementary material

Table S1. Environmental variables (mean ± 1 SD) at unbuffered and buffered reaches in 10 boreal streams. Variables showing significant difference between the reaches are shown in bold text (paired *t*-test, $p < 0.05$). Catchment land use was not included as the individual streams were nested in the same sub-catchments. Statistical significance: ** < 0.01, * < 0.05, †< 0.1.

VARIABLE	Unbuffered	Buffered	*t*-ratio	*p* value
Riparian buffer size (m^2)	**1321 ± 1473**	**45415 ± 38904**	**−6.37**	**
Length (m)	**38 ± 48**	**510 ± 321**	**−6.33**	**
Width (m)	**23 ± 18**	**85 ± 42**	**−6.04**	**
Tree density (trees/m^2)	0.04 ± 0.03	0.06 ± 0.02	−1.51	0.1644
Unmanaged grass (%)	**32±20**	**4.9±6.9**	**−4.27**	**
Herbs (%)	34.5±23.9	31.3±19.7	−0.13	0.9004
Moss/lichens (%)	**3.7±4.8**	**17.7±12.1**	**4.24**	**
Trees/shrubs (%)	**19±14**	**48±14.7**	**3.33**	**
Rocks/bedrock (%)	**6.4±5.7**	**16.8±9.5**	**2.58**	*
Plant litter (%)	**11.2±12.3**	**47±16.6**	**4.83**	**
Bare ground (%)	5.8±4.4	4.1±3.6	−0.93	0.3779
Managed grass (%)	**15.4±18.3**	**0.5±1.6**	**−3.08**	*
Bankfull width (m)	6.7 ± 3	7.3 ± 3.6	1.08	0.3098
Bankfull depth (cm)	64.2 ± 11.5	66.7 ± 14.5	0.54	0.6027
Channel width (m)	4.3 ± 2.7	4.5 ± 3.5	0.01	0.9934
Channel depth (cm)	**27 ± 11.7**	**20.3 ± 9.3**	**3.55**	**
Flow (m/s)	**0.1 ± 0.1**	**0.2 ± 0.1**	**−2.75**	*
Temperature (°C)	14.2 ± 1.1	13.8 ± 1.7	2.01	†
Instream shading (%)	**34 ± 19.5**	**69.2 ± 15.4**	**−4.04**	**
pH	**5.5 ± 2.7**	**5.9 ± 3.5**	**−2.55**	*
EC (mS/m^2)	43.1 ± 30.4	41.5 ± 30.6	0.83	0.4279
Total organic carbon (mg/l)	19.6 ± 2.3	18.8 ± 3	1.06	0.3177
NH_4 (µg/l)	113 ± 179.7	29.9 ± 20.8	1.62	0.1338
NO_3–N (µg/l)	1050 ± 1497	1063 ± 1452	−1.24	0.2446
Total P (µg/l)	68.7 ± 42.8	55.49 ± 28.8	1.07	0.3135
Algae (%)	3.3 ± 6.6	5.1 ± 8.2	−0.70	0.5044
Bedrock, boulders (%)	8.6 ± 6.4	15 ± 13.7	−2.00	†
Bryophytes (%)	6.0 ± 10.4	11 ± 12.9	-1.40	0.4163
CPOM (%)	**5.1 ± 4.7**	**9.6 ± 6.3**	**−2.83**	*
Large woody debris (%)	**3.1 ± 3**	**9 ± 6.9**	**−3.39**	**
FPOM (%)	4.1 ± 1.9	7 ± 8.5	−1.06	0.3149
Gravel (%)	39 ± 13.6	52 ± 19.8	-1.19	0.2648
Macrophytes (%)	**16 ± 11.7**	**1.1 ± 1.1**	**4.84**	**
Fine sediment (%)	**25 ± 7.4**	**5.9 ± 4.8**	**6.15**	**

Table S2. List of 62 families and 6 higher taxonomic groups, arranged by the highest abundance at the unbuffered sites.

