Received: 13 April 2020 | Revised: 14 October 2020 | Accepted: 11 November 2020
DOI: 10.1111/fwb.13657

ORIGINAL ARTICLE

Freshwater Biology WILEY

Anthropogenic litter is a novel habitat for aquatic macroinvertebrates in urban rivers

Hazel L. Wilson[1] | **Matthew F. Johnson**[1] | **Paul J. Wood**[2] | **Colin R. Thorne**[1] | **Markus P. Eichhorn**[3,4]

[1]School of Geography, University of Nottingham, Nottingham, U.K.

[2]Geography and Environment, Loughborough University, Leicestershire, U.K.

[3]School of Biological, Earth and Environmental Sciences, University College Cork, Cork, Ireland

[4]Environmental Research Institute, University College Cork, Cork, Ireland

Correspondence
Hazel L. Wilson, School of Geography, University of Nottingham, Nottingham, NG7 2TU, U.K.
Email: hazel.wilson@nottingham.ac.uk

Funding information
Engineering and Physical Sciences Research Council

Abstract

1. Anthropogenic litter (solid manufactured waste) is an understudied but pervasive element of river systems worldwide. Its physical structure generally differs from natural substrates, such as gravel and cobbles (hereafter *rocks*). Consequently, anthropogenic litter could influence ecological communities in urban rivers by providing novel habitats.
2. This study compares the macroinvertebrates recorded on anthropogenic litter with those on rocks to test whether the different substrates support distinct communities. Macroinvertebrates were collected from individual rocks and anthropogenic litter, predominantly plastic, metal, and glass, in three U.K. rivers.
3. Macroinvertebrate communities on anthropogenic litter were consistently more diverse than those found on rocks, reflecting its greater surface complexity, but the density of macroinvertebrates was similar among substrates. The community composition also varied between substrates, with five taxa only recorded on anthropogenic litter. Community differences largely reflected greater abundances of common taxa on anthropogenic litter, which were relatively insensitive to environmental quality. Plastic and fabric anthropogenic litter communities were the most dissimilar to those on rocks, probably due to their flexibility, which could replicate the physical structure of aquatic macrophytes.
4. Our findings indicate that anthropogenic litter supports a distinct and diverse community of macroinvertebrates in urban rivers, which are otherwise relatively homogenous in habitat structure.
5. Removal of anthropogenic litter from urban rivers may not be beneficial for local biodiversity. Understanding the functional habitats provided by anthropogenic litter could help better manage urban rivers to replace habitat lost through urbanisation.

KEYWORDS
community, conservation/biodiversity, invertebrates, pollution, running water/rivers/streams

1 | INTRODUCTION

Growing public and political interest around problems of anthropogenic litter (solid manufactured waste items, including but not limited to plastics) has encouraged a recent proliferation of studies into its occurrence and abundance in the environment, and its ecological impacts (e.g. Agamuthu et al., 2019; Beaumont et al., 2019). In marine ecosystems, anthropogenic litter has been shown to reduce organism fitness and cause mortality through entanglement and ingestion (Agamuthu et al., 2019; Kühn et al., 2015), expose organisms to harmful chemicals via leaching of pollutants (Rochman, 2015), modify physical habitat structure (Kiessling et al., 2015), and aid the spread of invasive species (Rech et al., 2016; Tyrrell & Byers, 2007). Despite urban rivers being some of the most anthropogenically modified landscapes on Earth (see review: Walsh et al., 2005), and acknowledgement of the persistence and prevalence of anthropogenic litter in urban rivers (e.g. McCormick & Hoellein, 2016; Rech et al., 2015), the effects of anthropogenic litter on these ecosystems have yet to be fully explored (Blettler et al., 2018).

Urban rivers are typically limited in habitat diversity and quality due to historical channelisation, dredging and bed/bank stabilisation works. Coupled with elevated concentrations of pollutants, and changed hydrological and sediment inputs, this has resulted in characteristic low diversity communities in many urban rivers (termed the *urban stream syndrome*: Walsh et al., 2005). Urban rivers also receive disproportionately large inputs of anthropogenic litter, which, although undesirable, may provide different and more complex shapes and textures of substrate. Anthropogenic litter may also interact with flow patterns, increasing habitat heterogeneity in a similar manner to large rocks, wood, and aquatic macrophytes. These natural habitat structures are largely absent in urban rivers due to regular removal practices and the high frequency of disturbance events (Blauch & Jefferson, 2019). Anthropogenic litter may therefore act as a proxy for habitats lost through urbanisation, supporting biodiversity that would otherwise be absent (Chapman & Clynick, 2006). For example, flexible anthropogenic litter may perform similar physical functions to aquatic macrophytes.

Macroinvertebrates are known to readily colonise artificial surfaces as long as they are non-toxic (e.g. the use of artificial substrate samplers; Beak et al., 1973). As their community structure is strongly related to habitat, especially the size, diversity, and arrangement of riverbed substrates (Death, 2000; Jowett, 2003), this makes them useful model organisms to assess the effects of anthropogenic litter on urban rivers. The atypical physical structure of anthropogenic litter could provide a novel habitat for some macroinvertebrate taxa, offering opportunities for adaptable species to colonise, and resulting in a community distinct from those living on natural substrates (Czarnecka et al., 2009). Anthropogenic litter with complex physical structure (e.g. items such as bottles which have interiors: Czarnecka et al., 2009; or items with rough surfaces: Boyero, 2003) may also be able to support a greater diversity of organisms through increasing available niche space. This may be especially true where the natural substrate is relatively inhospitable to macroinvertebrates, such as sandy or silty estuarine rivers and harbours with low bed stability (e.g. Francis & Hoggart, 2008; García-Vazquez et al., 2018). The quality and quantity of macroinvertebrate food resources are also affected by microhabitat conditions (Wallace & Webster, 1996) so changes in the abundance or diversity of food resources caused by anthropogenic litter may have cascading effects in macroinvertebrate communities. In addition, anthropogenic litter may preferentially support non-native species that may be better able to take advantage of the novel habitat than native species (Katsanevakis, 2008; Tyrrell & Byers, 2007).

The limited number of published studies examining fauna living on anthropogenic litter has been focussed on marine (e.g. Chapman & Clynick, 2006; Katsanevakis et al., 2007; García-Vazquez et al., 2018) rather than freshwater environments. These studies report that experimentally introduced anthropogenic litter on a sandy sea bed may locally increase the abundance and diversity of benthic communities, where it provides habitat for hard-substratum dwelling species that are otherwise absent (Katsanevakis et al., 2007). However, where comparable natural habitats are present, such as natural rocky reefs, there may be limited differences in patterns of colonisation of anthropogenic litter and natural substrates (Chapman & Clynick, 2006). So far, only one study has considered pre-existing in situ anthropogenic litter as a component of freshwater habitats (Czarnecka et al., 2009), where it was reported that the macroinvertebrate communities found on anthropogenic litter in a Polish reservoir were more diverse and considerably different in taxonomic composition from those on the surrounding sand bed, but were similar in diversity to those recorded on macrophytes. However, so far there have been no investigations of in situ anthropogenic litter undertaken within non-tidal river systems.

In this study, we compare macroinvertebrate communities inhabiting anthropogenic litter with those on natural rock substrates in three urban rivers to provide the first direct evaluation of the role of anthropogenic litter as riverine habitat. We anticipate that distinct communities would be recorded on the two substrate types, and that faunal diversity would be higher on anthropogenic litter given its heterogeneity relative to natural mineral substrates. If anthropogenic litter provides novel habitats, understanding how it affects macroinvertebrates is important in informing future urban stream management.

2 | METHODS

2.1 | Study sites

Sampling was conducted in three small (first or second order) urban gravel-bed rivers in Leicestershire and Nottinghamshire, U.K.: the River Leen, Black Brook, and Saffron Brook (Figure 1). Each river was sampled over two consecutive days in September and October 2018. Straightened reaches with homogenous substrate grain-size and morphology were selected to minimise any effect of natural morphological heterogeneity. Sites were similar in dimension, water quality, and discharge, but differed in urbanisation intensity (Table S1).

