

1 **Functional traits of hyporheic and benthic invertebrates reveal importance of wood-driven**  
2 **geomorphological processes in rivers**

3 Chiara Magliozzi<sup>a</sup>, Philippe Usseglio-Polatera<sup>b</sup>, Albin Meyer<sup>b</sup>, Robert C. Grabowski<sup>a\*</sup>

4 *<sup>a</sup>Water Science Institute, School of Water, Energy and Environment, Cranfield University,*  
5 *Cranfield, Bedfordshire, MK43 0AL*

6 *<sup>b</sup>Laboratoire Interdisciplinaire des Environnements Continentaux (LIEC, CNRS UMR 7360),*  
7 *Université de Lorraine, Metz, F-57070*

8 \*Corresponding author

9 Email address: r.c.grabowski@cranfield.ac.uk (Robert Grabowski)

10

11

12

13 This is the authors' version of the accepted manuscript. © 2019 This manuscript version is made

14 available under the CC-BY-NC-ND 4.0 license <http://creativecommons.org/licenses/by-nc-nd/4.0/>

15

16

17 The final published article is available from the journal Functional Ecology

18 <https://besjournals.onlinelibrary.wiley.com/journal/13652435>

19

20 **Abstract**

- 21 1. Large wood (LW) is a natural element of river environments and an integral component of  
22 many river restoration schemes to promote biodiversity. It is an important habitat in itself,  
23 but it also induces a wide range of hydraulic, hydrological, geomorphological, and chemical  
24 conditions that influence the ecological community. However, the effects of hydro-  
25 geomorphological processes induced by LW on local benthic and hyporheic invertebrates  
26 have not been well characterized.
- 27 2. A functional approach was applied to invertebrate data collected in a field survey at sites  
28 with LW and without LW (control), to investigate the response of hyporheic and benthic  
29 invertebrates' trait profiles in response to local LW-induced processes.
- 30 3. We hypothesized LW sites to be associated with different trait modalities than control sites  
31 in relation to wood-induced processes and conditions (i.e. hyporheic exchange flow, oxygen  
32 availability, temporal stability, organic matter, denitrification, hydraulic conductivity).  
33 Multivariate analyses and Partial Least Squares (PLS) Path Modelling were used to detect  
34 the differences in trait profiles between LW and control sites and to study the variation of  
35 traits as a function of hydrological, sedimentological, physical and chemical variables.
- 36 4. Biological (i.e. aquatic stages, reproduction), physiological (i.e. dispersal, feeding habits)  
37 and behavioural (i.e. substrate preferences) trait utilization by the hyporheic meiofauna  
38 differed between LW and control sites. At LW sites, the hyporheic meiofaunal assemblage  
39 was significantly associated with aquatic active dispersal, aquatic eggs and hard substrate  
40 preferences. This trait category selection was linked to changes in physical-sedimentological  
41 processes at LW sites when compared to control sites. Macrofaunal benthic and hyporheic

42 functional traits did not differ significantly between wood and control sites, suggesting  
43 similar functioning of these assemblages at the surface-subsurface interface.

44 5. This study found that LW affects invertebrate traits by altering fluvial processes to produce,  
45 locally, a mosaic of habitats. Hyporheic meiofauna trait responses to LW-processes have  
46 suggested (i) the crucial role of LW in supporting river benthic zone functioning, and thus  
47 (ii) a possible benefit to river restoration by enhancing functional interactions among  
48 different ecological niches.

49 *Keywords:* large wood, river ecology, macrofauna, meiofauna, hyporheic zone, river restoration.

## 50 1. Introduction

51 Rivers are dynamic environments that vary markedly over short distances and timescales.  
52 Consequently, organisms living in them are subjected to large differences and fluctuations in  
53 physico-chemical conditions, caused by variable water flow velocities, the movement of sediment,  
54 availability of food resources, and nutrient input. The adaptations that a species has to this  
55 environment appear in functional traits, the ensemble of morphological, physiological,  
56 phenological and behavioural attributes that reflect organismal performance, which determines the  
57 community fitness (McGill, Enquist, Weiher, & Westoby, 2006).

58 Trait-based approaches have been advocated as a mechanistic alternative to traditional taxonomic  
59 descriptors and applied from the organism-level to global biodiversity patterns to investigate  
60 changes and losses of ecosystem function (Gagic et al., 2015; Mondy & Usseglio-Polatera, 2013;  
61 Statzner & Bêche, 2010). They have been widely adopted to study benthic invertebrates, i.e.  
62 invertebrates living on or near the surface of the riverbed (Usseglio-Polatera, Richoux, Bournaud,  
63 & Tachet, 2001), but less commonly for the invertebrate community that lives deeper in the  
64 sediment, i.e. the hyporheic community (Descloux, Datry, & Usseglio-Polatera, 2014;  
65 Dunscombe, Robertson, Peralta-Maraver, & Shaw, 2018). However, a functional approach could  
66 help to investigate the hydrological, sedimentological, chemical and physical processes occurring  
67 in the hyporheic zone and their effects on local river invertebrate communities (HZ, Orghidan  
68 1959; Boulton, 2007).

69 The HZ is an ecotone below and surrounding the river bed, crucial to hydrological and ecological  
70 connectivity in rivers (Ward, 1989). It is a dynamic environment with a distinctive fauna

71 (hyporheos) and a subsurface water flow, named hyporheic exchange flow (HEF). Studies  
72 coupling taxonomy-based ecological and hydrological data on geomorphic structures (i.e. riffles  
73 and large wood) and HEF have provided evidence for the likely mechanisms by which HEF affects  
74 river ecology by controlling dissolved oxygen concentration and fine sediment deposition  
75 (Mathers, Millett, Robertson, Stubbington, & Wood, 2014), nutrients (Krause, Tecklenburg,  
76 Munz, & Naden, 2013), metabolic processes (Krause et al., 2011), and water temperature  
77 (Menichino & Hester, 2014). However, like the river at large, the physico-chemical conditions of  
78 the HZ vary spatially and temporally over small scales. There are a number of factors (i.e. geology,  
79 topography) that drive changes in the hyporheic physical environment in terms of flow, nutrient  
80 retention and temperature (Magliozzi, Grabowski, Packman, & Krause, 2018), meaning that  
81 organisms are likely to be exposed to spatially variable and temporally varying physical and  
82 chemical conditions and would possess functional traits enabling them to cope with selective  
83 environmental processes (e.g. denitrification, flow and sediment disturbance).

84 Large wood (LW; length > 1 m; diameter > 10 cm; Wohl et al., 2010), for example, is a natural  
85 hydrostatic-driver of HEF (Krause et al., 2014), enhancing HEF by increasing riverbed roughness  
86 and creating hydraulic gradients (Lautz, Siegel, & Bauer, 2006; Mutz, Kalbus, & Meinecke, 2007).  
87 LW induces multiple hydrological (i.e. flow deflection and scour), geomorphological (i.e.  
88 sediment entrainment and transport) and chemical (i.e. organic matter deposition, nutrient  
89 retention) processes that are key to river ecology (i.e. habitat for invertebrates) (Table 1) (Benke  
90 & Wallace, 2003) and to river restoration (Grabowski et al. 2019; Larson, Booth, & Morley, 2001).  
91 Reaches with LW are usually more geomorphologically and hydraulically heterogeneous in space  
92 and time than sites without LW (Gurnell, 2013; Gurnell & Grabowski, 2016; Krause et al., 2014).

93 They are usually characterized by steep head gradients and result in pronounced upwelling and  
94 downwelling zones upstream and downstream LW, exhibit enhanced oxygen availability, deeper  
95 hyporheic flows and longer residence times than sites without LW (Krause et al., 2014; Sawyer,  
96 Cardenas, & Buttle, 2011) (Table 1). LW and the geomorphological changes it induces in the  
97 channel, facilitate the deposition of organic material (i.e. litter) and sediment material (fine sand  
98 and coarse gravel) and promotes nutrient processes (i.e. nitrate accumulation or denitrification)  
99 (Blaen et al., 2018; Shelley, Klaar, Krause, & Trimmer, 2017). To this end, ecological research  
100 has shown that LW itself and the surrounding LW habitat have an effect on the benthic  
101 macroinvertebrate taxonomic structure, in terms of greater abundance, diversity and biomass than  
102 in absence of wood (Benke & Wallace, 2003; Thompson et al., 2018). However, very little  
103 information is available to investigate the existing connections between LW-induced processes  
104 and benthic and hyporheic functional traits (i.e. exception of feeding groups, Flores et al., 2017;  
105 Pilotto, Harvey, Wharton, & Pusch, 2016) for understanding the action of processes in the HZ.  
106 LW-induced hydro-geomorphological and chemical processes could favor the occurrence of  
107 specific behavioral, biological, morphological and physiological functional traits in river  
108 invertebrates (Table 2, Section S1).

109 The aim of this study is to investigate hyporheic and benthic invertebrates' functional traits in  
110 response to local LW-induced processes (Table 1). Functional trait expression is expected to differ  
111 in LW and control sites, taking into account LW-conditions and driving processes: i.e. increasing  
112 vertical hyporheic exchange, sediment hydraulic conductivity, oxygen and organic matter  
113 availability, and lower temporal stability (i.e. lower variability of environmental parameters in  
114 control than LW) and denitrification (Table 1). Specifically, we hypothesized that: (i) the trait

115 profiles of both macrofaunal and meiofaunal assemblages would differ between LW and control  
116 sites; (ii) specific behavioural, biological, morphological and physiological trait-modalities would  
117 differ in LW and control sites, as summarized in Table 2 (see also Section S1 in Supporting  
118 Information), for both macrofaunal and meiofaunal assemblages; and (iii) trait variation in LW  
119 and control sites could be explained by hydrological, physical, sedimentological and chemical  
120 environmental variables responding to LW-driven processes (Table 1).