	Unbuffered		Buffered	
	Mean	Std. Dev.	Mean	Std. Dev.
Pisidiidae	470.2	885.7	183.5	297.8
Gammaridae	448.7	542.7	303.1	360.2

	Unbuffered		Buffered	
	Mean	Std. Dev.	Mean	Std. Dev.
Chironomidae	192.7	220.1	103.5	78.4
Oligochaeta	180.4	167.6	123.9	92.8
Asellidae	147.0	244.8	38.9	33.7
Elmidae	132.3	286.4	137.7	251.9
Simuliidae	94.1	194.0	46.8	84.8
Nemouridae	69.5	103.0	23.5	27.8
Baetidae	60.3	107.5	75.9	85.5
Limnephilidae	51.6	35.4	30.5	19.4
Ephemeridae	22.4	61.8	12.6	22.1
Nematoda	20.6	63.1	3.6	4.6
Hydropsychidae	13.3	28.2	32.4	59.2
Ceratopogonidae	9.8	9.8	12.7	25.0
Bithyniidae	6.8	21.5	0.6	1.9
Polycentropodidae	6.0	9.9	9.0	14.7
Hydroptilidae	5.9	18.7	5.8	15.2
Erpobdellidae	5.7	9.8	2.1	4.0
Glossosomatidae	5.6	9.5	25.7	34.3
Empididae	5.2	10.5	8.6	18.4
Psychodidae	5.2	15.1	0.6	1.3
Limoniidae	4.8	10.3	0.8	1.9
Zygoptera	3.8	10.1	0.0	0.0
Tricladida	3.6	5.4	0.7	1.3
Lymnaeidae	3.1	4.2	0.9	2.2
Calopterygidae	2.7	4.5	0.0	0.0
Caenidae	1.8	5.7	7.8	24.7
Sialidae	1.7	2.9	0.4	1.0
Corduliidae	1.5	3.2	0.2	0.6
Glossiphoniidae	1.5	3.8	0.7	1.6
Leptoceridae	1.5	4.4	6.0	15.0
Acroloxidae	1.4	2.5	0.6	1.9
Neritidae	1.4	4.4	1.8	5.7
Rhyacophilidae	1.3	2.7	5.0	6.1
Heptageniidae	1.2	3.8	1.2	2.5
Hydrachnidiae	1.2	2.5	1.7	2.5
Tabanidae	1.2	2.5	0.0	0.0
Leuctridae	0.9	2.0	1.1	2.3
Haemopidae	0.8	2.5	0.0	0.0
Dytiscidae	0.6	1.9	0.0	0.0
Nepidae	0.6	1.9	0.0	0.0
Pediciidae	0.6	1.3	3.8	6.0
Scirtidae	0.6	1.9	0.7	1.9
Chrysomelidae	0.5	1.6	0.0	0.0
Gyrinidae	0.5	1.6	0.0	0.0
Haliplidae	0.2	0.6	0.7	2.2
Astacidae	0.1	0.3	0.0	0.0
Corixidae	0.1	0.3	0.0	0.0
Hydraenidae	0.1	0.3	6.8	16.8
Anisoptera	0.0	0.0	0.2	0.6
Chaoboridae	0.0	0.0	0.0	0.0
Cordulegastridae	0.0	0.0	0.9	2.8
Dreissenidae	0.0	0.0	0.0	0.0
Ephemerellidae	0.0	0.0	3.0	9.5
Lepidoptera	0.0	0.0	0.2	0.6
Lepidostomatidae	0.0	0.0	1.6	3.5
Leptophlebiidae	0.0	0.0	0.0	0.0

	Unbuffered		Buffered	
	Mean	Std. Dev.	Mean	Std. Dev.
Molannidae	0.0	0.0	0.3	0.9
Muscidae	0.0	0.0	0.0	0.0
Philopotamidae	0.0	0.0	0.0	0.0
Physidae	0.0	0.0	0.0	0.0
Planorbidae	0.0	0.0	0.3	0.9
Psychomyiidae	0.0	0.0	0.7	1.9
Ptychopteridae	0.0	0.0	0.6	1.9
Sericostomatidae	0.0	0.0	0.9	2.8
Stratiomyidae	0.0	0.0	0.0	0.0
Tipulidae	0.0	0.0	0.2	0.4
Valvatidae	0.0	0.0	0.7	2.2

Table S3. Average values of invertebrate taxa and biodiversity indices at the buffered and unbuffered reaches.