The predominant natural substrate (substrate is defined here as riverbed material on which an organism lives) at all sites was gravel

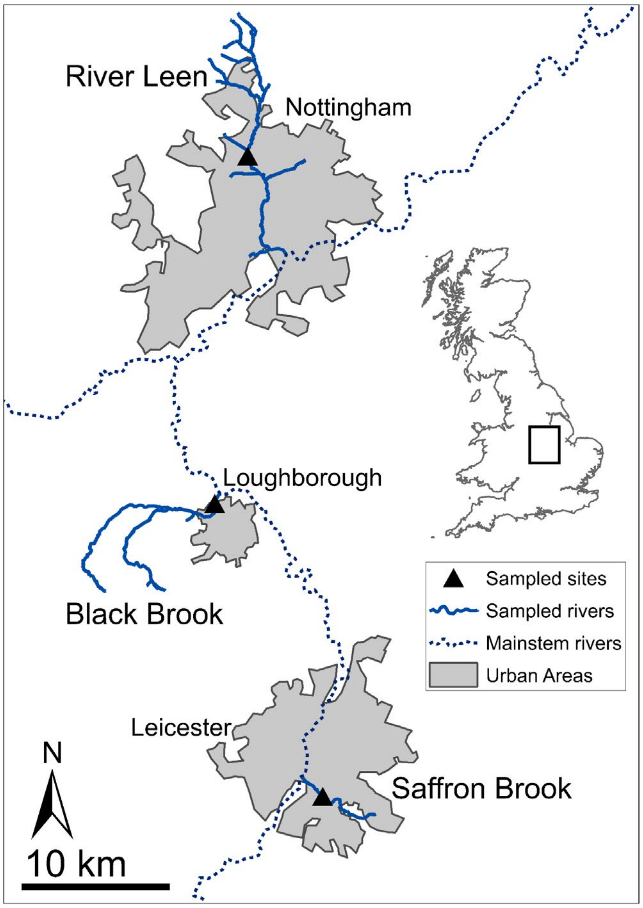

FIGURE 1 Map showing the three sampling sites (shown as triangles) on the River Leen, Black Brook, and Saffron Brook relative to the urban areas they flow through and the mainstem rivers

and cobbles (hereafter *rocks*), with some interstitial fine sediment (sand and silt). Rocks were comparable in size to anthropogenic litter pieces and could be easily isolated from the riverbed to collect the macroinvertebrates inhabiting them (similar to anthropogenic litter). Hence rocks were chosen for comparison with anthropogenic litter. Both rocks and anthropogenic litter were sampled from the riverbed surface for consistency. There was not any discernible structure to the bed sediments, such as armouring, as subsurface sediments were visually similar to those on the surface.

2.2 | Field methods

Anthropogenic litter density was assessed at each site by measuring the area of riverbed (average channel width × river length surveyed) containing 100 pieces of anthropogenic litter. Rock and anthropogenic litter samples were collected from the full width of the channel and the surface layer of the riverbed. Whilst moving upstream in a grid pattern, we collected alternately encountered anthropogenic litter items (providing 50 samples at each site), and a representative sub-sample of 50 rocks by pacing through the sampling area and taking the rock immediately at the sampler's foot (Wolman, 1954). Only items larger than 1 cm in their b-axis length were sampled, as smaller items were difficult to consistently collect and macroinvertebrate numbers would be low on such items. Items were described in terms of their material composition (fabric, glass, metal, plastic, masonry, rock, or other). Pieces of masonry (e.g. brick, concrete, and roofing tiles) were classified as rocks in comparisons of all anthropogenic litter types against all rocks, as it was thought that they may function like natural mineral substrates. However, masonry and rock samples were considered as separate materials in analyses of material types to test this assumption.

Macroinvertebrates were collected by transferring items (anthropogenic litter or rocks) from the riverbed into a 1-mm mesh kicknet held directly downstream (following Benke and Wallace's [2003] methodology for sampling macroinvertebrates on large wood). The contents of the net were placed into a sampling bag, along with the item, and preserved with industrial methylated spirit. Large or embedded items were cleaned of macroinvertebrates in the field by scrubbing a set area of 0.03 or 0.06 m^2 depending on their exposed area (0.03 m^2 was roughly equivalent to the median surface area of anthropogenic litter pieces) with a brush to dislodge macroinvertebrates into a kicknet held downstream (Pilotto et al., 2016).

2.3 | Laboratory methods

All anthropogenic litter and rock items were individually washed through a 500-μm mesh sieve, then manually processed to collect macroinvertebrates. Macroinvertebrates were identified to species or genus level where possible. Exceptions were Diptera and Sphaeriidae, which were identified to family, Oligochaeta to subclass, and Acarina to order. Taxonomic levels were consistent between samples and sites. Identification followed Holland (1972), Ellis (1978), Friday (1988), Wallace et al. (1990), Edington and Hildrew (1995), Reynoldson and Young (2000), Killeen et al. (2004), Elliott and Humpesch (2010), Cham (2012), Dobson et al. (2012), and Elliott and Dobson (2015). Trichoptera (caddisfly) pupae, unlike larvae, could only be identified to family level so were excluded from further analysis. The data analyses outlined in Section 2.4 were repeated with family level data, which included caddisfly pupae, and findings were qualitatively identical (Table S2).

The surface area of each item (anthropogenic litter or rock) was approximated by wrapping the item in tin foil and weighing the resultant foil pieces (1 g: 0.0214 m^2; Dudley et al., 2001). The surface area of flexible materials or items with complex shapes (e.g. plastic bags) was determined using equations for the surface area of the approximate geometric shape (Bergey & Getty, 2006). Items that were too large or embedded to be collected from the field were measured in situ.

2.4 | Data analysis

All statistical analysis was conducted using R statistical software (version 3.6.3; R Core Team, 2020). Completeness of sampling was assessed by calculating coverage for anthropogenic litter and rocks at each site. This measure of sample completeness estimates the proportion of total individuals in a community that belong to taxa in the sampled community (Chao & Jost, 2012). Macroinvertebrate density was calculated by dividing the total macroinvertebrate abundance across taxa by the sampled surface area of an item (0.03 or 0.06 m^2 for partially sampled items). Macroinvertebrate diversity was assessed by calculating Hill's numbers in *vegan* (Oksanen et al., 2019). The Hill series are defined to the order q (D^q), which determines the weighting of rare to abundant taxa for each index. D^0 is equivalent to observed taxa richness, which places greater emphasis on rare taxa as it is insensitive to relative frequencies (i.e. evenness); D^1 is equivalent to the exponential of Shannon's entropy, which is weighted towards common taxa; and D^2 to the inverse of Simpson's diversity, which is weighted towards highly abundant taxa (Tuomisto, 2010). Each point in the series therefore provides complementary information on taxa richness and evenness.

The mean surface area of rocks (including masonry) was four times smaller than that of anthropogenic litter items (rocks: 0.03 $m^2 \pm 0.01$ [*SE*], anthropogenic litter: 0.12 $m^2 \pm 0.02$; two-sample Wilcoxon $W = 16{,}899$, $p < 0.001$). Given that a strong positive relationship exists between item surface area and total macroinvertebrate abundance (Spearman's rank [R_s] = 0.80, $p < 0.001$), as well as between surface area and observed taxa richness (D^0; $R_s = 0.79$, $p < 0.001$), all subsequent analysis controlled for surface area (by including area in linear mixed effect models and generalised linear models) to account for this difference between substrates.

To test for differences in density and diversity (D^0, D^1, and D^2) between anthropogenic litter and rocks, linear mixed effects analysis was performed using *lme4* (Bates et al., 2015) with significance calculated for parameter estimates using *lmerTest* (Kuznetsova et al., 2017). To compare diversity, substrate (anthropogenic litter or rock) and sampled surface area were entered as fixed effects, and site (River Leen, Black Brook, or Saffron Brook) included as a random effect. Linear mixed effects models for density excluded surface area, as this factor is already incorporated into the calculation of density for each item, but otherwise model structure was identical. Model validation and checking followed the protocol in Zuur et al. (2009). Significance values for the effect of substrate type were identified by likelihood ratio tests (distributed as χ^2) of the full model against a null model without the substrate factor. Linear mixed effects analyses were repeated, substituting the substrate factor for material composition using a single factor with seven levels: fabric, glass, metal, masonry, plastic, rock, and other. Significant differences between material types were examined using parameter estimates and associated p values calculated using Satterthwaite approximation in *lmerTest*. Thus, we looked for differences between substrates (anthropogenic litter and rock), and between material types (fabric, glass, metal, masonry, plastic, rock, or other) in separate analyses.

