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Research Paper

River invertebrate biodiversity benefits from upstream urban woodland

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HIGHLIGHTS

- Literature review reveals the importance of woodland for urban riverine macroinvertebrate.
- Statistical analysis of selected urban rivers shows the influences of land cover and habitats.
- The benefit of woodland for aquatic macroinvertebrate is stronger than pasture and cropland.
- Bare ground, even in small amount, is detrimental to macroinvertebrates biodiversity.

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ABSTRACT

In urban environments, invertebrate communities are subjected to a broad mixture of impacts, including diffuse pollution. Pollutant mixtures and habitat degradation can combine to apply stress on community diversity. Water quality is influenced by the assemblage and mosaic of catchment land cover. Amongst a wider suite of Nature-Based Solutions, the value of urban woodland is increasingly recognized as having potential to support a range of ecosystem services. Despite an increasing focus on establishing urban woodland for aquatic conservation, its actual influence is yet to be manifested. Therefore, we explored trees' location in riparian and upstream catchment, within and outside of the urban area. We conducted a combination of systematic literature review and statistical analysis to better understand the woodland influence. Despite the wide range of bioindicators studied and broad worldwide spectrum of geo-climatic regimes covered, literature evidence for benefits were found in at least half the cases. With a focus on the overall family richness and the sensitive orders Ephemeroptera, Plecoptera and Trichoptera family richness as bioindicators, the statistical analysis comprised a national study in England covering 143 sites with substantial urban cover, totaling 4226 invertebrate community observations over 30 years. Two satellite-derived land cover maps were used to enable discrimination between urban and extra-urban woodland. The analysis supported the literature evidence that impervious land had negative effects and woodland positive effects. In the urban and upstream catchment, woodland was more important than pasture or cropland. There was some evidence of those woodland effects being more advantageous when trees are located within the urban area itself. Benefits attributable to woodland were distinctly apparent against a backdrop of improving macroinvertebrate diversity found to be synchronous with long-term reductions in urban pollution signatures. The presence of sparse land, even in small amounts, was detrimental to macroinvertebrate diversity. These areas of low vegetative cover might be detrimental due to high sediment input and legacy industrial contamination. Given the increasing accessibility of land cover data, the approach adopted in this case study is applicable elsewhere wherever macroinvertebrate community data are also available.

Abbreviations: AN, Anglian; ASPT, Average Score Per Taxon; BIOSYS, Biological system; B-IBI, Benthic Index of Biotic Integrity; BMI, Benthic Macroinvertebrate Index; BMWP, Biological Monitoring Working Party; EPT, Ephemeroptera, Plecoptera and Trichoptera; CCI, Community Conservation Index; EPT_FR, Family richness of the orders Ephemeroptera, Plecoptera and Trichoptera; FR, Family richness; GI, Green infrastructures; GLMM, Generalized linear mixed-effect model; HMS, Habitat modification score; LCM, Land Cover Map; MI, Midlands; NBS, Nature-Based Solution; NE, Northeast; NW, Northwest; PICO, Population-Intervention-Comparator-Outcome; Q1, the first question; Q2, the second question; QE, Quantitative experimental; QO, Quantitative observational; R, Review; SemiN, Semi-natural; SO, Southern; SW, Southwest; TH, Thames; UK, United Kingdom; Wood_in, Woodland inside; Wood_out, Woodland outside; Wood_t, Woodland total; WQX, Water Quality eXtension; WwTWs, Wastewater Treatment Works.

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1. Introduction

In well-preserved rivers, the heterogeneity of habitats is large, and aquatic invertebrate fauna diverse. However, a negative result of expanding cities across the world is the consequent impoverishment of associated aquatic ecosystems (Bernhardt and Palmer, 2007; White and Walsh, 2020). Development of urban areas and growing population commonly leads to increased pollution (Yang et al. 2021). Often, it also leads to requirements for channel modifications to control flooding and ensure navigation such as channel strengthening and riparian vegetation removal (González et al., 2017; White and Greer, 2006; Yang et al., 2021). However, human intervention such as, forest harvesting and stream channel bed and bank modification result in significant geomorphological impacts on stream channel morphology (Bylak & Kukuła, 2020). These inevitably simplify habitats (Kabir et al., 2022) and lead to reduction of biodiversity and population, which may significantly affect provision of ecosystem services (Bylak et al., 2022a). Moreover, urban rivers receive increased organic contaminants and heavy metals (for example, zinc and lead) from road runoff and industry (Awonaike et al., 2022; Li et al., 2021). The evidence is that the urban pollutant cocktail together with channel modifications harm local native aquatic species and reduce biodiversity (Lapointe et al., 2022). Despite the improvement in wastewater management, water quality is still problematic in the urban rivers, attributable to road run-off and impermeability of built-up areas (Bylak et al., 2022b). Habitat monitoring and spatially explicit species inventories are essential in evaluating the tradeoffs and complex stressors, and to solve the dilemma requires high-resolution spatial approaches (Vörösmarty et al., 2010; Liu et al., 2023).