	Unbuffered	**Buffered**
Taxa richness	24.2 ± 5.2	26.2 ± 6.3
EPT taxa richness	7.1 ± 2.9	9.3 ± 5
% EPT	14.1 ± 7.1	21.1 ± 16.5
Shannon-Wiener index (H′)	2.12 ± 0.4	2.23 ± 0.5
Simpson index (1-D)	0.79 ± 0.1	0.8 ± 0.1
Evenness (E)	0.36 ± 0.1	0.38 ± 0.1
Dominance	0.21 ± 0.1	0.20 ± 0.1

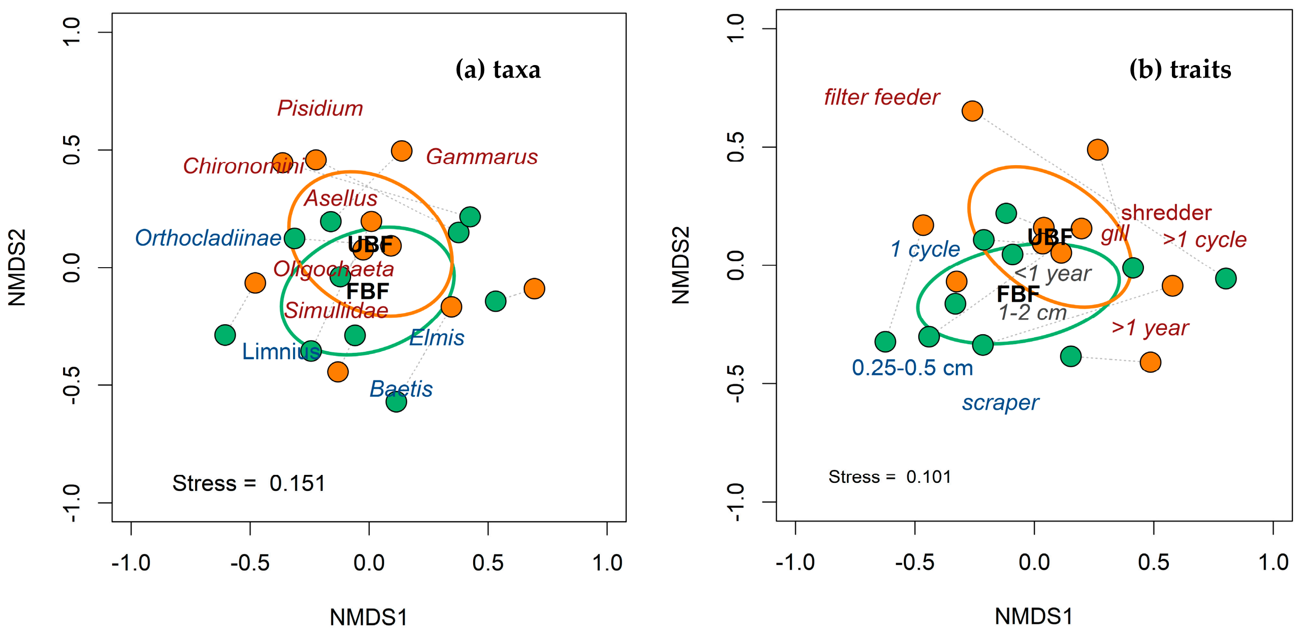


Figure S1. Unconstrained ordination (NMDS) of reaches based on Hellinger transformed taxa **(a)** and community weighted means of traits **(b).** Presented taxa and traits had the highest (top 10) contribution to average between group dissimilarity in SIMPER analysis (Table S4). The species and traits with are shown in dark brown color (associated to unbuffered reaches with orange ellipse and orange dots) and blue color (associated to buffered reaches with green ellipse and green dots) color. Traits shown in dark grey color (<1 year and 1–2 cm) had the same average community weighted means between the reaches.

Table S4. Analysis of similarity (SIMPER) of taxonomic and trait community differences between unbuffered (n = 10) and buffered (n = 10) reaches. Species contribution to average between group dissimilarity is shown in column "Contribution %". Community composition is shown as average of Hellinger transformed taxa abundance, while traits are shown as average community weighted means.