Macroinvertebrate community composition was compared using the *manyglm* function in *mvabund* (Wang et al., 2020). The function fits generalised linear models (GLMs) to the raw counts for each taxa assuming a negative binomial distribution, with substrate type, sampled surface area, and site as explanatory variables without interactions. A *sum-of-LR* test statistic was obtained with significance assigned using randomisation (999 permutations), where the p value is adjusted for multiple testing using step-down resampling. This approach deliberately specifies a mean–variance relationship, inherent to count data, meaning that it can address the problems of confounded location and dispersion effects and difficulty detecting effects expressed in low-variance taxa, common to distance-based community analysis such as SIMPER and PERMANOVA (Warton et al., 2012). *Manyglm* tests were also repeated substituting substrate for material composition.

Differences between communities were visualised using *boral* (Hui, 2020); a model-based approach to unconstrained ordination that fits a latent variable model to raw abundance data and can be interpreted in a similar way to non-metric multidimensional scaling ordination (Hui, 2015). Ordination assumed a negative binomial distribution, and sample identity effects were included so ordination is based on composition rather than relative abundance. Site was included as a fixed effect. Ordination was repeated for individual sites to visualise differences between material types within each site.

3 | RESULTS

3.1 | Anthropogenic litter abundance and composition

Anthropogenic litter was abundant at all sites: 4.2 items/m^2 in the River Leen; 1.1 items/m^2 in Saffron Brook; and 0.6 items/m^2 in Black Brook. Anthropogenic litter material types included fabric, glass, metal, plastic, ceramic, and wood. Fewer than five ceramic and wood items were collected across all sites so these have been collated hereafter as *other* for simplicity. The proportional abundance of anthropogenic litter materials was similar across all sites, with glass, metal, and plastic the dominant materials across sites. These materials each made up approximately one third of the total anthropogenic litter items (Table S3). All fabric items were flexible, as were 5% of metal items, and 69% of plastic items, but no other materials were flexible. Rocks were generally less morphologically complex than anthropogenic litter, having been rounded by fluvial processes. Whilst most rocks were of natural origin, some appeared to be failed bank protection (based on visual comparison with nearby rip-rap), and 10% were masonry (brick, concrete, or roofing tiles).

3.2 | Differences in macroinvertebrate density and diversity

Across all sites, a total of 16,894 individuals from 46 families (61 taxa) were collected (see Table S4 for full list of taxa). The completeness of sampling (checked by calculating coverage) was >0.99

for anthropogenic litter and rock at all sites, indicating that sampling was close to completion. As such, it is reasonable to compare estimates of diversity between anthropogenic litter and rocks, despite their differences in surface area. The density of macroinvertebrates was not significantly different between anthropogenic litter and rocks (χ^2 (1) = 0.81, p = 0.37), or between material types (χ^2 (6) = 7.73, p = 0.26; Table 1). However, macroinvertebrate diversity was significantly higher on anthropogenic litter than on rock, indicating a consistent pattern across all sites and for all diversity measures (χ^2 (1) = 24.54 (D^0), 22.63 (D^1), 12.28 (D^2), $p < 0.001$; Figure 2). On average, observed taxa richness (D^0) was nearly four taxa per item higher on anthropogenic litter than on rocks, with a mean of 8.3 ± 0.5 (*SE*) for anthropogenic litter and 4.6 ± 0.4 for rocks. This difference was reduced at a higher order of D, suggesting that the higher diversity on anthropogenic litter reflected greater numbers of low abundance taxa with a small number of dominant taxa.

Material type (fabric, glass, metal, plastic, masonry, rock, or other) also affected diversity measures (χ^2 (6) = 52.18 (D^0), 37.20 (D^1), 19.26 (D^2), $p < 0.005$; Figure 3). Glass and rock samples were considerably less diverse than other material samples (mean D^0 per item was 5.1 ± 0.5 and 4.2 ± 0.3, respectively), especially fabric (11.0 ± 1.9) and plastic (10.9 ± 0.9). These differences were significant; rock samples were significantly less diverse than masonry, fabric, plastic, and metal samples across all Hill's numbers. Glass samples were less diverse than plastic and metal samples at D^0 and D^1, but were not different from other materials at D^2. Plastic, metal, fabric, and masonry samples consistently had the highest diversity across Hill's numbers.

3.3 | Differences in macroinvertebrate community composition

We checked whether any taxa exclusively inhabited either anthropogenic litter or rocks, excluding taxa that occurred in fewer than five samples. This was necessary to verify that apparent associations were not due to low abundance of a taxon. Under these conditions, no taxa were recorded only on rocks, but five taxa were recorded exclusively on anthropogenic litter. These were: *Anisus vortex* (Gastropoda: total abundance of 25 across 13 samples), *Theromyzon tessulatum* (Hirudinea: 20 across 14 samples), *Calopteryx splendens* (Odonata: 12 across 6 samples), *Limnophora* spp. (Diptera: 10 across 7 samples), and *Bathyomphalus contortus* (Gastropoda: 10 across 7 samples). Of these, *Limnophora* spp. (80%) and *B. contortus* (90%) were found almost exclusively on flexible anthropogenic litter materials (either fabric or plastic).

Substrate type (anthropogenic litter or rock) significantly influenced macroinvertebrate communities among sites (LR test statistic = 508.5, $p < 0.001$). The observed differences were substantially driven by 11 taxa, all of which are native species; *Erpobdella octoculata*, *Glossiphonia complanata*, *Helobdella stagnalis*, and *T. tessulatum* (Hirudinea: Leeches), Oligochaeta, Sphaeriidae (Bivalvia), *Asellus aquaticus* and *Gammarus pulex/fossarum* agg. (Crustacea), Chironomidae (Diptera), *Mystacides azurea* (Trichoptera: Caddisfly), and *A. vortex*. These taxa were all more abundant on anthropogenic litter than rock, with more than 85% of occurrences on anthropogenic litter. Ordination indicated that although differences between sites were notable, substrate clearly affects communities along the axis of latent variable 1 (Figure 4).

Significantly different communities were also recorded between material types (fabric, glass, metal, plastic, masonry, rock, or other; LR test statistic (6) = 1,329.1, $p < 0.001$). Eleven taxa were responsible for the effect, most of which also displayed significantly different occurrences between substrates; *E. octoculata*, *G. complanata*, *H. stagnalis*, Oligochaeta, Sphaeriidae, *Oulimnius* spp. (Coleoptera: Beetles), *A. aquaticus*, *G. pulex/fossarum* agg., Chironomidae, *M. azurea*, and *P. flavomaculatus* (Trichoptera: Caddisfly). All of these taxa were more common on plastic; especially the three leeches (80% of occurrences on plastic items). Separate ordinations for each site indicated that metal, fabric, and especially plastic anthropogenic litter items supported the communities which were most dissimilar to those on rocks (Figure 5). In contrast, glass samples were similar in composition to those from rocks, as were masonry samples, despite the differences in diversity (D^0, D^1, and D^2) on these materials. The differences in community composition on different materials were more evident in Black Brook and Saffron Brook than the River Leen.