## 121 2 Material and Methods

### 122 2.1 Study area and design

123 The study was conducted in the Hammer stream, West Sussex, UK (catchment area 24.6 km<sup>2</sup>,  
124 Shelley, Klaar, Krause, & Trimmer, 2017). It is a woodland stream where LW occurs naturally  
125 and drives local hyporheic exchange flows (Shelley, Klaar, Krause, & Trimmer, 2017; section S2).  
126 Following geomorphological surveys, four reaches with a single in-channel LW were identified in  
127 both gravel and sand sections. The studied LWs were natural, active or complete jams, with a  
128 significant water afflux (Gippel, O'Neill, Finlayson, & Schnatz, 1996), and were stable during the  
129 study period. LW sites were located in different reaches, separated by a distance of >150 m (>20  
130 times the channel width) apart to avoid spatial dependencies in the studied local LW effects (Fig.  
131 1). Control sites were chosen in each reach upstream of the LW, in the gravel and sand sections.  
132 Sites were i) bare areas of the riverbed without woody material (wood > 3 cm in diameter or  
133 accumulation of woody fragments of smaller dimensions), and ii) located upstream of the LW by  
134 a distance of *ca.* 10 times the channel width. At this distance upstream, control sites were not  
135 affected by LW-induced hydrological and geomorphological processes (afflux caused by  
136 blockage) as confirmed by cross-sections, total station, and velocity measurements. Both LW and  
137 control sites were selected on relatively straight areas of the channel to avoid confounding effects  
138 of channel geomorphology on potential HEF.

### 139 2.2 Sampling protocol

140 Each sampling site was sampled in three occasions, in November 2016, May 2017 and August  
141 2017. Three replicates of hyporheic and benthic samples were taken within 1 m distance: i)



142 upstream, downstream and laterally to the LW between areas of maximum fine deposition and the  
143 pool to avoid erosional and sedimentation zones and ii) in control sites (Fig. 1). Hyporheic samples  
144 were collected using colonization pots (Crossman, Bradley, Milner, & Pinay, 2013) placed  
145 between 5 cm and 25 cm deep in the sediment, while benthic samples were taken using a Surber  
146 sampler (0.05 m<sup>2</sup>, mesh size = 500 µm) from the sediment surface. Pots were left *in-situ* for six  
147 weeks to allow sufficient time for invertebrate colonization (Coleman & Hynes, 1970). Hyporheic  
148 and benthic samples were collected on the same day. Immediately after collection the samples  
149 were stored in plastic jars with 90 % ethanol and returned to the laboratory, where they were rinsed  
150 with water and filtered over a set of sieves. For the colonization samples, a 500 µm sieve was used  
151 to retain hyporheic macrofaunal individuals; the rest of the sample was filtered through a 45 µm  
152 sieve for meiofauna, preserved in 100% ethanol, and stained with Rose Bengal. These meiofaunal  
153 samples were sorted within five days of collection (Stead et al., 2003).

154 The Surber samples were sieved with a 500 µm sieve and benthic meiofauna was not sampled  
155 given the coarser mesh size of the Surber net. All macrofaunal samples were preserved in 80%  
156 ethanol. Preserved samples were sorted and identified to the lowest taxonomic level possible,  
157 genus or species, under a stereomicroscope or an Olympus Bx50 (Olympus Optical) microscope.  
158 Some taxa (i.e. Plecoptera, Trichoptera) were damaged in collection, processing, or storage,  
159 possibly due to the high amount of fine sediment in the samples or physical abrasion during the  
160 sieving process, and thus identified only to family level. Meiofaunal taxa such as Nematoda,  
161 Oligochaeta, Cyclopoida, Acari, Anomopoda, Cladocera, Ctenopoda, Ostracoda were identified to  
162 order or class level (Dobson, Pawley, Fletcher, & Powell, 2012; Tachet, Richoux, Bournaud, &  
163 Usseglio-Polatera, 2010).

164

### 165 **2.3 Environmental data**

166 Environmental variables were measured in triplicate at each sampling site on every sampling  
167 occasion (Table 3). Temperature (T; °C), pH, dissolved oxygen (DO; %), electric conductivity  
168 (EC;  $\mu\text{S cm}^{-1}$ ) were measured with a multiparameter probe (Hannah HI98196). Velocity  
169 measurements were taken using a Flow Tracker Acoustic Doppler Velocimeter (SonTek) upstream  
170 and downstream LW and used with the channel width and water depth to calculate discharge  
171 (velocity-area method). A total station (TS06 Leica) and georeferential GPS (GS08plus, Leica  
172 Viva) were used to survey the location of LW pieces. The bankfull width, wetted width, and the  
173 orientation angle of each LW relative to the channel, alongside the length and diameter of each  
174 large wood were calculated using ArcGIS 10.1 (Table S5). Sediment cores (diameter 5 cm, depth  
175 25 cm) were collected for sediment grain size analysis (Blott & Pye, 2001) and organic content  
176 estimation by loss of ignition (incinerated at 550°C for 5 h) (Heiri, Lotter, & Lemcke, 2001).  
177 Median grain size, sorting coefficient, skewness and cumulative percentile values (i.e.  $D_{10}$ ,  $D_{90}$ )  
178 were calculated from the dry weight of the different sediment fractions using the geometric Falk  
179 and Ward (1957) method (GRADISTAT program; Blott & Pye, 2011). Wooden stakes of untreated  
180 *Pinus pinaster* were inserted into the sediment with colonization pots and used to estimate vertical  
181 patterns of interstitial oxygenation (Marmonier et al., 2004). Finally, sediment pore water at 25 cm  
182 depth was collected using minipiezometers (Lewandowski, Putschew, Schwesig, Neumann, &  
183 Radke, 2011) for measurements of nitrate, nitrite, ammonium and phosphate, discarding 1.5 to 2  
184 times the inner volume of the minipiezometer tube before filtering the sample. The samples were  
185 filtered into 5 mL sample vials using syringe filters (28 mm, 0.2  $\mu\text{m}$ ); a new filter was used for

186 each sample. After filtration, the samples were acidified (2 M HCl, pH *ca.* 2). Filtration and  
187 acidification were conducted within 30 minutes after the sample collection (Lewandowski,  
188 Putschew, Schwesig, Neumann, & Radke, 2011).

189

## 190 **2.4 Trait description**

191 The functional traits of both benthic invertebrate macrofauna (individuals retained by 500  $\mu\text{m}$   
192 sieve) in the benthic zone, and hyporheic invertebrate macrofauna (retained by 500  $\mu\text{m}$ ) and  
193 meiofauna (retained by 45  $\mu\text{m}$ ) in the hyporheic zone were investigated using a multivariate  
194 approach (Section 2.5.1). The traits used in this study consisted of behavioural, biological,  
195 morphological and physiological features identified in the literature as reflecting organismal  
196 performance and adaptations to environmental pressures (Table S1) (McGill, Enquist, Weiher, &  
197 Westoby, 2006). Each trait was described by 2 to 9 modalities (Table S1). The taxa of the benthic  
198 (71 taxa) and hyporheic (72 macrofaunal and 59 meiofaunal taxa) zones were coded, at genus or  
199 family level, according to their affinity to each category of a trait using a fuzzy coding approach  
200 (Chevenet, Dolédec, & Chessel, 1994). Trait tables from Tachet, Richoux, Bournaud, & Usseglio-  
201 Polatera (2010) and Descloux, Datry, & Usseglio-Polatera (2014) were used for coding  
202 macrofauna and meiofauna functional traits. Taxa such as Nematoda, Oligochaeta, Cyclopoida,  
203 Acari, Anomopoda, Copepoda, Ctenopoda and Ostracoda (52.72% overall abundance in hyporheic  
204 meiofauna samples, Table S4) were described as mean trait profiles of their potential families in  
205 the corresponding biogeographic area (Descloux, Datry, & Usseglio-Polatera 2014). The affinities  
206 of taxa for the modalities of a trait were converted into relative abundance distributions so that the  
207 sum of the trait modality affinity scores for an individual trait and a given taxon equals one.

208

## 209 **2.5 Data analysis**

### 210 **2.5.1 Biological data**

211 Hyporheic macrofauna, hyporheic meiofauna, and benthic macrofauna were analysed separately  
212 because a preliminary correspondence analysis conducted on faunal abundances showed that there  
213 were significant differences between sampling methods (colonisation pots *vs* Surbers) and between  
214 ecological zones (benthic *vs* hyporheic). Abundances of all identified taxa were merged by reach,  
215 treatment (wood *vs* control) and sampling campaign (period). The mean trait profile of sample  
216 assemblages was obtained by weighting the individual trait profiles of corresponding taxa by their  
217 log-transformed ( $x+1$ ) abundances in the sample. Rare taxa ( $< 5$  individuals over the whole  
218 sampling design) were removed to avoid extremes in the analysis (Cao, Larsen, & Thorne, 2001;  
219 Gauch, 1982). Then, within reach x campaign analysis (Within Class Analysis, WCA) (*wca*  
220 function of the R package *ade4*; Dray, Dufour, & Thioulouse, 2017) was performed to assess  
221 whether trait composition in i) hyporheic meiofauna and macrofauna and ii) benthic assemblages  
222 was identical in wood and control sites. The WCA performs a particular case of principal  
223 component analysis (PCA) with respect to the variable of interest (i.e. wood *vs* control in this  
224 study) (Benzécri, 1983). It is an effective method to eliminate the effects of confounding variables  
225 (i.e. reach and campaign date in this study) in the analysed dataset (Castella, Richardot-Coulet,  
226 Roux, & Richoux, 1991; Dolédec & Chessel, 1989; Dole-Olivier, , Marmonier, & Beffy, 1997;  
227 Van Looy, Floury, Ferréol, Prieto-Montes, & Souchon, 2016). Subsequently, the conditional  
228 inference tree approach (CIT) (*ctree* function R package *party*; Hothorn, Hornik, Strobl, & Zeileis,  
229 2017) was applied to distinguish groups of sites with significantly different combinations of trait

230 profiles, based on their coordinates along the successive factorial axes in WCA. CIT is a recursive,  
231 non-parametric, partitioning method that allows estimating regression relationships between  
232 variables (Hothorn, Hornik, & Zeileis, 2006; Section 5 in Supporting Information). In our study,  
233 CIT was tested using Bonferroni permutation test (9999 permutations,  $\alpha = 0.01$ ). Finally, taxon  
234 trait-profiles among wood and control sites ( $n = 48$ ) were compared using the non-parametric  
235 Wilcoxon signed-rank test. Bonferroni corrections ( $p$ -value  $< 0.001$ ) were applied for selecting  
236 trait modalities with significant differences between LW vs control sites.