Taxon	Contribution %	Cumulative %	Unbuffered	Buffered
Community composition				
Gammarus pulex	3.9	7.1	0.41 ± 0.2	0.39 ± 0.3
Pisidium sp.	3.1	12.7	0.35 ± 0.2	0.29 ± 0.2
Limnius volckmari	2.5	17.3	0.11 ± 0.1	0.23 ± 0.2
Simuliidae	2.4	21.6	0.16 ± 0.2	0.15 ± 0.1
Elmis aenea	2.3	25.9	0.14 ± 0.1	0.22 ± 0.2
Asellus aquaticus	2.1	29.7	0.21 ± 0.2	0.15 ± 0.1
Chironomini	1.9	33.1	0.19 ± 0.1	0.09 ± 0.1
Baetis sp.	1.8	36.3	0.09 ± 0.1	0.10 ± 0.2
Orthocladiinae	1.7	39.5	0.12 ± 0.1	0.15 ± 0.1
Oligochaeta	1.6	42.5	0.30 ± 0.1	0.31 ± 0.1
Trait composition				
# of cycles per year > 1	1.0	5.8	0.56 ± 0.1	0.48 ± 0.2
# of cycles per year = 1	1.0	11.6	0.41 ± 0.1	0.48 ± 0.2
shredder	1.0	17.4	0.39 ± 0.2	0.34 ± 0.1
filter-feeder	1.0	23.0	0.28 ± 0.2	0.20 ± 0.1
gill respiration	0.9	28.3	0.63 ± 0.1	0.59 ± 0.1
scraper	0.9	33.5	0.21 ± 0.1	0.33 ± 0.1
size 0.25–0.5 cm	0.8	38.4	0.24 ± 0.1	0.30 ± 0.1
life cycle > 1 year	0.7	42.7	0.45 ± 0.1	0.45 ± 0.1
life cycle < 1 year	0.7	47.0	0.55 ± 0.1	0.55 ± 0.1
size 1–2 cm	0.7	50.8	0.34 ± 0.1	0.27 ± 0.1

Table S5. Macroinvertebrate taxa scores (n = 94) from the partial redundancy analysis model (pRDA) conditioning out confounding influences of instream properties as well as spatial structure and catchment characteristics. Invertebrate taxa are sorted from highest to lowest scores on RDA1.