TABLE 1 Results of all statistical tests, showing test statistics, degrees of freedom (*df*) and significance (*p*) values

Statistical test	Parameter tested	Differences between substrates (anthropogenic litter and rock)			Differences between materials (fabric, glass, masonry, metal, plastic, rock, and other)		
		Test statistic	*df*	*p*	Test statistic	*df*	*p*
LME model	Density	0.81	1	0.3686	7.73	6	0.2586
	D^0 (observed taxa richness)	24.54	1	<0.001	52.18	6	<0.001
	D^1 (exponential of Shannon's entropy)	22.63	1	<0.001	37.20	6	<0.001
	D^2 (inverse of Simpson's diversity index)	12.28	1	<0.001	19.26	6	0.003
manyglm	Community composition	508.5	1	<0.001	1,329.1	6	<0.001

Note: For full details on how statistical tests were performed see Section 2.4 'Data analysis'. linear mixed effect (LME) models tested for differences in density and diversity (D^0, D^1 and D^2) between substrates and between materials by including substrates/material and surface area as fixed effects (surface area was excluded for density tests), and site as a random effect. The test statistic for LME models is the χ^2 test statistic of a likelihood ratio test. The *manyglm* function tested for differences in community composition between substrates and materials, calculating a sum-of-LR test statistic and associated *p* value with 999 permutations.

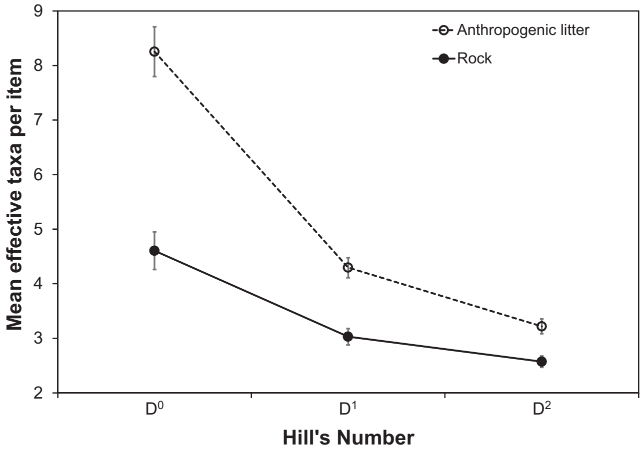

FIGURE 2 Mean Hill's numbers of D^0 (observed taxa richness), D^1 (exponential of Shannon's entropy), and D^2 (inverse of Simpson's diversity index) calculated on all anthropogenic litter samples (dashed line) and all rock samples (including masonry; solid line). Error bars represent standard errors

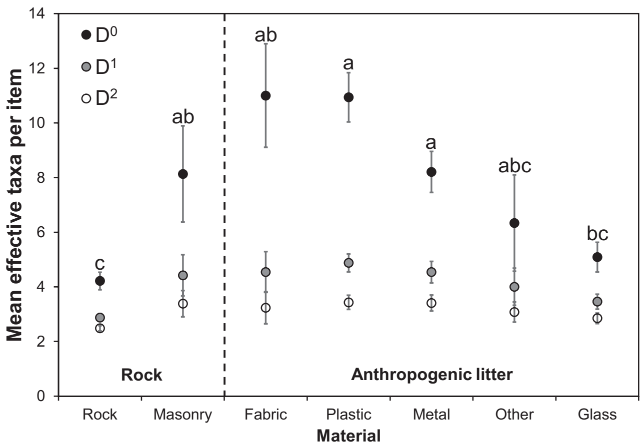

FIGURE 3 Mean Hill's numbers of D^0 (observed taxa richness; black circles), D^1 (exponential of Shannon's entropy; grey circles), and D^2 (inverse of Simpson's diversity index; empty circles) calculated on all samples within each material categories (rock, masonry, fabric, plastic, metal, other, and glass). Error bars represent standard errors. Materials labelled with the same letter did not differ significantly from one another. Significant differences are only shown for D^0; see Table S5 for the full model outcomes

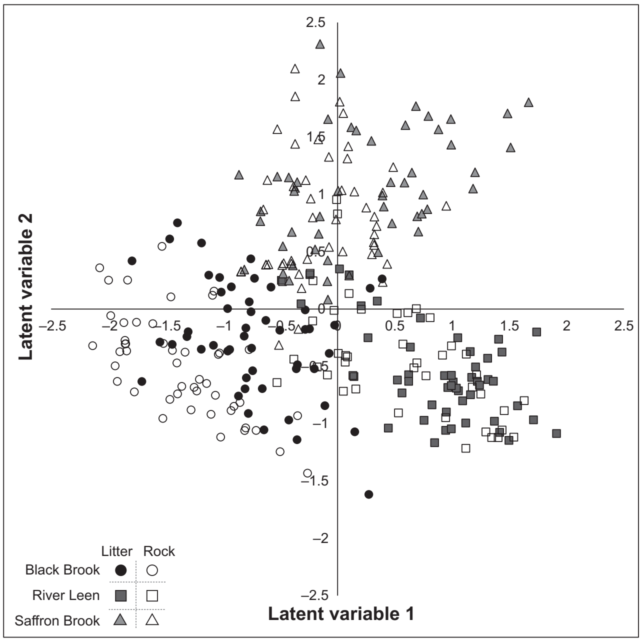

FIGURE 4 Output of latent variable model ordination of macroinvertebrate data for all sites. Symbol shape shows site: Black Brook as circles, River Leen as squares, and Saffron Brook as triangles. Shaded symbols are anthropogenic litter samples, empty symbols are rock samples (including masonry)

4 | DISCUSSION

Anthropogenic litter is inhabited by a wide range of macroinvertebrates in our study rivers, supporting a greater diversity of organisms than rocks (the dominant natural substrate). Macroinvertebrate communities inhabiting these two different substrates were also distinct, indicating that anthropogenic litter typical of urban rivers can significantly alter macroinvertebrate community composition and biodiversity. Additional differences exist between anthropogenic litter material types, suggesting that the physical and chemical characteristics of materials are important controls on macroinvertebrate micro-distribution. Given the prevalence of anthropogenic litter both in this study and reported in other urban rivers (Hoellein et al., 2014; McCormick & Hoellein, 2016; Rech et al., 2014, 2015), it probably affects macroinvertebrate communities in many urban rivers.

4.1 | Differences between types of anthropogenic litter and rock

Previous research on anthropogenic litter in a Polish reservoir (Czarnecka et al., 2009) and on beaches around the Baltic Sea (García-Vazquez et al., 2018) argued that the greater diversity of macroinvertebrates they recorded on anthropogenic litter reflected the inhospitable nature of the natural substrate (sand) in waterbodies studied. Sand is inherently unstable and provides a poor surface for most macroinvertebrates and their food (Jowett, 2003). Therefore, anthropogenic litter represented a scarce resource (hard and stable substrate) favoured by many macroinvertebrates (Czarnecka et al., 2009). Hard substrates were not lacking in the rivers studied here, but macroinvertebrate communities on anthropogenic litter and rocks were nonetheless significantly different, suggesting that other factors may influence community composition.

Anthropogenic litter was on average larger than rocks. Although surface area was controlled for in statistical analysis, so we can be confident that there is a difference between substrates independent of size, other variables linked to substrate size may be important in structuring macroinvertebrate communities. For instance, the stability of rocks generally increases with size. Stable features in rivers, such as boulders or wood, are known to support high macroinvertebrate abundance and diversity