237

### 238 **2.5.2 Environment-trait relationships**

239 The relationship between environmental data and taxon traits was investigated by applying the  
240 Partial Least Squares (PLS) Path Modelling (Wold, 1982) using the *plspm* function of the R  
241 package *plspm* (Sanchez, Trinchera, & Russolillo, 2017). PLS was applied to link hydrological,  
242 physical, sedimentological and chemical variables to the variations of invertebrate trait modalities  
243 (Fig. S1). PLS is a statistical method that quantifies the relationships between observed manifest  
244 (indicators or items) and latent variables (indirectly measured - LVs) in a system of multiple linear  
245 regressions (Vinzi, Trinchera, & Amato, 2010). In the last few years, this approach has been  
246 increasingly applied to a wide range of disciplines including econometrics, social sciences and  
247 ecology (Bizzi, SurrIDGE, & Lerner, 2013; Villeneuve, Piffady, Valette, Souchon, & Usseglio-  
248 Polatera, et al., 2018). First, the PLS approach includes the estimation of the latent variables as  
249 linear combinations of their respective blocks of manifest variables (Tenenhaus, Vinzi, Chatelin,  
250 & Lauro, 2005). This first step is an iterative process in which the latent variables are calculated  
251 as the weighed sum of their manifest variables till convergence of the weights is reached

252 (Tenenhaus, Vinzi, Chatelin, & Lauro, 2005). The calculations are performed on the outer model,  
253 which links the manifest variables to the corresponding latent variables (Vinzi, Trinchera, &  
254 Amato, 2010). At the end of the first step, the method calculates the path coefficients between  
255 latent variables by ordinary least square regressions on the inner model, which accounts for the  
256 relationships between latent variables (Tenenhaus, Vinzi, Chatelin, & Lauro, 2005). The last step  
257 of the PLS analysis involves the computation of the loadings by simple correlations in the outer  
258 model. In this study, the LVs (hydrological, physical, chemical and sedimentological variables)  
259 were standardized and expressed as formative indicators (manifest variables that form the latent  
260 variables) while the latent trait-based variables (i.e. “trait modalities”) were measured in a  
261 reflective way (manifest variables are considered as being caused by the latent variables) (Fig. S1)  
262 (Tenenhaus, Vinzi, Chatelin, & Lauro, 2005). PLS analysis was executed on a sub-set of  
263 significant trait modalities (Section 2.5.1). The quality of the model was assessed using  $R^2$   
264 determination coefficients (Croutsche, 2002) and bootstrap validation (number of resamples:  
265 1000) was used to validate the parameter estimates. All the coefficients presented in this work  
266 were significant at 95% confidence interval (Götz, Liehr-Gobbers, & Krafft, 2010). Finally, the  
267 latent variables were evaluated with respect to trait modalities by looking at the effects (direct and  
268 total) of each construct on the trait variation (Sanchez, 2013). The contributions in percentage of  
269 direct and total (direct + indirect) effects were calculated in wood and control conditions, for each  
270 significant trait modality.

271

## 272 **3. Results**

### 273 **3.1 Hyporheic and benthic trait profiles between wood and control sites**

274 The functional trait profiles of the hyporheic meiofauna differed between wood and control sites,  
275 as confirmed by the WCA (F1 = 12.8%, F2 = 10.0% of explained variance; Fig. 2a) and CIT  
276 approach (Fig. 2b). The ordination plots of single trait modalities showed that many trait modalities  
277 were differently expressed in wood and control sites (Fig. S2), but these differences were  
278 statistically significant (Wilcoxon's test, Bonferroni adjusted p-value < 0.001) for only six of them:  
279 i) aquatic active dispersal, ii) aquatic eggs, iii) aquatic nymphs, and preferences for iv) twigs and  
280 roots, v) sand and vi) hard substrates (i.e. flags, boulders, cobbles and pebbles; Fbcp in Fig. 3 and  
281 Table S2). Control sites were characterized by trait specific substrate preferences (i.e. twigs and  
282 roots and sand) and some aquatic stages (i.e. nymph) (Fig. 3). The functional trait profiles of both  
283 hyporheic and benthic macrofauna did not differ between wood and control sites (F1 = 11.0% and  
284 9.1%, F2 = 10.3% and 8.8% of explained variance for hyporheic and benthic macrofauna,  
285 respectively; Figs. S3, S4), and no trait modalities exhibited statistically significant differences  
286 between control and LW sites (Wilcoxon's test, Bonferroni adjusted p-value < 0.001). Macrofaunal  
287 assemblages were characterized by trait modalities that were not significantly different (p-value  $\geq$   
288 0.05, Table S3, Fig. S5) in LW and control sites.

289

### 290 **3.2 Environmental-trait relationships**

291 PLS analysis was applied to the six significant meiofaunal traits. The PLS inner model showed  
292 moderate prediction capacity of meiofaunal trait modality utilization by LVs ( $R^2$ : 47 % in wood  
293 and 55 % in control) (Fig. 4). Sedimentological and chemical variables were well explained in  
294 both control and wood sites ( $55\% < R^2$  values  $< 61\%$ ,  $40\% < R^2$  values  $< 62\%$ , Fig. 4). Physical  
295 variables were weakly to moderately explained by the model with  $R^2$  values varying from 14% to

296 35%. Sedimentological and physical LVs had the greatest effects on trait modalities (25%-44%  
297 and 22%-43%, respectively) despite the response patterns differing between sites (Fig. 5a). Trait  
298 modalities at wood sites were affected mostly by physical variables (43%) with important effects  
299 for sedimentological and hydrological LVs (respectively 25% and 20%; Fig. 5a). In control sites,  
300 the direct effects of sedimentological and chemical LVs explained most of the trait variation (44  
301 % and 31%), whereas hydrological variables had only a minor effect (3%). When looking at the  
302 total effects, the contribution of LVs to trait variation changed, due to indirect effects (Fig. 5a). A  
303 higher effect of hydrology (+16% to +29%) and a decrease in the effect of sedimentological  
304 variables (-7% to -18%) were shown in both control and wood sites (Fig. 5a). Finally,  
305 sedimentological and physical LVs exhibited higher impact (50-80%) on substrate preferences (i.e.  
306 sand and twigs/roots) and aquatic stages (i.e. egg, nymph) variation, in control sites (Fig. 5b). In  
307 wood sites, the relative contribution of the LVs to the trait variation was more similar among  
308 modalities (Fig. 5b).

309

310

311

#### 312 **4. Discussion**

313 This study investigated multiple functional traits of meiofaunal and macrofaunal invertebrates to  
314 study their response to LW-induced processes in rivers. Wood and control site hyporheic  
315 assemblages exhibited different profiles of traits, with general patterns emerging in terms of  
316 responses to wood and wood-induced processes. In this section we discuss wood-related traits in



317 the hyporheic and benthic zones (Section 4.1) and the major environmental predictors of trait  
318 modality variation (Section 4.2).

319

#### 320 **4.1 Wood-related traits of the meiofauna and macrofauna in LW habitats**

321 Our study found that meiofaunal functional trait profiles differed in wood and control sites,  
322 suggesting functional relationships between traits and environmental forces in the HZ, and  
323 upholding our first hypothesis that LW would affect the trait profiles of the hyporheic meiofauna.  
324 Significant differences between LW and control sites were recorded for individual biological,  
325 physiological and behavioural meiofaunal trait modalities, reflecting organismal adaptations in the  
326 HZ. These specific trait modalities partly support our second hypothesis that multiple functional  
327 traits and trait-modalities would be affected by LW.

328 Significant trait modalities in LW included aquatic active dispersal, aquatic eggs and hard substrate  
329 preferences (Fig. 3). These trait modalities relate strongly to temporal instability, flow disturbance  
330 and sediment hydraulic conductivity (Bilton, Freeland, & Okamura, 2001; Descloux, Datry, &  
331 Marmonier, 2014; Larsen, Pace, & Ormerod, 2011). Active aquatic dispersal was recorded as  
332 significant behavioural feature, counter to our expectations (Table 2), for meiofaunal assemblages  
333 in LW, suggesting that hyporheic hydrology might not play a strong role in determining where  
334 meiofaunal species occur both spatially and temporally (see also Section 4.2). Active aquatic  
335 dispersal entails self-generating organism movements often associated with flightless aquatic  
336 invertebrates that display an active behaviour triggered by changing and unstable environmental  
337 conditions (Stubbington et al., 2017; Tonkin et al., 2017). However as the cues that trigger aquatic  
338 and hyporheic insects to disperse are still an active area of research (Bilton, Freeland, & Okamura,

339 2001), active aquatic dispersal in a heterogeneous and temporally varying environment may be  
340 advantageous. This is supported by the presence of more meiofaunal organisms with aquatic eggs  
341 in LW sites. Previous studies have already observed invertebrates dispersing in variable habitats  
342 by differential egg hatching regimes (e.g. differences in temperature leading to rapid hatching or  
343 germination when dormancy is broken) (Brock, Nielsen, Shiel, Green, & Langley, 2003; Zwick,  
344 1996). Wood meiofaunal assemblages also showed substrate preferences for cobbles and pebbles  
345 (Fbcp in Fig. 3), possibly due to the more heterogeneous habitat conditions and presence of patches  
346 of much coarser sediment around LW (Table 3) (Pilotto, Bertocin, Harvey, Wharton, & Pusch,  
347 2014).

348 Functional traits of hyporheic and benthic macrofaunal assemblages did not differ significantly  
349 across sites, thereby our first and second hypotheses that trait profiles of macrofaunal and  
350 meiofaunal assemblages differ between LW and control sites (Table 2) were not upheld. This result  
351 might suggest that the dominant macrofaunal species (hyporheic and benthic) exhibited similar  
352 combination of traits (in coherence with the biomass-ratio hypothesis of Grime (1998)) and, at the  
353 scale of both benthic and hyporheic zones, were driven by similar functional relationships to  
354 environmental processes and forces. Therefore assemblages could have similar functioning and  
355 functional divergence (i.e. low niche differentiation, lack or few specialist species), in the study  
356 site (Villéger, Mason, & Mouillot, 2008). Results might also suggest a relatively stable taxonomic  
357 diversity for macrofaunal assemblages at wood vs control scale, and a decrease in functional space  
358 with possibly the loss of specialist species with narrow niches between benthic and hyporheic  
359 zones (Villéger, Mason, & Mouillot, 2008). Finally, the implemented sampling design did not  
360 allow to efficiently depict the variability of functional traits at LW scale, with respect - for example

361 - to erosional and deposition areas or flow paths. This might be another reason why functional  
362 differences in macroinvertebrate assemblages between LW and control sites were not detected in  
363 the results.