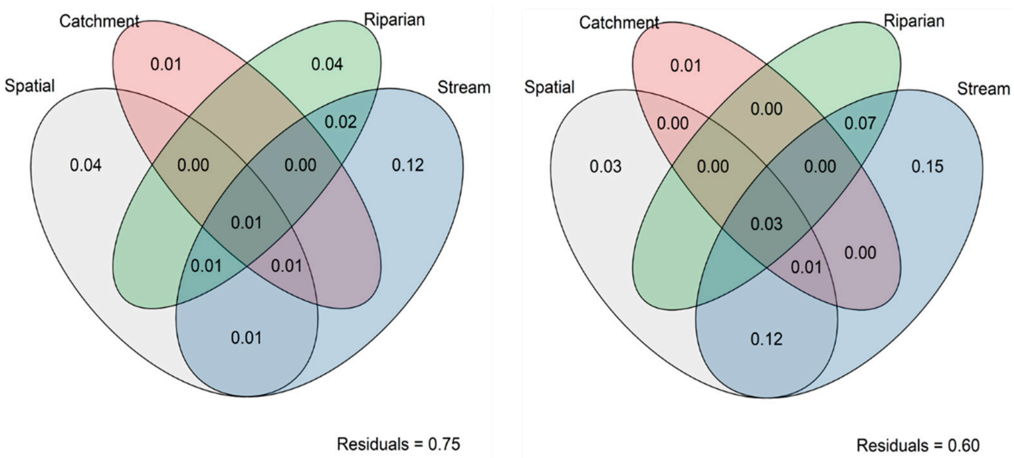
	RDA1	RDA2		RDA 1	RDA2
Gammarus pulex	0.3105	0.0211	Pisidium	−0.1504	−0.0500
Baetis sp.	0.1729	0.0482	Simuliidae	−0.1304	0.0519
Baetis rhodani	0.0972	-0.0199	*Limnius volckmari*	−0.1055	−0.0218
Elmis aenea	0.0418	−0.0402	*Amphinemura borealis*	−0.0848	0.0097
Oulimnius sp.	0.0361	0.0210	*Nemoura cinerea*	−0.0776	0.0069
Anabolia nervosa	0.0360	−0.0052	Chironomini	−0.0761	0.0724
Orthocladiinae	0.0263	−0.0981	*Asellus aquaticus*	−0.0668	0.0284
Nemoura avicularis	0.0238	−0.0186	Nematoda	−0.0555	−0.0282
Erpobdella octoculata	0.0212	0.0078	*Nemoura* sp.	−0.0442	0.0290
Hydroptila sp.	0.0211	−0.0226	Tanytarsini	−0.0386	0.0195
Agapetus ochripes	0.0161	−0.0297	Oligochaeta	−0.0343	−0.0006
Leuctra sp.	0.0157	0.0134	*Hydropsyche pellucidula*	−0.0327	0.0044
Tricladida	0.0155	0.0146	*Pericoma* sp.	−0.0318	−0.0051
Hydrachnidiae	0.0138	−0.0069	Limnephilidae	−0.0308	0.0460
Oulimnius tuberculatus	0.0137	0.0406	*Radix balthica*	−0.0268	0.0495
Rhyacophila sp.	0.0136	−0.0226	*Ephemera vulgata*	−0.0195	0.0103
Caenis rivulorum	0.0135	−0.0198	*Glossiphonia* sp.	−0.0170	0.0027
Lepidostoma hirtum	0.0131	−0.0143	*Tipula* sp.	−0.0159	−0.0059
Ceratopogonidae	0.0129	−0.0364	*Lype reducta*	−0.0133	−0.0031
Tanypodinae	0.0126	−0.0329	*Hydropsyche siltalai*	−0.0131	−0.0816
Polycentropus flavomaculatus	0.0121	0.0038	*Hydraena* sp.	−0.0109	−0.0530
Haliplus sp.	0.0111	−0.0020	Empididae	−0.0096	−0.0471

	RDA1	RDA2		RDA 1	RDA2
Hydropsyche angustipennis	0.0103	0.0457	*Haemopis sanguisuga*	−0.0091	0.0005
Somatochlora metallica	0.0097	0.0134	*Sialis lutaria*	−0.0078	−0.0006
Prodiamesinae	0.0096	−0.0337	*Baetis niger*	−0.0073	0.0024
Polycentropus irroratus	0.0086	0.0005	*Halesus* sp.	−0.0072	0.0079
Hydropsyche sp.	0.0084	−0.0129	Limoniidae	−0.0060	−0.0036
Cyrnus trimaculatus	0.0083	−0.0065	Dytiscidae	−0.0057	0.0020
Valvata piscinalis	0.0083	−0.0065	*Nepa cinerea*	−0.0055	0.0049
Helobdella stagnalis	0.0079	0.0050	*Theromyzon tessulatum*	-0.0055	0.0049
Bithynia tentaculata	0.0076	0.0005	*Calopteryx virgo*	−0.0053	0.0022
Theodoxus fluviatilis	0.0074	-0.0081	*Sialis lutaria* gr.	−0.0052	0.0069
Ephemerella mucronata	0.0070	−0.0145	*Rhyacophila fasciata*	−0.0045	−0.0122
Anisoptera	0.0065	−0.0015	*Calopteryx* sp.	−0.0044	0.0136
Athripsodes sp.	0.0060	−0.0234	Tabanidae	−0.0041	0.0143
Gyraulus acronicus	0.0055	−0.0043	*Centroptilum luteolum*	−0.0028	−0.0149
Molanna angustata	0.0055	−0.0043	*Heptagenia sulphurea*	−0.0026	−0.0137
Ceraclea sp.	0.0054	−0.0113	Zygoptera	−0.0024	0.0097
Eloeophila sp.	0.0052	−0.0008	*Dicranota* sp.	−0.0006	0.0049
Baetis vernus	0.0037	0.0290	*Plectrocnemia* sp.	0.0000	−0.0272
Oxyethira sp.	0.0035	0.0054	*Rhyacophila nubila*	0.0004	−0.0144
Amphinemura sp.	0.0028	0.0045	*Acroloxus lacustris*	0.0007	0.0161
Ptychoptera sp.	0.0027	−0.0120	*Donacia* sp.	0.0012	0.0019
Elodes sp.	0.0026	−0.0061	*Orectochilus villosus*	0.0012	0.0019
Astacidae	0.0024	0.0026	*Cordulegaster boltonii*	0.0015	−0.0059
Calopteryx splendens	0.0021	0.0032	*Sericostoma personatum*	0.0015	−0.0059
Lepidoptera	0.0021	−0.0064	*Sigara* sp.	0.0020	0.0032