Forming a type of green infrastructure or Nature-Based Solution (NBS) (that also includes green roofs, constructed wetlands and bioswales etc.), urban forestry provides a range of ecosystem services and benefits (Choi et al., 2021). Green infrastructure includes engineered structures but can also include natural and conserved vegetated land (Jones et al., 2022). Conservation and reintroduction of forestry has been increasingly used to address issues affecting urban areas worldwide (McMillan et al., 2014). Establishment of urban NBS (including woodland) seeks to achieve environmental and societal co-benefits. These co-benefits include carbon sequestration, air purification, water regulation, habitat and biodiversity improvement, and recreational opportunities (Derkzen et al., 2015; Nijnik and Miller, 2013; Vieira et al., 2018). The majority of functions that woodlands provide, make a direct contribution to provisioning ecosystem services (e.g. tree roots take up water and reduce runoff, directly preventing flooding) but for aquatic biodiversity there are a more complex set of relationships at play (Ogden et al., 2013). Consequently, it is not known how terrestrial tree coverage influences aquatic communities, for example freshwater macroinvertebrates.

Woodlands influence urban water quality in multiple ways (Nisbet et al., 2011; Piffer et al., 2021). The influences can depend on whether the woodland is located inside or outside of the urban area or whether in a riparian zone. For example, the size, age and species of trees will be different between the inside (special requirements for surrounding buildings, recreation and to be unified) and outside (higher diversity of tree species and resistance ability) of a city; which result in differences in food supply (leaf litter) and shelter/refuge (root or dead wood in the river) for the related aquatic macroinvertebrates (Gurnell et al., 2007; Jonsson and Sponseller, 2021; Stoler and Relyea, 2020; Tyrväinen et al., 2005). Due to space limitation, woodlands or green spaces within cities can become fragmented and their growth restricted. Nevertheless, they provide significant refuge and corridors for maintaining invertebrate richness (Bulhoes et al., 2021). The relatively larger woodlands located outside cities receive less pollution, can foster more invertebrate species and support higher biodiversity (White and Walsh, 2020).

Beneficial woodland functions differ in relation to their proximity to rivers. Riparian trees alongside rivers provide direct benefits to macroinvertebrates, whereas the benefits from trees located far from rivers (defined as catchment trees) are indirect. Reduction in erosion, pollutant transfer and the moderation in runoff volumes brought about by woodland in the upstream catchment are beneficial indirect pathways (Acreman et al., 2021; Piffer et al., 2021). Direct pathways are related to how trees influence in-channel habitat (Buffagni et al., 2019), including the effects of canopies regulating water temperature (Bonacina et al., 2023). Therefore, benefits received depend on the spatial relationship and proximity between woodland as the source and macroinvertebrate as the receptor (Harper et al., 1997). The magnitude of species richness difference between situations with or without trees in the riparian zone depends substantially on the level of artificial habitat modification (Cao and Natuhara, 2019). Rivers in highly urbanized areas usually have impermeable banks and lack of tree coverage. Modified rivers may have flow regulated by dams which in turn affects habitat (Pal et al., 2020). Features of modified rivers may have negative impacts on macroinvertebrates (Dunbar et al., 2010). Whilst functioning of woodlands to cool rivers and act as barriers to sediment and contaminant transport is accepted and understood, the significance of their effects on macroinvertebrate diversity is unclear.