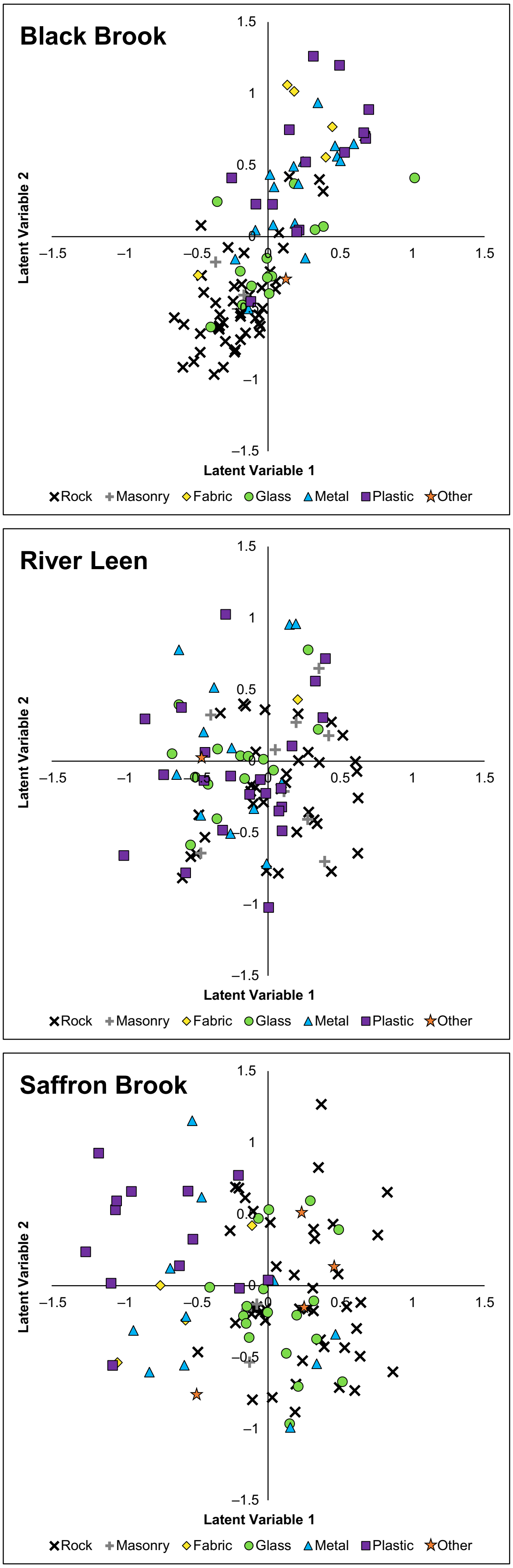

FIGURE 5 Output of latent variable model ordination of macroinvertebrate data for all sites separately to more easily show differences between material types (rock, masonry, fabric, glass, metal, plastic, other), which are shown using different shaped symbols

(Death & Winterbourn, 1995; Nakano et al., 2018). These substrates may help macroinvertebrates avoid dislodgement, provide more reliable food resources, and act as flow refuges (Jowett, 2003). Unstable, highly mobile substrates are likely to be inhabited by less diverse communities (Death, 2008), because substrate movement will inhibit colonisation and continually reset successional trajectories (Czarnecka et al., 2009). Predicting the relative stability of anthropogenic litter is complicated by its wide variety of shapes and densities (Williams & Simmons, 1997), and therefore, unlike rocks, is it not strongly associated with size. For example, low-density plastic bags are easy to entrain but conversely more likely to become stranded on obstacles such as vegetation or to become partially buried (McCormick & Hoellein, 2016). An added complication is that recruitment of anthropogenic litter in urban rivers can occur independently of flow stage (McCormick & Hoellein, 2016), making it difficult to estimate its exposure time in the river. Further investigation of these dynamics of anthropogenic litter, and the ways it differs to natural substrates, would help build our understanding of the ways anthropogenic litter may affect macroinvertebrate distribution. Nonetheless, the presence of biofilm on all anthropogenic litter and rocks sampled in this study, and the low flows during summer months prior to sampling, means that most items will have been exposed long enough for the colonisation of macroinvertebrates to have occurred.

Small-scale complexity, at a scale similar to the body length of macroinvertebrates, is known to be an important control of faunal distribution (Boyero, 2003; Robson & Barmuta, 1998). For example, colonisation experiments on introduced substrates of varied complexities have demonstrated that macroinvertebrate diversity increases with greater substrate complexity (Adamiak-Brud et al., 2015; Boyero, 2003; Clifford et al., 1989; Clifford et al., 1992; Robson & Barmuta, 1998). Basic life-functions, such as respiration, metabolism, locomotion, and reproduction, are affected by the physical characteristics of the habitat (Lancaster & Downes, 2013), so a more structurally diverse habitat is thought to support greater biodiversity. Likewise, complex surfaces allow macroinvertebrates to shelter from hydraulic stress, enabling conservation of energy and preventing accidental entrainment into drift (Brooks et al., 2005), as well as providing shelter from predators (Everett & Ruiz, 1993). In this study, we found that macroinvertebrate communities on smooth and flat glass and rocks were less diverse than those on other material types. Similarly, masonry samples (mostly bricks with complex holes or grooves) supported a much higher macroinvertebrate diversity (for D^0, D^1, and D^2) than rocks, despite there being limited difference in community composition on the two materials. This suggests that although rock and masonry habitats are functionally similar, and so support comparable communities, the greater complexity of masonry samples means that they can support more diverse macroinvertebrate communities.

As well as differences in diversity on anthropogenic litter and rock, differences in the macroinvertebrate community composition recorded on different materials suggests that these materials function as distinct habitat types because of their variation in physical structure. For instance, the similar communities found on rocks, masonry, and glass could relate to their rigid and hard structure. In contrast, plastic and fabric sample communities were clearly distinct from rocks. These distinctions between materials were much less clear in the River Leen, where anthropogenic litter and rock communities were more homogenous. The reasons for this are not known. A symptom of urban rivers with degraded habitat is community homogenisation (i.e. urban stream syndrome: Walsh et al., 2005); however, the River Leen had the highest mean D^0 per sample (7.5, compared to 7.0 in Black Brook, and 4.8 in Saffron Brook), suggesting that it is not urbanised to the extent of only being able to support disturbance-tolerant taxa. A possible explanation is that the higher density of anthropogenic litter in the River Leen (4.2 items/m^2), and therefore greater proximity between materials, has enabled migration of macroinvertebrates between items, and increased community similarity. In Black Brook and Saffron Brook, the anthropogenic litter was more isolated within the riverbed, and so communities were more variable, as reported by Czarnecka et al. (2009).

Plastic and fabric macroinvertebrate communities were the most diverse and most dissimilar to those on rocks. The most obvious difference between fabric, plastic, and rocks, is that all fabric and most plastic items were flexible, suggesting that substrate flexibility may influence and structure macroinvertebrate distributions. The closest natural analogue for this type of habitat is macrophytes or organic detritus. It is possible that anthropogenic litter could provide a substitute for this type of habitat, which is commonly removed and thus absent from many urban rivers (Old et al., 2014; Walsh et al., 2005). For instance, flexible anthropogenic litter could replicate the geomorphic role of macrophyte stands in lowland rivers (e.g. Folkard, 2011), where macrophytes locally reduce flow velocity and encourage the deposition of the fine sediments and organic detritus.

There were no macrophytes to sample in the urban river reaches studied, but taxa that are typically associated with aquatic vegetation were abundant on flexible materials. Of those taxa found only on anthropogenic litter, three tend to live on macrophytes: *C. splendens*, *A. vortex*, and *B. contortus*. *C. splendens* larvae have strong preferences for complex vegetation, which provides cover and plentiful prey species (Goodyear, 2000). The gastropods *A. vortex* and *B. contortus*, which were primarily found on plastic, generally inhabit plants which provide shelter, oxygenate flows, and provide a surface for biofilm development which they feed on by scraping (Boycott, 1936). Other taxa also showed associations with flexible materials, although they were also on rocks and other types of anthropogenic litter. *Asellus* spp. and *Gammarus* spp. are omnivorous detritivores that live amongst and feed on decomposing plant material (Gledhill et al., 1993). These taxa are unable to consume anthropogenic litter but were still strongly associated with it in this study (especially plastic; 53 and 48%, and fabric: 31 and 30% of occurrences respectively), suggesting that the accumulation of fine organic matter around flexible materials could attract shredders and collectors. The fine sediment collected around flexible materials may also provide habitat for organisms that prefer soft sediments (e.g. Sphaeriidae, Oligochaeta, and some Chironomidae, all of which were recorded in greater numbers on plastic and fabric). However, if macrophytes were present in these rivers, it is possible that many of these taxa would preferentially inhabit this natural substrate, especially those taxa that directly feed on macrophytes. Past studies have recorded different macroinvertebrate communities on plastic and natural leaves, with lower macroinvertebrate abundance and diversity on plastic leaves (Hofer & Richardson, 2007; Quinn et al., 2000).