Table S6. Trait scores (n = 39) from the partial redundancy analysis model (pRDA) conditioning out confounding influences of instream properties as well as spatial structure and catchment characteristics. Invertebrate taxa are sorted from highest to lowest scores on RDA1 axis. RDA2 is equivalent to PC1 axis, due to a one variable model (% Canopy).

	RDA1	RDA2
size 0.25–0.5 cm	0.0983	0.1001
1 cycle per year	0.0944	0.0448
filter feeder	0.0747	0.3239
tegument breathing	0.0455	0.0972
size 0.5–1 cm	0.0402	0.0502
aerial active dispersal	0.0356	−0.0671
plastron breathing	0.0263	−0.0465
sand substrate preference	0.0182	0.0423
mud substrate preference	0.0156	0.0974
aerial passive dispersal	0.0136	0.0810
predator	0.0134	0.0181
silt substrate preference	0.0121	0.0716
life cycle < 1 year	0.0112	−0.0085
gravel substrate preference	0.0071	−0.0540
scraper	0.0063	−0.2488
deposit feeder	0.0058	−0.0063
slow flow	0.0045	0.0497
parasite	0.0041	0.0109
null flow	0.0013	0.2102
size 4–8 cm	0.0009	−0.0008
<1 cycle per year	0.0008	0.0333
spiracle breathing	0.0001	−0.0067
size > 8 cm	−0.0002	−0.0001
size < 0.25 cm	−0.0002	0.0005

	RDA1	RDA2
fast flow	−0.0003	−0.1104
macrophytes substrate preference	−0.0040	−0.0159
flags/boulders/cobbles/pebbles substrate preference	−0.0042	−0.1157
medium flow	−0.0060	−0.1510
microphytes substrate preference	−0.0102	−0.0052
life cycle > 1 year	−0.0112	0.0085
organic/detritus/litter substrate preference	−0.0131	0.0248
aquatic active dispersal	−0.0171	−0.0713
twigs/roots substrate preference	−0.0224	−0.0463
aquatic passive dispersal	−0.0319	0.0593
size 2–4 cm	−0.0534	−0.0950
gill breathing	−0.0719	−0.0440
size 1–2 cm	−0.0857	−0.0549
>1 cycle per year	−0.0952	−0.0781
shredder	−0.1043	−0.1058



(a) taxa **(b) traits**

Figure S2. Venn diagram showing variation partitioning (VP) of taxonomic **(a)** and trait **(b)** composition of macroinvertebrate communities in 20 study reaches. Shown are total variations explained by set of predictors described as spatial (PCNM1, PCNM9, PCNM10), catchment (catchment area), riparian (% of canopy cover and rock/bedrock) and instream (nitrate, total phosphorus, % of algae and gravel) parameters. Values < 0 are not shown on the diagram.

Instream habitats alone, characterized by nutrients (nitrate, total phosphorus), substratum (gravel) and food resource (algae), explained 12–15% of the total variation in taxonomic ($F_{3,11}$=1.74, $p = 0.022$) and trait composition ($F_{4,11}$=1.75, $p = 0.065$), respectively (Figure 3). By contrast, riparian characteristics (% of canopy cover and rock/bedrock), catchment area nor spatial location were significant ($p > 0.05$). However, the shared variation between instream habitat and riparian characteristics explained 2% of the variability in taxonomic composition and 7% in trait composition. The independent and shared contribution of instream and riparian habitats significantly explained variability in taxonomic composition ($F_{5,11}$=2.52, $p = 0.003$) and trait composition ($F_{5,11}$=, $p = 0.035$).