Macroinvertebrates play an important role in freshwater food webs. They are both prey and predator (Jadhav et al., 2022; Kroetsch et al., 2020). Macroinvertebrate communities containing only pollution–tolerant species or very little diversity may indicate an unhealthy waterbody. Species show differing ability to withstand contaminant pressures in their larval as opposed to their adult stage (Wesner, 2019). Biodiversity is increasingly considered as an endpoint in environmental regulations (Lima et al., 2023; Sigmund et al., 2023; Tittensor et al., 2014). Typically approaches adopted examine: (i) the overall community family richness (FR) and (ii) the sensitive orders Ephemeroptera, Plecoptera and Trichoptera (EPT, more commonly known as mayfly, stonefly, and caddisfly, respectively) family richness (EPT_FR). The EPT orders represent both the terrestrial and aquatic environmental condition since their larvae and adult stages have different living preferences (Manning and Sullivan, 2021).

To explore the limits of existing understanding, this study began with a systematic review based on the relevant research on the influence of woodlands on macroinvertebrate communities in urban rivers. Secondly, we undertook a statistical analysis using a database of English rivers that brings together macroinvertebrate community ecology, water quality, level of exposure to wastewater, habitat modification and land cover data. To avoid the complex influence from multiple stressors, and to pinpoint more specifically the effects of urban land cover on urban diffuse pollution, the data was filtered to eliminate basins which are (i) large, (ii) with substantial wastewater influence, and (iii) of low urban land cover share. This ensures relationships are robust and generalizable. To achieve this objective of addressing the impact of land cover pattern we combined two remotely sensed maps of different resolutions, which allowed for the discrimination of woodland inside the urban area from that outside (peripheral) and also for identifying other specific green infrastructure (in urban areas). Although used extensively in some other fields, recent acquisition of finer resolution remotely sensed land cover data has not often been applied to questions related to aquatic biodiversity. Integrating the various data sources described above enables emerging questions to be better addressed as summarized visually in the workflow (Fig. 1). Together, the case study statistical analysis and the literature review were used to address the following emerging research questions:

Q1: Is the share of woodland positively correlated with aquatic macroinvertebrate biodiversity?

Q2: Is it important for woodland to be located inside of the urban area to confirm a positive correlation?

2. Methods and Materials

2.1. Bibliometric analysis and screening processes

Bibliometric analysis was based on literature screening from Google Scholar, Scopus and Web of Science using the following Boolean "topic search" items: "KEY (urban* OR cit* OR town*) AND (tree* OR forest* OR woodland*) AND ("green infrastructure" OR "green space" OR "nature based solution" OR nbs OR "low impact development" OR lid) AND (water OR river* OR stream OR aqua*) AND (macroinvert*)". We did the search on 19th July 2021, and yielded a return of 283 from Google Scholar, 167 from Scopus and 68 from Web of Science. All articles have been screened under the widely-adopted Population-Intervention-Comparator-Outcome (PICO) structure (Collins et al., 2015) at abstract and full-text level. Articles failing to pass the requirements of the four PICO elements (Table 1, Table S2) were removed. Finally, the articles passing the full-text screening comprised the final study material for further *meta*-analysis. The further analysis included 8 elements (Table 2) to enable the evidence mapping exercise and to answer our two research questions. There are four possible choices to answer each of the questions: (1) positive (for Q1, this confirms beneficial relationships between woodland and macroinvertebrates related bioindicators; for Q2, this confirms benefits from woodland inside the urban area), (2) negative (evidenced harmful), (3) uncertain (findings that include both advantages and disadvantages from woodlands or relationships that are not significant) and (4) unknown (although passed our criteria, but not able to answer the questions).

Table 1
Population-intervention-Comparator-Outcome (PICO) screening criteria.

Item	Definition	Criterion	Categories
Population	Targeted study area	Water in urban areas not influenced by sewage effluents	River / stream / creek, lake / pond, wetland
Intervention	Proposed intermediary impacts	Factors related to trees, affect aquatic invertebrates	Water temperature reduction, water quality improvement, soil erosion / sediment control, flow regime alteration, supplementation of habitat, food availability increment
Comparator	Control or difference in land cover	Presence/absence or a significantly different percentage of woodlands in urban areas	Deforest upstream, Gradient of vegetation, Percentage of woodland land cover, Catchment impervious / attenuated impervious area
Outcome	Subject of responder	Aquatic macroinvertebrates	Biodiversity index (e.g., FR, EPT_FR, composition, functional groups), benthic macroinvertebrates index (e.g., BMWP, ASPT, BMI, B-IBI, CCI) , abundance / density of the community