As well as interacting with fine sediments and organic matter, anthropogenic litter may also affect other macroinvertebrate food resources. We observed that biofilm, an important food for scrapers, had developed on the exposed surface of anthropogenic litter, as well as on rocks. If this biofilm is of a different quality or quantity to that which develops on rocks, this could influence macroinvertebrate distribution. For instance, it has been shown that more complex surfaces are more quickly colonised by biofilm and that this in turn will attract macroinvertebrates (Clifford et al., 1992). Distinct biofilm communities have been found to colonise different materials in marine environments (studies tested a range of plastic polymers and glass; Oberbeckmann et al., 2014; Pinto et al., 2019), meaning that biofilm quality could be affected by material composition. However, a more comprehensive study of different materials in an urban river only found differences in biofilm composition and gross primary production between solid surfaces (plastic, glass, aluminium, and tiles) and soft organic materials (leaf litter and cardboard), rather than between all material types (Hoellein et al., 2014). Further research into a wider range of food resources and materials in rivers is necessary to expand our understanding of this topic.

The differences in community composition between substrates were driven by the taxa that differed most in abundance between anthropogenic and rock samples. These tended to be generalist taxa which are tolerant of poor habitat conditions. Anthropogenic litter samples were dominated by Chironomidae, Oligochaeta, and *A. aquaticus*, which dominate communities where there is organic enrichment and low dissolved oxygen concentrations (Armitage et al., 1995; Pennak, 1978). The corresponding high abundances of macroinvertebrates that feed on these taxa may be an indirect response to the increase in prey availability. This includes *Limnophora* spp. (which was only found on anthropogenic litter), the four leech species (especially *E. octoculata* and *H. stagnalis*; Elliott & Dobson, 2015), and *P. flavomaculatus* (Edington & Hildrew, 1995). All of these taxa were recorded more frequently on fabric or plastic than on rocks in this study. During sample collection it was noted that some plastic bags were associated with organic-rich fine sediments and accompanying signs of anoxia. In marine and estuarine environments, plastic bags have been linked to localised anoxia through preventing gas and nutrient exchange process at the sediment–water interface (Green et al., 2015), although this effect is moderated when they are regularly in motion (Clemente et al., 2018), which possibly explains why we still found diverse communities on such materials. The reduced difference between anthropogenic litter and rock diversity at higher Hill's numbers suggests that although the complexity of anthropogenic litter can support a diverse fauna, the taxa that are best able to exploit anthropogenic litter are those of lower conservation value, which can tolerate reduced habitat quality, and so numerically dominate the communities.

4.2 | Implications for river management

The rivers studied here were limited in habitat heterogeneity, as is typical of urban rivers globally (Walsh et al., 2005). In such cases, the habitat provided by anthropogenic litter may support biodiversity, both by providing complex and stable habitat for a wide range of organisms, and by representing a unique habitat distinct from rock substrates. Although rocks were the more abundant substrate in the rivers studied here, anthropogenic litter supported novel and more diverse communities, including five unique taxa. In urban rivers where it is not possible to restore instream large wood or macrophytes, anthropogenic litter may accidentally offset a lack of habitat diversity by providing an analogue for these natural substrates which are typically absent. In particular, these results suggest that flexible materials may replicate in-channel macrophyte habitat. It is possible that where anthropogenic litter provides a novel habitat structure, such as in sandy habitats (García-Vazquez et al., 2018), it may enable colonisation by non-native taxa that would not inhabit these environments under natural conditions (Tyrrell & Byers, 2007). Although this was not observed in the rivers studied here, it should be considered in future investigations, especially as urban areas are key sites for the establishment and spread of non-native and invasive species (Francis et al., 2019).

Anthropogenic litter removal and reduction of inputs should be the aim of management strategies, given that rivers are a key source of marine anthropogenic litter (Rech et al., 2014), anthropogenic litter is environmentally damaging (Rochman, 2015), and because of the negative societal and social impacts of littered waterways (Williams & Deakin, 2007). However, the results presented herein suggest that the removal of anthropogenic litter from urban rivers may not lead to biodiversity improvements in the immediate area and may even reduce biodiversity at the local scale. Anthropogenic litter removal efforts should therefore be carefully managed to reduce disturbance to the wider environment (Chapman & Clynick, 2006). This could mean preferentially removing some materials rather than others or improving habitat complexity following the clearance of anthropogenic litter to replace the removed habitat.

Importantly, these responses to anthropogenic litter suggest that even small-scale enhancement of substrate complexity could have positive effects on the local-scale biodiversity and ecological health of urban rivers (Francis & Hoggart, 2008). Understanding the types of habitat provided by anthropogenic litter and comparison to a wider range of natural substrates such as macrophytes and large wood, could help inform mechanisms to provide these functions using alternative and less damaging materials.

ACKNOWLEDGMENTS

This work was supported by the Engineering and Physical Sciences Research Council, UK [grant number EP/N50970X/1]. Field data collection was assisted by Richard Mason, Neven Tandarić, Emma Higgins, Vanessa Cutts, Philip Jagessar, and Harry Sanders. Thanks also to two anonymous reviewers and the associate editor for comments that substantially improved the clarity of the results presented in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Open Science Framework at https://doi.org/10.17605/OSF.IO/K24T7 (Wilson et al., 2020)

ORCID

Hazel L. Wilson https://orcid.org/0000-0002-3658-6512
Matthew F. Johnson https://orcid.org/0000-0003-1336-5490
Paul J. Wood https://orcid.org/0000-0003-4629-3163
Colin R. Thorne https://orcid.org/0000-0002-2450-9624
Markus P. Eichhorn https://orcid.org/0000-0002-3381-0822

REFERENCES

Adamiak-Brud, Ż., Jabłońska-Barna, I., Bielecki, A., & Terlecki, J. (2015). Settlement preferences of leeches (Clitellata: Hirudinida) for different artificial substrates. *Hydrobiologia*, *758*, 275–286. https://doi.org/10.1007/s10750-015-2359-1

Agamuthu, P., Mehran, S. B., Norkhairiah, A., & Norkhairiyah, A. (2019). Marine debris: A review of impacts and global initiatives. *Waste Management and Research*, *37*(10), 987–1002. https://doi.org/10.1177/0734242X19845041

Armitage, P. D., Pinder, L. C., & Cranston, P. (1995). *The Chironomidae. Biology and ecology of non-biting midges*. Dordrecht, Netherlands: Springer.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48.

Beak, T., Griffing, T. C., & Appleby, A. G. (1973). Use of artificial substrate samplers to assess water pollution. In J. Cairns, & K. Dickson (Eds.), *Biological methods for the assessment of water quality* (pp. 227–241). West Conshohocken, PA: ASTM International.

Beaumont, N. J., Aanesen, M., Austen, M. C., Börger, T., Clark, J. R., Cole, M., Hooper, T., Lindeque, P. K., Pascoe, C., & Wyles, K. J. (2019). Global ecological, social and economic impacts of marine plastic. *Marine Pollution Bulletin*, *142*, 189–195. https://doi.org/10.1016/j.marpolbul.2019.03.022

Benke, A. C., & Wallace, J. B. (2003). Influence of wood on invertebrate communities in streams and rivers. *American Fisheries Society Symposium*, *37*, 149–177.

Bergey, E. A., & Getty, G. M. (2006). A review of methods for measuring the surface area of stream substrates. *Hydrobiologia*, *556*, 7–16. https://doi.org/10.1007/s10750-005-1042-3

Blauch, G. A., & Jefferson, A. J. (2019). If a tree falls in an urban stream, does it stick around? Mobility, characteristics, and geomorphic influence of large wood in urban streams in northeastern Ohio, USA. *Geomorphology*, *337*, 1–14. https://doi.org/10.1016/j.geomorph.2019.03.033

Blettler, M. C. M., Abrial, E., Khan, F. R., Sivri, N., & Espinola, L. A. (2018). Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps. *Water Research*, *143*, 416–424. https://doi.org/10.1016/j.watres.2018.06.015

Boycott, A. E. (1936). The habitats of fresh-water Mollusca in Britain. *Journal of Animal Ecology*, *5*(1), 116–186. https://doi.org/10.2307/1096

Boyero, L. (2003). The effect of substrate texture on colonization by stream macroinvertebrates. *Annales De Limnologie - International Journal of Limnology*, *39*(3), 211–218. https://doi.org/10.1051/limn/2003017

Brooks, A. J., Haeusler, T., Reinfelds, I., & Williams, S. (2005). Hydraulic microhabitats and the distribution of macroinvertebrate assemblages in riffles. *Freshwater Biology*, *50*(2), 331–344. https://doi.org/10.1111/j.1365-2427.2004.01322.x

Cham, S. (2012). *Field guide to the larvae and exuviae of British dragonflies*. Peterborough, UK: The British Dragonfly Society.