364

#### 365 **4.2 Environmental drivers of hyporheic meiofauna trait variation**

366 Trait variation in LW and control sites was mainly explained by sedimentological and physical  
367 variables, although their relative contributions differed between sites. In this study, wood-related  
368 physical LVs, described by pH, conductivity, dissolved oxygen and, temperature, were the most  
369 important in explaining the overall variation of taxon traits (Fig. 4), implying that these traits  
370 exhibit strong relationships to local LW environmental conditions when viewed at local scale. The  
371 relative contribution of LVs to wood-trait variation is similar among modalities, underscoring a  
372 similar importance of all studied environmental drivers at LW sites

373 Control sites exhibited higher homogeneity in sedimentological variables, suggesting an increase  
374 in temporal stability partly due to the absence of wood-induced physical processes (Table 1).  
375 Sedimentological variables explained more than the 25% of hyporheic meiofaunal trait variation  
376 for all significant modalities (Fig. 5b). They explained much more of the variation of traits in  
377 control sites than LW sites, although significant trait modalities did not reflect a strong  
378 sedimentological impact (Fig. 5b). This finding is supported by other studies that have observed  
379 weaker effects of sediment size on hyporheic than epibenthic trait profiles (Descloux, Datry, &  
380 Marmonier, 2013; Descloux, Datry, & Usseglio-Polatera, 2014). Chemical and physical LVs  
381 explained 50% of the hyporheic meiofaunal trait variation for aquatic stages, dispersal and  
382 substrate preferences (Fig. 5b). Chemical LVs explained much more of the variation of traits for

383 hyporheic meiofaunal assemblages in control than wood sites (Fig. 4). This result is consistent  
384 with a recently published study on the , sandy section of the Hammer stream that shows LW sites  
385 were characterized by short hyporheic flow-paths inhibiting local nitrate reduction (Shelley,  
386 Klaar, Krause, & Trimmer, 2017). The responses of benthic invertebrate assemblages to nutrients  
387 are well documented, but those of the hyporheic meiofaunal assemblages are far less known  
388 (Marmonier et al., 2012). Certain groups of invertebrates have proved to be good indicators of  
389 moderately eutrophic rivers. Many caddisflies belonging to the Glossosomatidae, Psychomyiidae  
390 and Hydropsychidae families for example, have been found intolerant or withstanding only a low-  
391 moderate range of nitrate concentrations (Nijboer, 2004; Pacioglu, Moldovan, Shaw, & Robertson,  
392 2016). In our study, Psychomyiidae and *Hydropsyche* spp. instars were observed in hyporheic  
393 samples of control sites exhibiting higher concentrations of ammonium and phosphates than LW  
394 sites, thus supporting previous finding by providing a global indication of the chemical conditions  
395 in the HZ. Besides, other taxonomic groups (e.g. Chironomidae, Oligochaeta, Nematoda and  
396 Amphipoda), widespread among wood and control sites, have demonstrated high tolerance to  
397 nutrients in previous studies (Pacioglu, Moldovan, Shaw, & Robertson, 2016).  
398 Finally, our findings confirmed the mechanistic impact of LW on hyporheic meiofauna trait-  
399 selection as the result of a combination of LW-driving processes. The effects are more pronounced  
400 on meiofaunal than macrofaunal assemblages highlighting the importance of LW in triggering  
401 physical and sedimentological impacts on faunal communities of lowland systems. LW impacts  
402 on hyporheic meiofauna are potentially important given that many benthic invertebrate species  
403 rely closely on the HZ in their life cycle (Robertson & Wood, 2010). Our findings provide further

404 evidence of the mechanisms responsible for local invertebrate assemblage structure in LW,  
405 reflecting adaptations to dominant regional and local environmental stresses.

## 406 **5. Conclusions**

407 The functional trait approach offers a mechanistic alternative to traditional taxonomy-based  
408 approach for studying functional relationships between invertebrates and wood-habitats. The  
409 hyporheic zone and river connectivity are interrelated structural and functional properties of  
410 heterogeneous environments (Ward, 1989). Large wood plays a key role in promoting vertical  
411 hydrological connectivity (Lautz, Siegel, & Bauer, 2006) and, as evidenced in this study,  
412 ecological functions. Both hydrological connectivity and ecological functions are crucial to river  
413 functionality (e.g. “biodiversity maintenance”; Liebold & Norberg, 2004) and, as a result, to river  
414 management (Kondolf et al., 2006).

415 Our results suggest that a high variability of local abiotic conditions in LW sites promotes species  
416 traits related to temporal instability and low refugia availability (Townsend & Hildrew, 1994). As  
417 result, LW would likely promote the sustainability of r-strategist species and in turn contribute to  
418 maintain the global richness/biodiversity of local invertebrate assemblages by facilitating long-  
419 term temporal coexistence between r- and K-strategists at reach scale. r-strategists would exhibit  
420 an adaptive advantage for living in more unstable habitats, which function as refugia (following  
421 the Intermediate Disturbance Hypothesis (IDH) theory; Connell, 1978). Perhaps, sediment  
422 disturbance around the LW, a process not measured in this study, is an important, and possibly  
423 under-appreciated, environmental control of hyporheic and benthic invertebrate assemblages and  
424 should be considered in the future.

425 Finally, in the context of river restoration, large wood has been gradually integrated into  
426 management strategies as a means of improving the biodiversity and conservation value of lowland  
427 rivers (Grabowski et al, 2019; Larson, Booth, & Morley, 2001). Yet, such approaches have not  
428 always given due attention to the ecological effects of physical processes potentially promoting  
429 ecological responses. Our study confirmed the significant effect of large wood on biological,  
430 physiological and behavioural traits of the hyporheic meiofauna, suggesting a crucial role in  
431 supporting river benthic zone functioning, and thus a possible benefit to river restoration by  
432 enhancing functional interactions among different ecological niches. Such data are essential within  
433 a process-driven and strategic framework to effective restoration planning (Wohl, Lane, & Wilcox,  
434 2015) and has heuristic value for generating further hypotheses about invertebrate functional  
435 responses to LW.

436 **Authors' Contributions**

437 C. Magliozzi designed, collected the data, analysed the dataset and wrote the manuscript. P.  
438 Usseglio-Polatera coded the species traits, supervised the analysis and contributed to the  
439 discussions and editing throughout the manuscript. A. Meyer assisted in the analysis, interpretation  
440 and editing of the manuscript. R. Grabowski provided guidance on structure, advice and editing of  
441 the manuscript. All authors approved the manuscript and have no competing interests to declare.

442 **Acknowledgements**

443 This work was supported by the Marie Skłodowska-Curie Action, Horizon 2020 within the project  
444 HypoTRAIN (Grant agreement number 641939). Thanks to the Leibniz-Institute of Freshwater  
445 Ecology and Inland Fisheries (IGB) for performing the pore water chemical analysis.

446

447 **Data Accessibility**

448 The ecological data collected for this project is available on the Cranfield University data  
449 repository (Grabowski & Magliozzi, 2019). The data includes (i) abundances of invertebrates and  
450 traits and (ii) environmental conditions for the wood and control sites on the River Hammer.

451

452 **References**

- 453 Benke, A. C., & Wallace, J. B. (2003). Influence of wood on invertebrate communities in streams  
454 and rivers. *American Fisheries Society Symposium*, 37, 149–177.
- 455 Benzécri, J. P. (1983). Analyse de l'inertie intra-classe par l'analyse d'un tableau de  
456 correspondances. *Les Cahiers de l'Analyse des données*, 8 (3), 351-358.
- 457 Bilton, D. T., Freeland, J. R., & Okamura, B. (2001). Dispersal in freshwater invertebrates. *Annual*  
458 *Review of Ecology and Systematics*, 32, 159–181.  
459 [doi.org/10.1146/annurev.ecolsys.32.081501.114016](https://doi.org/10.1146/annurev.ecolsys.32.081501.114016).
- 460 Bizzi, S., Surridge, B. W., & Lerner, D. N. (2013). Structural equation modelling: a novel statistical  
461 framework for exploring the spatial distribution of benthic macroinvertebrates in riverine  
462 ecosystems. *River Research and Applications*, 29, 743–759. [doi.org/10.1002/rra.2563](https://doi.org/10.1002/rra.2563).
- 463 Blaen, P. J., Kurz, M. J., Drummond, J. D., Knapp, J. L., Mendoza-Lera, C., Schmadel, N. M.,  
464 Klaar, M. J., ... & Ward, A. S. (2018). Woody debris is related to reach-scale hotspots of lowland  
465 stream ecosystem respiration under baseflow conditions. *Ecohydrology*, e1952.  
466 <https://doi.org/10.1002/eco.1952>
- 467 Blott, S. J., & Pye, K. (2001). Gradistat: a grain size distribution and statistics package for the  
468 analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, 26, 1237–1248.  
469 [doi.org/10.1002/esp.261](https://doi.org/10.1002/esp.261)



470 Boulton, A. J. (2007). Hyporheic rehabilitation in rivers: restoring vertical connectivity.  
471 *Freshwater Biology*, 52, 632–650. doi.org/10.1111/j.1365-2427.2006.01710.x

472 Brock, M., Nielsen, D. L., Shiel, R. J., Green, J. D., & Langley, J. D. (2003). Drought and aquatic  
473 community resilience: the role of eggs and seeds in sediments of temporary wetlands. *Freshwater*  
474 *Biology*, 48, 1207–1218. doi.org/10.1046/j.1365-2427.2003.01083.x

475 Cao, Y., Larsen, D. P. & Thorne R. ST - J. (2001). Rare species in multivariate analysis for  
476 bioassessment: some considerations. *Journal of the North American Benthological Society*, 20:  
477 144–153. https://doi.org/10.2307/1468195

478 Castella, E., Richardot-Coulet, M., Roux, C. & Richoux, P. (1991). Aquatic macroinvertebrate  
479 assemblages of two contrasting floodplains: The Rhône and Ain rivers, France. *Regulated Rivers:*  
480 *Research & Management*, 6, 289-300. https://doi.org/10.1002/rrr.3450060407

481 Chevenet, F., Dolédec, S., & Chessel, D. (1994). A fuzzy coding approach for the analysis of long-  
482 term ecological data. *Freshwater Biology*, 31, 295–309. doi.org/10.1111/j.1365-  
483 2427.1994.tb01742.x

484 Coleman, M. J., & Hynes, H. (1970). The vertical distribution of the invertebrate fauna in the bed  
485 of a stream. *Limnology and Oceanography*, 15, 31–40. doi.org/10.4319/lo.1970.15.1.0031

486 Connell, J. H. (1978). Diversity in tropical rain forests and coral reefs. *Science*, 199, 1302–1310.  
487 DOI: 10.1126/science.199.4335.1302

488 Crossman, J., Bradley, C., Milner, A., & Pinay, G. (2013). Influence of environmental instability  
489 of groundwater-fed streams on hyporheic fauna, on a glacial floodplain, Denali National Park,  
490 Alaska. *River Research and Applications*, 29, 548–559. doi.org/10.1002/rra.1619

491 Croutsche, J. J. (2002). Étude des relations de causalité: Utilisation des modèles d'équations  
492 structurelles (approche méthodologique). *La Revue des Sciences de Gestion: Direction et Gestion*,  
493 p. 81.