2.2. England urban river investigation

2.2.1. Rationale, database screening and workflow

As many drivers aside from land cover influence river macroinvertebrate biodiversity, a number of preparatory steps are needed before addressing the research questions with statistical analysis. First, we eliminate effects of wastewater by taking a subset of the macroinvertebrate sampling sites for which estimated wastewater exposure was zero (details can be found in: Qu et al., 2023). As urban hydrology is very complex and related to locally-specific engineering, the spatiotemporal variability in sewer outflows during extreme storm events have not been explicitly taken into account in the present study. Next, in order to identify the influence of woodland in urban rivers additional steps are required. The database of English rivers covers a wide spatial and temporal range (over 30 years, whole of England), therefore spatiotemporal factors are likely to be substantial in explaining river macroinvertebrate diversity. Hence, we bring together physical characteristics of potential explanatory variables including spatial, temporal, and local river characteristics. We combined these with the land cover variables in statistical analysis. By doing so we can separate the influence of climate factors, temporal change and river habitats from broader land cover factors.

2.2.2. Macroinvertebrate data sources and samples selection

Macroinvertebrate data was compiled by the Environment Agency and is publicly available on the national ecology database (BIOSYS, biological system, https://environment.data.gov.uk/ecology/explorer/). It contains taxonomic composition of aquatic macroinvertebrates from freshwater river surveys across England. The aquatic

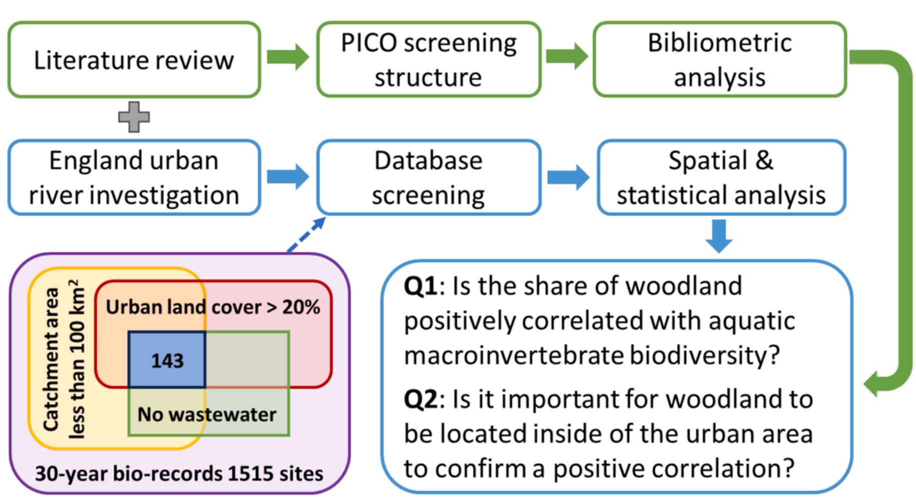

Fig. 1. Framework to understand and analyze the relationship between woodland and freshwater invertebrate biodiversity. PICO represents 'Population-Intervention-Comparator-Outcome' screening criteria.

Table 2
Critical appraisal criteria.

Criterion	Appraisal entry
Geographic location	Latitude, longitude (plus City/country)
Study type	Quantitative observational (QO), quantitative experimental (QE), review (R)
Study scale	Catchment, riparian, Both
Woodland location	Inside of urban area, outside of urban area
Study area size	Descriptive
Length of observation	Long (> 2 years), moderate (1–2 years), short (< 1 year)
Monitoring frequency	High (> seasonal), moderate (seasonal – annual), low (once)
Number of sites	Many (> 50), moderate (10–50), few (< 10)

macroinvertebrates were collected following a standardized 3-minute kick sampling protocol (Murray-Bligh et al., 1997). Because of species level recording was patchy before 2014, similarly, abundance recordings were in a semi-quantitative manner before 2000. The biological data, therefore, focused on presence-absence recording at the family level, which consistent over time.

To focus on urban rivers without substantial wastewater influence, the samples for analyzing in this study have gone through three steps of screening from a total of 1515 sites (those macroinvertebrate sites from Environment Agency having more than 10 years of observations since 1989). Firstly, the sites were selected with catchment area less than 100 km^2 and urban land cover greater than 20 %. Secondly, we excluded the sites exposed to sewage wastewater (either without any local wastewater treatment plants or under the simulated wastewater detected limit of the modelling). The wastewater exposure was simulated by the LF2000 WQX (LowFlows2000 Water Quality eXtension) model (Williams et al., 2003) based on a 40-year climate record and a combination of location and flow of Wastewater Treatment Works (WwTWs) in England (Balaam et al., 2010). Thirdly, we exclude the sites before 1989 because only a few macroinvertebrate samples were collected before that year. Finally, 4226 samples relating to 143 sites across England have been selected (location showing in Fig. 2).