Chao, A., & Jost, L. (2012). Coverage-based rarefaction and extrapolation: Standardizing samples by completeness rather than size. *Ecology*, *93*, 2533–2547. https://doi.org/10.1890/11-1952.1

Chapman, M. G., & Clynick, B. G. (2006). Experiments testing the use of waste material in estuaries as habitat for subtidal organisms. *Journal of Experimental Marine Biology and Ecology*, *338*(2), 164–178. https://doi.org/10.1016/j.jembe.2006.06.018

Clemente, C. C. C., Paresque, K., & Santos, P. J. P. (2018). The effects of plastic bags presence on a macrobenthic community in a polluted estuary. *Marine Pollution Bulletin*, *135*, 630–635. https://doi.org/10.1016/j.marpolbul.2018.07.070

Clifford, H. F., Casey, R. J., & Saffran, K. A. (1992). Short-term colonisation of rough and smooth tiles by benthic macroinvertebrates and algae (chlorophyll a) in two streams. *Journal of the North American Benthological Society*, *11*(3), 304–315.

Clifford, H. F., Gotceitas, V., & Casey, R. J. (1989). Roughness and color of artificial substratum particles as possible factors in colonization of stream invertebrates. *Hydrobiologia*, *175*(2), 89–95. https://doi.org/10.1007/BF00765119

Czarnecka, M., Poznańska, M., Kobak, J., & Wolnomiejski, N. (2009). The role of solid waste materials as habitats for macroinvertebrates in a lowland dam reservoir. *Hydrobiologia*, *635*, 125–135. https://doi.org/10.1007/s10750-009-9905-7

Death, R. G. (2000). Invertebrate–substratum relationships. In K. J. Collier, & M. J. Winterbourn (Eds.), *New Zealand stream invertebrates: Ecology and implications for management* (pp. 57–178). Hamilton, NZ: New Zealand Limnological Society.

Death, R. G. (2008). Effects of floods on aquatic invertebrate communities. In J. Lancaster, & R. D. Briers (Eds.), *Aquatic insects: Challenges to populations* (pp. 103–121). Wallingford, UK: CAB International.

Death, R. G., & Winterbourn, M. J. (1995). Diversity patters in stream benthic invertebrate communities: The influence of habitat stability. *Ecology*, *76*(5), 1446–1460.

Dobson, M., Pawley, S., Fletcher, M., & Powell, A. (2012). *Guide to Freshwater Invertebrates*. Cumbria, UK: Freshwater Biological Association.

Dudley, J. L., Arthurs, W., & Hall, T. J. (2001). A comparison of methods used to estimate river rock surface areas. *Journal of Freshwater Ecology*, *16*(2), 257–261. https://doi.org/10.1080/02705060.2001.9663810

Edington, J. M., & Hildrew, A. G. (1995). *Caseless caddis larvae of the British Isles*. FBA Scientific Publication. No. 53.

Elliott, J. M., & Dobson, M. (2015). *Freshwater leeches of Britain and Ireland*. FBA Scientific Publication. No. 69.

Elliott, J. M., & Humpesch, U. H. (2010). *Mayfly larvae (Ephemeroptera) of Britain and Ireland: Keys and a review of their ecology*. FBA Scientific Publication. No. 66.

Ellis, A. E. (1978). *British freshwater bivalve mollusca – Keys and notes for the identification of the species. Synopses of the British Fauna (New Series)*, 11. London, UK: Academic Press for the Linnean Society of London.

Everett, R. A., & Ruiz, G. M. (1993). Coarse woody debris as a refuge from predation in aquatic communities: An experimental test. *Oecologia*, *93*(4), 475–486. https://doi.org/10.1007/BF00328954

Folkard, A. M. (2011). Vegetated flows in their environmental context: a review. *Proceedings of the Institution of Civil Engineers – Engineering and Computational Mechanics*, *164*(1), 3–24.

Francis, R. A., Chadwick, M. A., & Turbelin, A. J. (2019). An overview of non-native species invasions in urban river corridors. *River Research and Applications*, *35*(8), 1269–1278. https://doi.org/10.1002/rra.3513

Francis, R. A., & Hoggart, S. P. G. (2008). Waste not, want not: The need to utilize existing artificial structures for habitat improvement along urban rivers. *Restoration Ecology*, *16*(3), 373–381. https://doi.org/10.1111/j.1526-100X.2008.00434.x

Friday, L. E. (1988). *A key to the adults of British water beetles*. Field Studies Council.

García-Vazquez, E., Cani, A., Diem, A., Ferreira, C., Geldhof, R., Marquez, L., … Perché, S. (2018). Leave no traces – Beached marine litter shelters both invasive and native species. *Marine Pollution Bulletin*, *131*, 314–322. https://doi.org/10.1016/j.marpolbul.2018.04.037

Gledhill, T., Sutcliffe, D. W., & Williams, W. D. (1993). *British Freshwater Crustacea Malacostraca: A key with ecological notes*. FBA Scientific Publication. No. 52

Goodyear, K. G. (2000). A comparison of the environmental requirements of larvae of the Banded Demoiselle *Calopteryx splendens* (Harris) and the Beautiful Demoiselle *C. virgo* (L.). *Journal of the British Dragonfly Society*, *16*(2), 33–51.

Green, D. S., Boots, B., Blockley, D. J., Rocha, C., & Thompson, R. (2015). Impacts of discarded plastic bags on marine assemblages and ecosystem functioning. *Environmental Science and Technology*, *49*(9), 5380–5389. https://doi.org/10.1021/acs.est.5b00277

Hoellein, T. J., Rojas, M., Pink, A., Gasior, J., & Kelly, J. J. (2014). Anthropogenic litter in urban freshwater ecosystems: Distribution and microbial interactions. *PLoS One*, *9*, e98485. https://doi.org/10.1371/journal.pone.0098485

Hofer, N., & Richardson, J. S. (2007). Comparisons of the colonisation by invertebrates of three species of wood, Alder leaves, and plastic 'leaves' in a temperate stream. *International Review of Hydrobiology*, *92*(6), 647–655. https://doi.org/10.1002/iroh.200610979

Holland, D. G. (1972). *A key to the larvae, pupae and adults of the British species of Elminthidae*. FBA Scientific Publication. No. 26.

Hui, F. K. C. (2015). BORAL – Bayesian ordination and regression analysis of multivariate abundance data in R. *Methods in Ecology and Evolution*, *7*(6), 744–750.

Hui, F. K. C. (2020). *Boral: Bayesian Ordination and Regression Analysis. R Package Version 1.8*. https://CRAN.Rs-project.org/package=boral

Jowett, I. G. (2003). Hydraulic constraints on habitat suitability for benthic invertebrates in gravel-bed rivers. *River Research and Applications*, *19*(5–6), 495–507. https://doi.org/10.1002/rra.734

Katsanevakis, S. (2008). Marine debris, a growing problem: Sources, distribution, composition and impacts. In T. N. Hoefer (Ed.), *Marine pollution: New research* (pp. 53–100). New York, NY: Nova Science Publishers.

Katsanevakis, S., Verriopoulos, G., Nicolaidou, A., & Thessalou-Legaki, M. (2007). Effect of marine litter on the benthic megafauna of coastal soft bottoms: A manipulative field experiment. *Marine Pollution Bulletin*, *54*(6), 771–778. https://doi.org/10.1016/j.marpolbul.2006.12.016

Kiessling, T., Gutow, L., & Thiel, M. (2015). Marine litter as habitat and dispersal vector. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine anthropogenic litter* (pp. 141–181). Cham, Switzerland: Springer International Publishing.