494 Descloux, S., Datry, T., & Marmonier, P. (2013). Benthic and hyporheic invertebrate assemblages  
495 along a gradient of increasing streambed colmation by fine sediment. *Aquatic Sciences*, 75, 493–  
496 507. doi.org/10.1007/s00027-013-0295-6

497 Descloux, S., Datry, T., & Usseglio-Polatera, P. (2014). Trait-based structure of invertebrates  
498 along a gradient of sediment colmation: Benthos versus hyporheos responses. *Science of the Total  
499 Environment*, 466, 265–276. doi.org/10.1016/j.scitotenv.2013.06.082

500 Dole-Olivier, M. - J., Marmonier, P. & Beffy J. - L. (1997). Response of invertebrates to lotic  
501 disturbance: is the hyporheic zone a patchy refugium?. *Freshwater Biology*, 37, 257-276.  
502 <https://doi.org/10.1046/j.1365-2427.1997.00140.x>

503 Dolédec, S., & Chessel, D. (1989). Seasonal successions and spatial variables in freshwater  
504 environments. II. Distinction between seasonal and environmental effects within faunistic data (in  
505 French). *Acta Oecologica*, 10, 207–232.

506 Dray, S., Dufour, A. B., & Thioulouse, J. (2017). *ade4: Analysis of Ecological Data: Exploratory  
507 and Euclidean Methods in Environmental Sciences*. R package version, 1.7-10.

508 Dunscombe, M., Robertson, A., Peralta-Maraver, I., & Shaw, P. (2018). Community structure and  
509 functioning below the streambed across contrasting geologies. *Science of the Total Environment*,  
510 630, 1028–1035. doi.org/10.1016/j.scitotenv.2018.02.274

511 Flores, L., Giorgi, A., González, J. M., Larrañaga, A., Díez, J. R., & Elosegi, A. (2017). Effects of  
512 wood addition on stream benthic invertebrates differed among seasons at both habitat and reach  
513 scales. *Ecological Engineering*, 106, 116–123. doi.org/10.1016/j.ecoleng.2017.05.036

514 Gagic, V., Bartomeus, I., Jonsson, T., Taylor, A., Winqvist, C., Fischer, C., Slade, E. M., ...  
515 Bommarco, R. (2015). Functional identity and diversity of animals predict ecosystem functioning  
516 better than species- based indices. *Proceedings of the Royal Society of London B: Biological*  
517 *Sciences*, 282, 20142620. DOI:10.1098/rspb.2014.2620

518 Gauch, H.G. (1982). *Multivariate analysis in community ecology*. Cambridge University Press,  
519 Cambridge, UK.

520 Gippel, C. J., O'Neill, I. C., Finlayson, B. L., & Schnatz, I. (1996). Hydraulic guidelines for the  
521 re-introduction and management of large woody debris in lowland rivers. *Regulated Rivers*  
522 *Research & Management*, 12, 223–236.

523 Götz, O., Liehr-Gobbers, K., & Krafft, M. (2010). Evaluation of structural equation models using  
524 the partial least squares (pls) approach. *Handbook of Partial Least Squares*, pp. 691–711, Springer.

525 Grabowski, R. C., Gurnell, A. M., Burgess-Gamble, L., England, J., Holland, D., Klaar, M. J., ...  
526 Wharton, G. (2019). The current state of the use of large wood in river restoration and  
527 management. *Water and Environment Journal*. doi: 10.1111/wej.12465.

528 Grabowski, R. & Magliozzi, C. (2019). Effects of large wood on invertebrate assemblages in the  
529 bed of a lowland river using a functional trait approach (Version 1). figshare.  
530 <https://doi.org/10.17862/cranfield.rd.7539305.v1>

531 Grime, J. (1998). Benefits of plant diversity to ecosystems: immediate, filter and founder effects.  
532 *Journal of Ecology*, 86, 902–910. doi.org/10.1046/j.1365-2745.1998.00306.x.

533 Gurnell, A. M., & Grabowski, R. C (2016). Vegetation-hydrogeomorphology interactions in a low-  
534 energy, human-impacted river. *River Research and Applications*, 3, 202–215. doi:  
535 10.1002/rra.2922.

536 Gurnell, A. M. (2013). Wood in fluvial systems. In Shroder Jr., J. and Wohl, E. (eds) *Treatise on*  
537 *Geomorphology* (pp. 163–188). San Diego, CA, USA: Academic Press.

538 Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic  
539 and carbonate content in sediments: reproducibility and comparability of results. *Journal of*  
540 *Paleolimnology*, 25, 101–110. doi.org/10.1023/A:10081196

541 Hothorn, T., Hornik, K., Strobl, C., & Zeileis, A. (2017). party: A Laboratory for Recursive  
542 Partytioning. R package version, 1.2-4.

543 Hothorn, T., Hornik, K., & Zeileis, A. (2006). Unbiased recursive partitioning: A conditional  
544 inference framework. *Journal of Computational and Graphical Statistics*, 15, 651–674.

545 Kaller, M. D. and Kelso, W. E. (2007). Association of macroinvertebrate assemblages with  
546 dissolved oxygen concentration and wood surface area in selected subtropical streams of the  
547 southeastern USA. *Aquatic Ecology*, 41, 95–110.

548 Kondolf, G., Boulton, A., O’Daniel, S., Poole, G., Rahel, F., Stanley, E., Wohl, E., ... Nakamura,  
549 K. (2006). Process-based ecological river restoration: visualizing three-dimensional connectivity  
550 and dynamic vectors to recover lost linkages. *Ecology and Society*, 11, 5.

551 Krause, S., Klaar, M. J., Hannah, D. M., Mant, J., Bridgeman, J., Trimmer, M., & Manning Jones,  
552 S. (2014). The potential of large woody debris to alter biogeochemical processes and ecosystem  
553 services in lowland rivers. *Wiley Interdisciplinary Reviews: Water*, 1, 263-275.  
554 <https://doi.org/10.1002/wat2.1019>

555 Krause, S., Tecklenburg, C., Munz, M., & Naden, E. (2013). Streambed nitrogen cycling beyond  
556 the hyporheic zone: Flow controls on horizontal patterns and depth distribution of nitrate and  
557 dissolved oxygen in the upwelling groundwater of a lowland river. *Journal of Geophysical  
558 Research: Biogeosciences*, 118, 54–67. [doi.org/10.1029/2012JG002122](https://doi.org/10.1029/2012JG002122)

559 Larsen, S., Pace, G., & Ormerod, S. (2011). Experimental effects of sediment deposition on the  
560 structure and function of macroinvertebrate assemblages in temperate streams. *River Research and  
561 Applications*, 27, 257–267. [doi.org/10.1002/rra.1361](https://doi.org/10.1002/rra.1361)

562 Larson, M. G., Booth, D. B., & Morley, S. A. (2001). Effectiveness of large woody debris in stream  
563 rehabilitation projects in urban basins. *Ecological Engineering*, 18, 211–226.  
564 doi.org/10.1016/S0925-8574(01)00079-9

565 Lautz, L. K., Siegel, D. I., & Bauer, R. L. (2006). Impact of debris dams on hyporheic interaction  
566 along a semi-arid stream. *Hydrological Processes*, 20, 183–196. doi.org/10.1002/hyp.5910

567 Lewandowski, J., Putschew, A., Schwesig, D., Neumann, C., & Radke, M. (2011). Fate of organic  
568 micropollutants in the hyporheic zone of a eutrophic lowland stream: Results of a preliminary field  
569 study. *Science of the Total Environment*, 409, 1824–1835.  
570 doi.org/10.1016/j.scitotenv.2011.01.028

571 Magliozzi, C., Grabowski, R., Packman, A. I., & Krause, S. (2018). Toward a conceptual  
572 framework of hyporheic exchange across spatial scales. *Hydrology and Earth System Sciences*,  
573 22, 6163-6185. <https://doi.org/10.5194/hess-22-6163-2018>, 2018.

574 Marmonier, P., Archambaud, G., Belaidi, N., Bougon, N., Breil, P., Chauvet, E., ... Vervier, P.  
575 (2012). The role of organisms in hyporheic processes: gaps in current knowledge, needs for future  
576 research and applications. *Annales de Limnologie-International Journal of Limnology*, 48, 253–  
577 266. doi.org/10.1051/limn/2012009

578 Marmonier, P., Delettre, Y., Lefebvre, S., Guyon, J., & Boulton, A. (2004). A simple technique  
579 using wooden stakes to estimate vertical patterns of interstitial oxygenation in the beds of rivers.  
580 *Archiv für Hydrobiologie*, 160, 133–143. doi.org/10.1127/0003-9136/2004/0160-0133

581 Mathers, K. L., Millett, J., Robertson, A. L., Stubbington, R., & Wood, P. J. (2014). Faunal  
582 response to benthic and hyporheic sedimentation varies with direction of vertical hydrological  
583 exchange. *Freshwater Biology*, 59, 2278–2289. doi.org/10.1111/fwb.12430

584 Matthaei, C., Peacock, K. A., & Townsend, C. R. (1999). Scour and fill patterns in a New Zealand  
585 stream and potential implications for invertebrate refugia. *Freshwater Biology*, 42, 41–57.  
586 doi.org/10.1046/j.1365-2427.1999.00456.x

587 McGill, B. J., Enquist, B. J., Weiher, E., & Westoby, M. (2006). Rebuilding community ecology  
588 from functional traits. *Trends in Ecology & Evolution*, 21, 178–185.  
589 doi.org/10.1016/j.tree.2006.02.002

590 Menichino, G. T., & Hester, E. T. (2014). Hydraulic and thermal effects of in-stream structure-  
591 induced hyporheic exchange across a range of hydraulic conductivities. *Water Resources*  
592 *Research*, 50, 4643–4661. doi.org/10.1002/2013WR014758

593 Mondy, C. P., & Usseglio-Polatera, P. (2013). Using conditional tree forests and life history traits  
594 to assess specific risks of stream degradation under multiple pressure scenario. *Science of the Total*  
595 *Environment*, 461, 750–760. doi.org/10.1016/j.scitotenv.2013.05.072

596 Mutz, M., Kalbus, E., & Meinecke, S. (2007). Effect of instream wood on vertical water flux in  
597 low-energy sand bed flume experiments. *Water Resources Research*, 43, 1–10.  
598 doi.org/10.1029/2006WR005676

599 Nijboer, R. (2004). The ecological requirements of *Agapetus fuscipes* CURTIS (Glossosomatidae),  
600 a characteristic species in unimpacted streams. *Limnologica-Ecology and Management of Inland*  
601 *Waters*, 34, 213–223. doi.org/10.1016/S0075-9511(04)80046-X

602 Orghidan, T. (1959). Ein neuer Lebensraum des unterirdischen Wassers: der hyporheische Biotop.  
603 *Archiv für Hydrobiologie*, 55, 392–414.