The biodiversity assessment was at the family level, since the identification undertaken by the Environment Agency was not as detailed as species level until 2014. We used two bioindicators to describe the macroinvertebrate biodiversity: (i) FR representing the general number of families presented in a sample of overall community, (ii) EPT_FR representing the number of families in the pollution sensitive order. These are widely used long-time recording biotic indicators which allow us to compare with other rivers around the world.

2.2.3. Description of the land cover and river habitat survey

For each macroinvertebrate site the catchment land cover and derivative land cover upstream of the site was extracted. Two land cover maps are used in this study. The first one is Land Cover Map 2015 (LCM_2015) (Rowland et al., 2017), a dataset with 25 m resolution that is specific to the United Kingdom (UK). From this we used 4 categories: woodland (abridged as Wood_out in this study), seminatural (SemiN), urban and arable land cover. The second map is ESA (European Space Agency) 2020 land cover map (LCM_2020) (Zanaga et al. 2021; Fletcher et al., 2022) a global dataset with 10 m resolution. From this we used 8 categories: woodland (distinguished as Wood_t in this study), wetland, grass, water, built, crop, shrub and sparse land (Table 3). This enabled us to identify woodland inside urban area (Wood_in), as cities and towns within LCM_2015 are classed as wholly urban, whereas LCM_2020 provides information on vegetation, including trees and greenspaces in these areas apart from built. By taking advantage of these two maps, we were also able to estimate the share of green infrastructures (GI) by "urban minus built" (Table 3). It potentially represents the permeable land in the urban area. The analysis uses land cover maps that originate from different years. Whilst this is not ideal, land cover within England has not changed substantially between these years (Fig. S2). Therefore, this is the best available option for our purposes.

A sub-set of sites (92) gave extra information about the river habitat survey results from the UK Environment Agency BIOSYS database. There are three indicators provided from the river habitat survey: (i) habitat modification score (HMS, range from 0 to 6000 +), (ii) habitat modification class (including 5 classes, describe the rivers from pristine/semi-natural to severely modified based on the HMS) (Raven et al., 1997; Raven et al., 1998). The river HMS quantifies the extent, potential impact and persistence of engineering structures on river channels,