Killeen, I., Aldridge, D., & Oliver, G. (2004). *Freshwater bivalves of Britain and Ireland*. Shropshire, UK: Field Studies Council.

Kühn, S., Bravo Rebolledo, E. L., & van Franeker, J. A. (2015). Deleterious effects of litter on marine life. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine anthropogenic litter* (pp. 75–116). Cham, Switzerland: Springer International Publishing.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2017). lmerTest package: Tests in linear mixed effects models. *Journal of Statistical Software*, *82*(13), 1–26. https://CRAN.R-project.org/package=lmerTest
Lancaster, J., & Downes, B. J. (2013). *Aquatic entomology*. Oxford University Press.
McCormick, A. R., & Hoellein, T. J. (2016). Anthropogenic litter is abundant, diverse, and mobile in urban rivers: Insights from cross-ecosystem analyses using ecosystem and community ecology tools. *Limnology and Oceanography*, *61*(5), 1718–1734. https://doi.org/10.1002/lno.10328
Nakano, D., Nagayama, S., Kawaguchi, Y., & Nakamura, F. (2018). Significance of the stable foundations provided and created by large wood for benthic fauna in the Shibetsu River, Japan. *Ecological Engineering*, *120*, 249–259. https://doi.org/10.1016/j.ecoleng.2018.05.032
Oberbeckmann, S., Loeder, M. G. J., Gerdts, G., & Osborn, A. M. (2014). Spatial and seasonal variation in diversity and structure of microbial biofilms on marine plastics in Northern European waters. *FEMS Microbiology Ecology*, *90*(2), 478–492. https://doi.org/10.1111/1574-6941.12409
Oksanen, J., Blanchet, F. G., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., & Wagner, H. (2019). *Vegan: Community Ecology Package*. *R package version 2.5-6*. https://CRAN.R-project.org/package=vegan
Old, G. H., Naden, P. S., Rameshwaran, P., Acreman, M. C., Baker, S., Edwards, F. K., Sorensen, J. P. R., Mountford, O., Gooddy, D. C., Stratford, C. J., Scarlett, P. M., Newman, J. R., & Neal, M. (2014). Instream and riparian implications of weed cutting in a chalk river. *Ecological Engineering*, *71*, 290–300. https://doi.org/10.1016/j.ecoleng.2014.07.006
Pennak, R. W. (1978). *Fresh-water Invertebrates of the United States*, 2nd ed. New York, NY: John Wiley and Sons.
Pilotto, F., Harvey, G. L., Wharton, G., & Pusch, M. T. (2016). Simple large wood structures promote hydromorphological heterogeneity and benthic macroinvertebrate diversity in low-gradient rivers. *Aquatic Sciences*, *78*(4), 755–766. https://doi.org/10.1007/s00027-016-0467-2
Pinto, M., Langer, T. M., Hüffer, T., Hofmann, T., & Herndl, G. J. (2019). The composition of bacterial communities associated with plastic biofilms differs between different polymers and stages of biofilm succession. *PLoS One*, *14*(6), e0217165. https://doi.org/10.1371/journal.pone.0217165
Quinn, J. M., Smith, B. J., Burrell, G. P., & Parkyn, S. M. (2000). Leaf litter characteristics affect colonisation by stream invertebrates and growth of *Olinga feredayi* (Trichoptera: Conoesucidae). *New Zealand Journal of Marine and Freshwater Research*, *34*(2), 273–287.
R Core Team (2020). *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing. https://www.R-project.org/
Rech, S., Borrell, Y., & García-Vazquez, E. (2016). Marine litter as a vector for non-native species: What we need to know. *Marine Pollution Bulletin*, *113*(1–2), 40–43. https://doi.org/10.1016/j.marpolbul.2016.08.032
Rech, S., Macaya-Caquilpán, V., Pantoja, J. F., Rivadeneira, M. M., Jofre Madariaga, D., & Thiel, M. (2014). Rivers as a source of marine litter - A study from the SE Pacific. *Marine Pollution Bulletin*, *82*, 66–75. https://doi.org/10.1016/j.marpolbul.2014.03.019
Rech, S., Macaya-Caquilpán, V., Pantoja, J. F., Rivadeneira, M. M., Kroeger, C. C., & Thiel, M. (2015). Sampling of riverine litter with citizen scientists — findings and recommendations. *Environmental Monitoring and Assessment*, *187*(335), 1–18. https://doi.org/10.1007/s10661-015-4473-y
Reynoldson, T. B., & Young, J. O. (2000). *A key to the British freshwater triclads*. FBA Scientific Publication. No. 58.
Robson, B. J., & Barmuta, L. A. (1998). The effect of two scales of habitat architecture on benthic grazing in a river. *Freshwater Biology*, *39*(2), 207–220. https://doi.org/10.1046/j.1365-2427.1998.00271.x
Rochman, C. M. (2015). The complex mixture, fate and toxicity of chemicals associated with plastic debris in the marine environment. In M. Bergmann, L. Gutow, & M. Klages (Eds.), *Marine Anthropogenic Litter* (pp. 117–140). Cham, Switzerland: Springer International Publishing.
Tuomisto, H. (2010). A consistent terminology for quantifying species diversity? Yes, it does exist. *Oecologia*, *164*, 853–860. https://doi.org/10.1007/s00442-010-1812-0
Tyrrell, M. C., & Byers, J. E. (2007). Do artificial substrates favour nonindigenous fouling species over native species? *Journal of Experimental Marine Biology and Ecology*, *342*(1), 54–60.
Wallace, B. J., & Webster, J. R. (1996). The role of macroinvertebrates in stream ecosystem function. *Annual Review of Entomology*, *41*, 115–139. https://doi.org/10.1146/annurev.en.41.010196.000555
Wallace, I. D., Wallace, B., & Philipson, G. N. (1990). *A key to the case-bearing caddis larvae of Britain and Ireland*. FBA Scientific Publication. No. 51.
Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. (2005). The urban stream syndrome: Current knowledge and the search for a cure. *Journal of the North American Benthological Society*, *24*(3), 706–723. https://doi.org/10.1899/04-028.1
Wang, Y., Naumann, U., Eddelbuettel, D., Wilshire, J., & Warton, D. (2020). *Mvabund: Statistical Methods for Analysing Multivariate Abundance Data*. *R package version 4.1.3*. https://CRAN.R-project.org/package=mvabund
Warton, D. I., Wright, S. T., & Wang, Y. (2012). Distance-based multivariate analyses confound location and dispersion effects. *Methods in Ecology and Evolution*, *3*(1), 89–101. https://doi.org/10.1111/j.2041-210X.2011.00127.x
Williams, A. T., & Simmons, S. L. (1997). Movement patterns of riverine litter. *Water, Air, and Soil Pollution*, *98*, 119–139. https://doi.org/10.1007/BF02128653
Williams, I. D., & Deakin, N. (2007). Littering of a watercourse in north-west England. *Proceedings of the Institution of Civil Engineers*, *160*(ME4), 201–207. https://doi.org/10.1680/muen.2007.160.4.201
Wilson, H. L., Johnson, M. F., Wood, P. J., Thorne, C. R., & Eichhorn, M. P. (2020). *Inverts.index*. Open Science Framework. https://doi.org/10.17605/OSF.IO/K24T7
Wolman, M. G. (1954). A method of sampling coarse river-bed material. *Transactions American Geophysical Union*, *35*(6), 951–956. https://doi.org/10.1029/TR035i006p00951
Zuur, A. F., Ieno, E. N., Walker, N. J., Saveliev, A. A., & Smith, G. M. (2009). *Mixed effects models and extensions in ecology with R*. New York: Springer.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Wilson HL, Johnson MF, Wood PJ, Thorne CR, Eichhorn MP. Anthropogenic litter is a novel habitat for aquatic macroinvertebrates in urban rivers. *Freshw Biol*. 2020;00:1–11. https://doi.org/10.1111/fwb.13657