604 Pacioglu, O., Moldovan, O. T., Shaw, P., & Robertson, A. (2016). Response of invertebrates from  
605 the hyporheic zone of Chalk rivers to eutrophication and land use. *Environmental Science and*  
606 *Pollution Research*, 23, 4729–4740. doi.org/10.1007/s11356-015-5703-0

607 Pilotto, F., Bertocin, A., Harvey, G. L., Wharton, G., & Pusch, M. T. (2014). Diversification of  
608 stream invertebrate communities by large wood. *Freshwater Biology*, 59, 2571–2583.  
609 doi.org/10.1111/fwb.12454

610 Pilotto, F., Harvey, G. L., Wharton, G., & Pusch, M. T. (2016). Simple large wood structures  
611 promote hydromorphological heterogeneity and benthic macroinvertebrate diversity in low-  
612 gradient rivers. *Aquatic Sciences*, 78, 755–766. doi.org/10.1007/s00027-016-0467-2

613 Robertson, A., & Wood, P. (2010). Ecology of the hyporheic zone: origins, current knowledge and  
614 future directions. *Fundamental and Applied Limnology/Archiv für Hydrobiologie*, 176, 279–289.  
615 doi.org/10.1127/1863-9135/2010/0176-0279



616 Sanchez, G. (2013). *Pls path modeling with r*. Berkeley: Trowchez Editions.

617 Sanchez, G., Trinchera, L., & Russolillo, G. (2017). *plspm: Tools for Partial Least Squares Path*  
618 *Modeling (PLS-PM)*. R package version, 0.4.9.

619 Sawyer, A. H., Cardenas, B. M., & Buttles, J. (2011). Hyporheic exchange due to channel-  
620 spanning logs. *Water Resources Research*, 47, W08502. doi:10.1029/2011WR010484

621 Shelley, F., Klaar, M., Krause, S., & Trimmer, M. (2017). Enhanced hyporheic exchange flow  
622 around woody debris does not increase nitrate reduction in a sandy streambed. *Biogeochemistry*,  
623 136, 353–372. doi.org/10.1007/s10533-017-0401-2

624 Statzner, B., & Bêche, L.A. (2010). Can biological invertebrate traits resolve effects of multiple  
625 stressors on running water ecosystems? *Freshwater Biology*, 55, 80–119. doi.org/10.1111/j.1365-  
626 2427.2009.02369.x

627 Stead, T. K., Schmid-Araya, J. M., & Hildrew, A. G. (2003). All creatures great and small: patterns  
628 in the stream benthos across a wide range of metazoan body size. *Freshwater Biology*, 48, 532–  
629 547. doi.org/10.1046/j.1365-2427.2003.01025.x

630 Stubbington, R., Bogan, M. T., Bonada, N., Boulton, A. J., Datry, T., Leigh, C., & Vander Vorste,  
631 R. (2017). *The biota of intermittent rivers and ephemeral streams: aquatic invertebrates*.

632 Intermittent Rivers and Ephemeral Streams, pp. 217–243, Elsevier. doi.org/10.1016/B978-0-12-  
633 803835-2.00007-3

634 Tachet, H., Richoux, P., Bournaud, M., & Usseglio-Polatera, P. (2010). Invertébrés d’eau douce.  
635 Systématique, biologie, écologie. (2nd edition). CNRS éditions, Paris.

636 Tenenhaus, M., Vinzi, V. E., Chatelin, Y. M., & Lauro, C. (2005). Pls path modeling.  
637 Computational Statistics & Data Analysis, 48, 159–205.

638 Thompson, M. S., Brooks, S. J., Sayer, C. D., Woodward, G., Axmacher, J. C., Perkins, D. M., &  
639 Gray, C. (2018). Large woody debris rewilding rapidly restores biodiversity in riverine food webs.  
640 Journal of Applied Ecology, 55, 895–904. doi.org/10.1111/1365-2664.13013

641 Tonkin, J. D., Shah, T., Devi, R., Shah, D. N., Hoppeler, F., Jähnig, S. C., & Pauls, S. U. (2017).  
642 Metacommunity structuring in Himalayan streams over large elevational gradients: the role of  
643 dispersal routes and niche characteristics. Journal of Biogeography, 44, 62–74.  
644 doi.org/10.1111/jbi.12895

645 Townsend, C. R., & Hildrew, A. G. (1994). Species traits in relation to a habitat templet for river  
646 systems. Freshwater Biology, 31, 265–275. doi.org/10.1111/j.1365-2427.1994.tb01740.x

647 Usseglio-Polatera, P., Richoux, P., Bournaud, M., & Tachet, H. (2001). A functional classification  
648 of benthic macroinvertebrates based on biological and ecological traits: application to river  
649 condition assessment and stream management. Archiv für Hydrobiologie. Supplement band.  
650 Monographische Beiträge, 139, 53–83.

651 Van Looy, K., Floury, M., Ferréol, M., Prieto-Montes, M. & Souchon, Y. (2016). Long-term  
652 changes in temperate stream invertebrate communities reveal a synchronous trophic amplification  
653 at the turn of the millennium. *Science of the Total Environment*, 565, 481-488.  
654 <https://doi.org/10.1016/j.scitotenv.2016.04.193>

655 Villéger, S., Mason, N. W., & Mouillot, D. (2008). New multidimensional functional diversity  
656 indices for a multifaceted framework in functional ecology. *Ecology*, 89, 2290–2301.  
657 [doi.org/10.1890/07-1206.1](https://doi.org/10.1890/07-1206.1).

658 Villeneuve, B., Piffady, J., Valette, L., Souchon, Y., & Usseglio-Polatera, P. (2018). Direct and  
659 indirect effects of multiple stressors on stream invertebrates across watershed, reach and site  
660 scales: A structural equation modelling better informing on hydromorphological impacts. *Science*  
661 *of the Total Environment*, 612, 660–671. [doi.org/10.1016/j.scitotenv.2017.08.197](https://doi.org/10.1016/j.scitotenv.2017.08.197)

662 Vinzi, V. E., Trinchera, L., & Amato, S. (2010). Pls path modeling: from foundations to recent  
663 developments and open issues for model assessment and improvement. *Handbook of partial least*  
664 *squares*, pp. 47–82, Springer.

665 Wagenhoff, A., & Olsen, D. (2014). Does large woody debris affect the hyporheic ecology of a  
666 small New Zealand pasture stream? *New Zealand Journal of Marine and Freshwater Research*,  
667 48, 547–559. [doi.org/10.1080/00288330.2014.924539](https://doi.org/10.1080/00288330.2014.924539)

668 Ward, J. (1989). The four-dimensional nature of lotic ecosystems. *Journal of the North American*  
669 *Benthological Society*, 8, 2–8. [doi.org/10.2307/1467397](https://doi.org/10.2307/1467397)

670 Wohl, E., Lane, S. N., & Wilcox, A. C. (2015). The science and practice of river restoration. *Water*  
671 *Resources Research*, 51, 5974-5997. doi:10.1002/2014WR016874.

672 Wohl, E., Cenderelli, D. A., Dwire, K. A., Ryan-Burkett, S. E., Young, M. K., & Fausch, K. D.  
673 (2010). Large in-stream wood studies: a call for common metrics. *Earth Surface Processes and*  
674 *Landforms*, 35, 618–625. doi.org/10.1002/esp.1966

675 Wold, H. (1982) Soft modelling: the basic design and some extensions. *Systems Under Indirect*  
676 *Observation, Part II* pp. 36–37.

677 Zwick, P. (1996). Variable egg development of *Dinocras* spp. (Plecoptera, Perlidae) and the  
678 stonefly seed bank theory. *Freshwater Biology*, 35, 81–100. doi.org/10.1046/j.1365-  
679 2427.1996.00482.x

680

681 **Tables and Figures**

682 Table 1: Hypothesized effects of wood to promote (+) or inhibit (-) key  
 683 processes and conditions.

<b>Processes &amp; Conditions</b>	<b>Wood</b>	<b>Control</b>	<b>References</b>
1. Hyporheic exchange flow	+	-	Krause et al., 2014
2. Oxygen availability	+	-	Kaller & Kelso, 2007
3. Temporal stability	-	+	Gurnell, 2013
4. Organic matter	+	-	Blaen et al., 2018
5. Denitrification	-	+	Klaar, Krause, & Trimmer, 2017
6. Hydraulic conductivity	+	-	Mutz, Kalbus, & Meinecke, 2007

684

685 Table 2: Trait modalities predicted to be significantly enhanced by the habitat conditions in  
 686 the site type (Large wood or Control). Numbers in bold indicate processes (see Table 1 for  
 687 codes) that are hypothesized to have a strong influence in driving the predicted trait  
 688 modality.

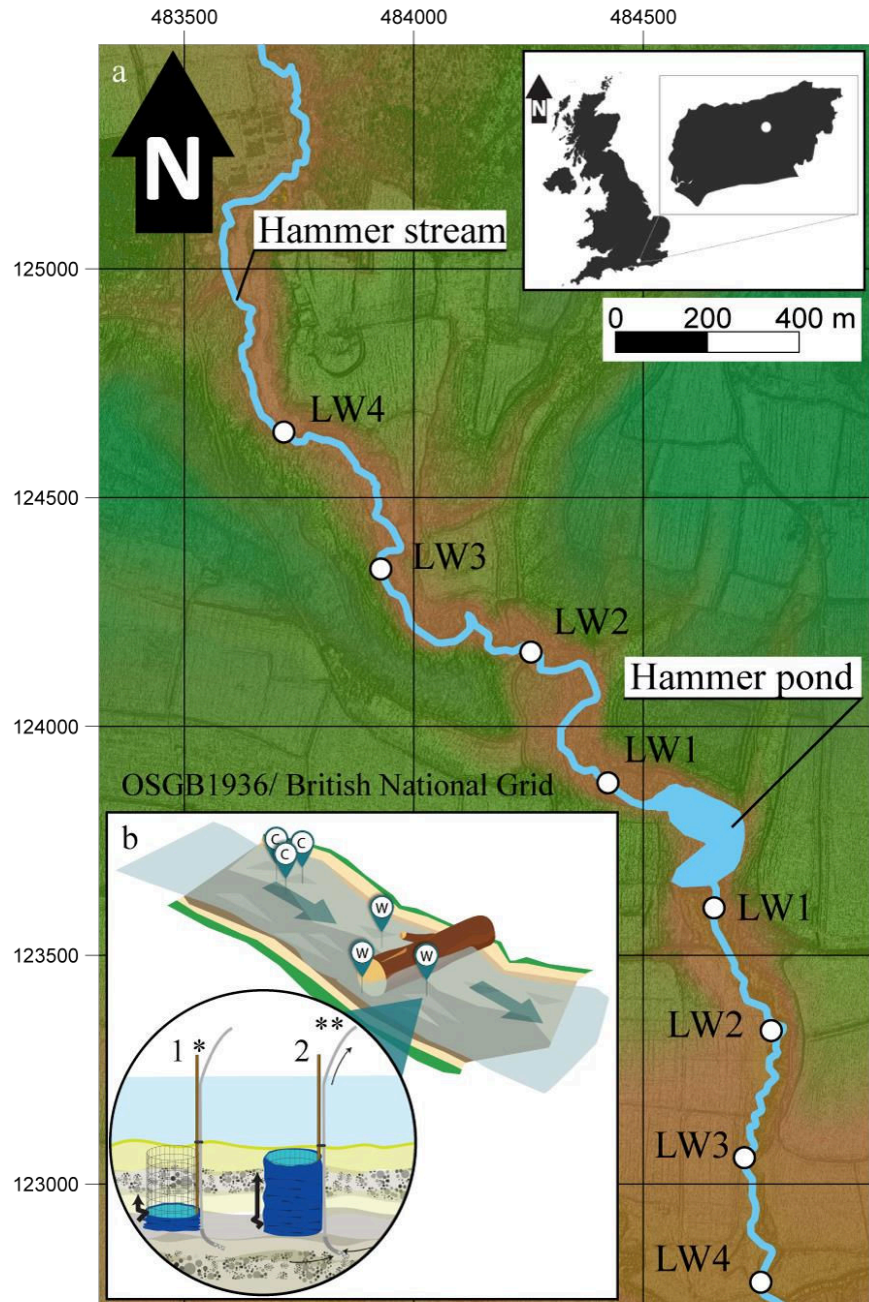
	<b>Traits</b>	<b>Large wood</b>	<b>Control</b>	<b>Processes</b>
<b>Behavioural</b>	Locomotion	attached	interstitial, burrowers, crawlers	<b>1, 6</b>
	Substrate preferences	organic detritus, litter, roots	mud, silt	<b>1, 4, 6</b>
	Velocity preferences	fast/medium	slow, null	1
	Dispersal	aquatic passive	aquatic active	1
<b>Biological</b>	Aquatic stages	larva, egg	adult, nymph	1, <b>3, 2</b>
	Nb cycles/yr	> 1	≤ 1	1, <b>3</b>
	Reproduction techniques & resistance forms	high fecundity, resistance stages	low fecundity, none or few resistance stages	3
	Size	small		<b>3</b>
<b>Morphological</b>	Body form	flattened, streamlined	cylindrical, spherical	1, <b>6</b>
	Body flexibility	low/intermediate	high	1, <b>6</b>
<b>Physiological</b>	Feeding habits	filter feeders, shredders	deposit feeders	1, <b>4, 5</b>
	Food	microphytes, dead plants (≥ 1 mm)	detritus (< 1 mm) microorganisms	4, 5
	Respiration	spiracle, gills	tegument	2

689

690 Table 3: Mean hydrological, physical, sedimentological and chemical variables ( $\pm sd$ ) recorded at wood and control sites in the gravel  
691 and control reaches of the Hammer stream between October 2016 and August 2017. Mean Water Depth (MW), Discharge (Q),  
692 Conductivity (EC), Dissolved Oxygen (DO), Temperature (T), Sediment Grain Size: D10, D50, D90, Sorting Coefficient (SO),  
693 Skewness (SK), Sediment Organic Matter (OM), Oxygen Depth (OD), Ammonium  $NH_4^+$ , Nitrate  $NO_3^-$ , Nitrite  $NO_2^-$ , Phosphate (SRP).  
694 Detection limit of 0.1 mg N L<sup>-1</sup> for Nitrate, 0.01mg N L<sup>-1</sup> for Nitrite, and 0.03 mg N L<sup>-1</sup> for Ammonium.

	Control-Gravel	Wood-Gravel	Control-Sand	Wood-Sand
<b>Hydrological variables</b>				
MW (m)	0.20 $\pm$ 0.14	0.28 $\pm$ 0.09	0.26 $\pm$ 0.09	0.31 $\pm$ 0.11
Q (m <sup>3</sup> s <sup>-1</sup> )	0.07 $\pm$ 0.03	0.09 $\pm$ 0.05	0.05 $\pm$ 0.02	0.06 $\pm$ 0.02
<b>Physical variables</b>				
EC ( $\mu$ S cm <sup>-1</sup> )	249.71 $\pm$ 19.10	243.29 $\pm$ 19.26	237.68 $\pm$ 19.62	223.58 $\pm$ 30.40
DO (%)	89.50 $\pm$ 19.96	97.66 $\pm$ 34.75	91.40 $\pm$ 28.17	91.54 $\pm$ 40.09
pH	7.23 $\pm$ 0.39	7.02 $\pm$ 0.23	6.85 $\pm$ 0.60	6.67 $\pm$ 0.58
T (°C)	13.07 $\pm$ 3.43	12.48 $\pm$ 3.11	12.26 $\pm$ 2.68	11.78 $\pm$ 3.11
<b>Sedimentological variables</b>				
D10 (cm)	0.91 $\pm$ 1.11	4.06 $\pm$ 5.09	0.04 $\pm$ 0.01	0.16 $\pm$ 0.02
D90 (cm)	10.68 $\pm$ 2.13	31.15 $\pm$ 10.16	3.04 $\pm$ 8.93	3.14 $\pm$ 6.30
D50 (cm)	4.34 $\pm$ 2.14	14.09 $\pm$ 7.83	0.14 $\pm$ 0.15	0.39 $\pm$ 0.14
SO (cm)	0.001 $\pm$ 0.001	0.003 $\pm$ 0.001	0.001 $\pm$ 0.000	0.002 $\pm$ 0.000
SK (cm)	-0.0001 $\pm$ 0.0001	-0.0002 $\pm$ 0.0002	-0.0001 $\pm$ 0.0001	-0.0001 $\pm$ 0.0001
OM (%)	0.25 $\pm$ 0.16	1.10 $\pm$ 0.82	2.81 $\pm$ 2.89	12.70 $\pm$ 7.27
OD (cm)	5.87 $\pm$ 4.68	6.25 $\pm$ 2.77	4.40 $\pm$ 2.71	5.44 $\pm$ 3.13
<b>Chemical variables</b>				
NH <sub>4</sub> <sup>+</sup> (mg N L <sup>-1</sup> )	0.13 $\pm$ 0.12	0.09 $\pm$ 0.06	1.89 $\pm$ 1.28	0.54 $\pm$ 0.41
NO <sub>3</sub> <sup>-</sup> (mg N L <sup>-1</sup> )	7.04 $\pm$ 3.47	7.24 $\pm$ 3.10	0.69 $\pm$ 0.43	0.67 $\pm$ 0.42
NO <sub>2</sub> <sup>-</sup> (mg N L <sup>-1</sup> )	0.02 $\pm$ 0.02	0.02 $\pm$ 0.01	0.01 $\pm$ 0.01	0.01 $\pm$ 0.01
SRP (mg PO <sub>4</sub> L <sup>-1</sup> )	0.06 $\pm$ 0.04	0.05 $\pm$ 0.04	0.58 $\pm$ 0.42	0.26 $\pm$ 0.30

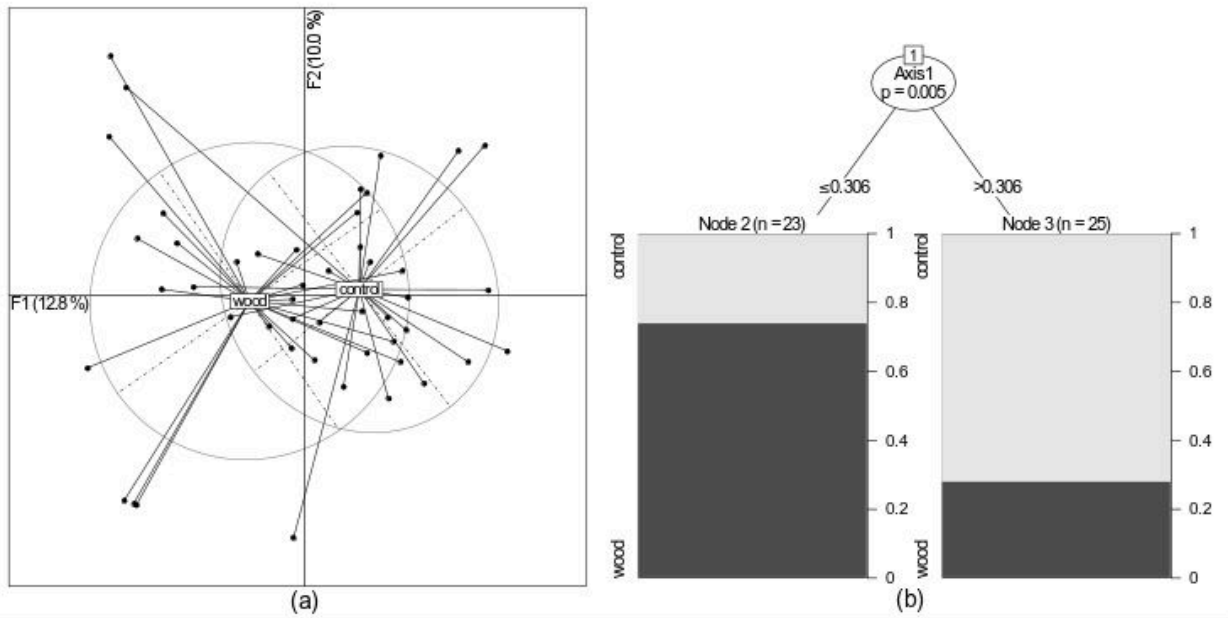
695



696 Figure 1: The study was conducted in the Hammer stream, West Sussex, UK. Invertebrates were sampled  
 697 at 4 sites in sand (upstream Hammer pond) and gravel (downstream Hammer pond) sections (LW 1-4), with  
 698 three replicates taken in control and around the LW (b) using colonization pots and Surber net. Inset (left):  
 699 an illustration of sampling around the LW and of the colonization pot equipped with wood stakes (\*) and  
 700 minipiezometer (\*\*). The pot is cylindrical steel cages (mesh size 1 cm<sup>2</sup>), a tarpaulin bag with reinforced



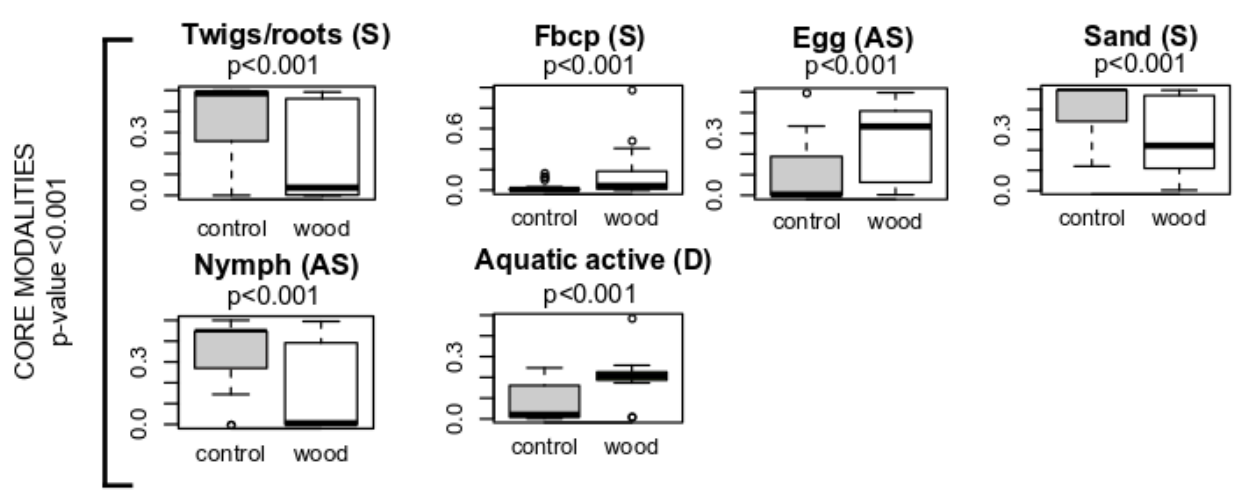
701 top and cable which is placed around the base of each pot before inserting the pot in the excavated hole.  
702 b1) pot is positioned into the river bed. b2) during the extraction, cable is pulled vertically, driving the wire-  
703 reinforced tops to the surface and extending the tarpaulin bags.



705 Figure 2: Hyporheic meiofauna trait profiles among wood and control sites. (a) First factorial plane  
 706 of WCA giving the locations of the 48 samples gathered by wood and control sites. Labels are  
 707 located at the weighted average (i.e. the centre of the star) of corresponding samples (solid circles).  
 708 The ellipses of inertia are defined as the 95% confidence interval around the centroids, and the  
 709 percentage of the total variance explained is indicated for each axis. (b) CIT (9999 Bonferroni  
 710 permutations;  $\alpha = 0.01$ ) testing the significance of differences in wood and control site locations  
 711 on the first WCA factorial plane (response variables: coordinates of samples along F1 and F2; n =  
 712 number of samples).

713

714

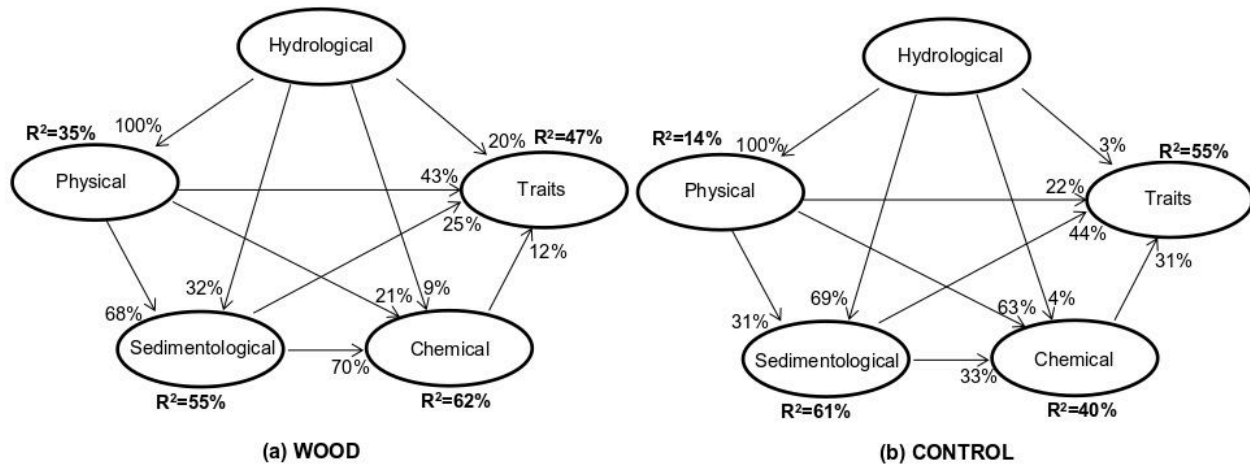


715

716 Figure 3: Relative frequency of trait modalities (see Table S1 for abbreviations) for hyporheic  
717 meiofauna in control vs LW sites. Only trait modalities exhibiting significant differences  
718 (Wilcoxon test, adjusted p-values < 0.001) between control and LW sites are presented. Traits are  
719 indicated in bracket: AS = Aquatic stages, D = Dispersal, S = Substrate preferences.

720

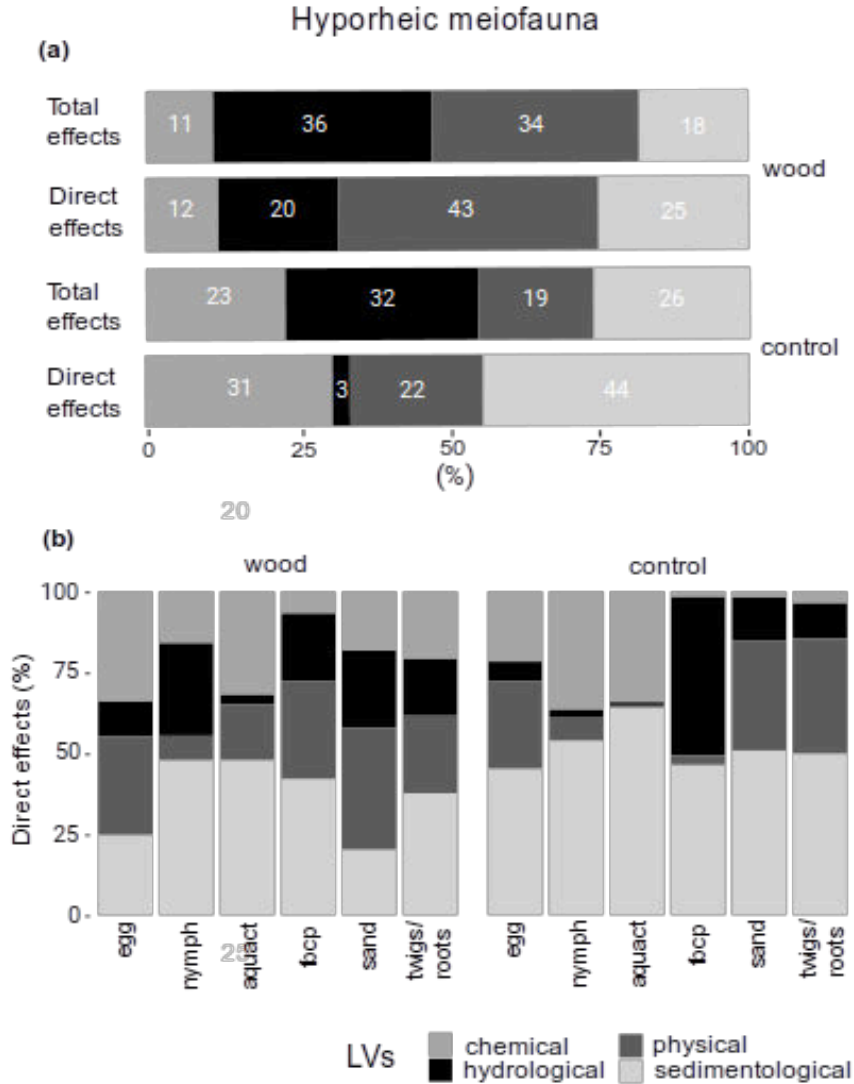
HYPORHEIC MEIOFAUNA



721

722 Figure 4: PLS path models for the hyporheic meiofauna in (a) wood and (b) control sites, showing  
 723 latent variables connected by direct effects. R<sup>2</sup> is reported for each internal model and for the  
 724 contributions of latent variables to the variation in trait modalities (in bold).

725



726 Figure 5: (a) Relative contribution (%) of latent variables (LVs) to the variation of the trait  
 727 modalities of hyporheic meiofauna significantly differing between wood and control sites  
 728 (Wilcoxon test, adjusted p-value < 0.001), based on direct and total (= direct + indirect) effects.  
 729 (b) Direct effects of LVs on the trait modalities of hyporheic meiofauna significantly differing  
 730 between wood and control sites (Wilcoxon test, adjusted p-value < 0.001).

# Functional traits of hyporheic and benthic invertebrates reveal importance of wood-driven geomorphological processes to rivers

Magliozzi, Chiara

2019-06-04

Attribution-NonCommercial-NoDerivatives 4.0 International

---

Magliozzi C, Usseglio-Polatera P, Meyer A, Grabowski RC. (2019) Functional traits of hyporheic and benthic invertebrates reveal importance of wood-driven geomorphological processes to rivers, *Functional Ecology*, Volume 33, Issue 9, September 2019, pp. 1758-1770

<https://doi.org/10.1111/1365-2435.13381>

*Downloaded from CERES Research Repository, Cranfield University*