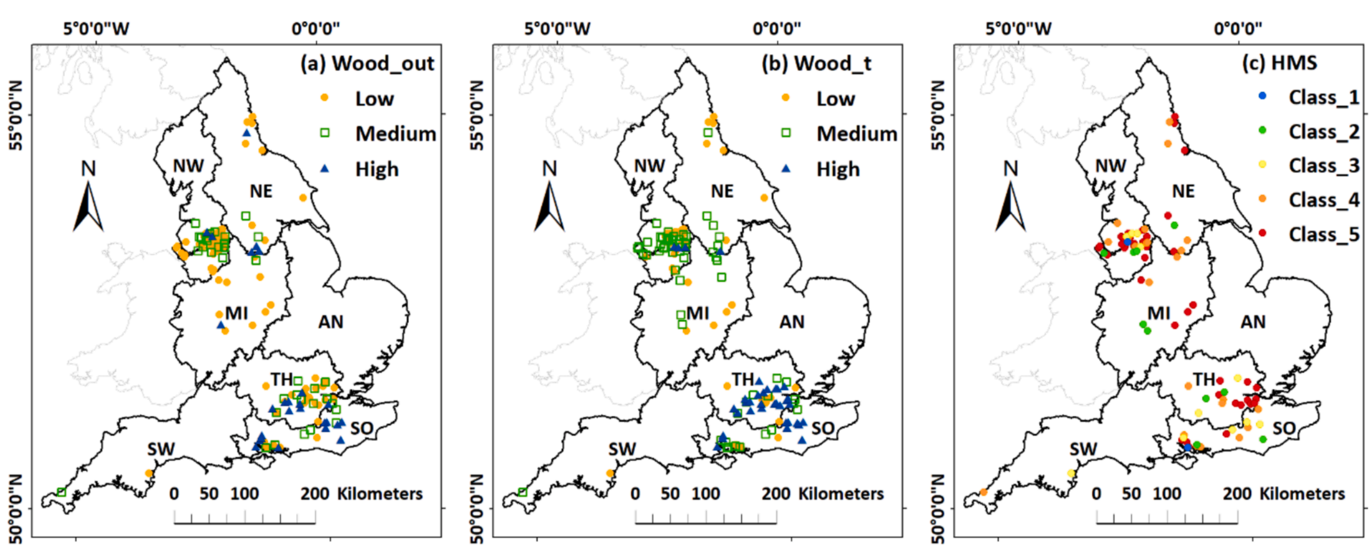

Fig. 2. Location of the 143 sites which passed the criteria (<100 km^2, >20 % urban, without wastewater influence) and the number of sites for different share of (a) outside woodland (Wood_out) and (b) total woodland (Wood_t) land cover. Location of the 92 sites with their class of (c) river habitat modification score (HMS). The abbreviations NW represent for Northwest, NE for Northeast, MI for Midlands, AN for Anglian, TH for Thames, SW for Southwest, SO for Southern. These regions defined by watershed by Environment Agency, United Kingdom.

Table 3
Land cover categories included in this study.

Map	Abbreviation	Name	Description
LCM_2015	Wood_out	Woodland outside	Woodland outside of urban or arable land
	SemiN	Seminatural land	Grassland, littoral Rock, waterbodies
	Arable	Arable land	Arable and Horticulture land
	Urban	Urban	Urban
LCM_2020	Wood_t	Woodland total	Tree cover, total woodland cover
	Wetland	Wetland	Herbaceous wetland
	Grass	Grass	Grassland
	Water	Water	Permanent water bodies
	Built	Built	Built-up land
	Crop	Crop	Cropland
	Shrub	Shrub	Shrubland
	Bare	Bare land	Sparse land / bare ground
Derivative land cover	Wood_in	Woodland inside	Woodland total (LCM_2020) - Woodland outside (LCM_2015)
	GI	Green infrastructures	Urban (LCM_2015) - Built (LCM_2020)

banks and riparian zones (Walker et al., 2002), which reflects the level of riparian trees coverage, as well as the instream habitat diversity and river morphology alterations.

2.2.4. Spatial and statistical analysis methods

The analysis methods include two parts: a descriptive summary for data visualization (see in Result 3.2.1, Table 5 & Fig. 2), and statistical analysis (see in Result 3.2.2 and 3.2.3, Figs. 3, 4, 5 & 6).

Descriptive summary: The classification of low, medium and high levels of two types of woodland (Table 5) used the Natural Breaks method (Jenks, 1967) by ArcGIS (De Smith et al., 2007). This method is based on the feature of data and identifies breaks at places that best group similar values together and maximizes the differences between classes. The difference between habitat modification classes was tested between the Class 5 and the rest (Class 1 to 4) such that each contains a similar number of sites (Table 5).

Statistical analysis: Analyses were performed in the R programming environment (R-4.3.1, R Development Core Team). The patterns of 30-year trends have been smoothed by local polynomial regression fitting (using function 'loess' in package 'stats' (Cleveland et al., 1988). The grey error bands display the 0.95 confidence intervals around the smoothed curves. The significance of biological indicators' difference among each pair of divisions were tested by the Kruskal-Wallis test (Kruskal and Wallis, 1952). All land cover parameters together with habitat modification score were tested with Pearson's correlation coefficient for correlation and multi-co-linearity. We then applied the random forest model (Liaw, 2022) to rank the importance of parameters and identify the key factors most closely associated with the macroinvertebrates biological indices. The random forest models were created using function 'randomForest' in R package 'randomForest'. To test the significance of any trends, generalized linear mixed models were used. The top predictors were included in the generalized linear mixed model (GLMM) for testing of their significance and to estimate the response of biological indices (Schall, 1991). The GLMM models were created using function 'glmmTMB' in R package 'glmmTMB'.

3. Results

3.1. Literature review and bibliometric analysis

3.1.1. Evidence map

Among the 518 articles from the three search engines, 34 studies worldwide passed the screening. The prevalence of relevant studies has increased greatly in recent years with 31 of the 34 studies published since 2010. Of the remainder only 2 studies reported observations before 2000. Geographically at continental resolution (Fig. S1), the distribution

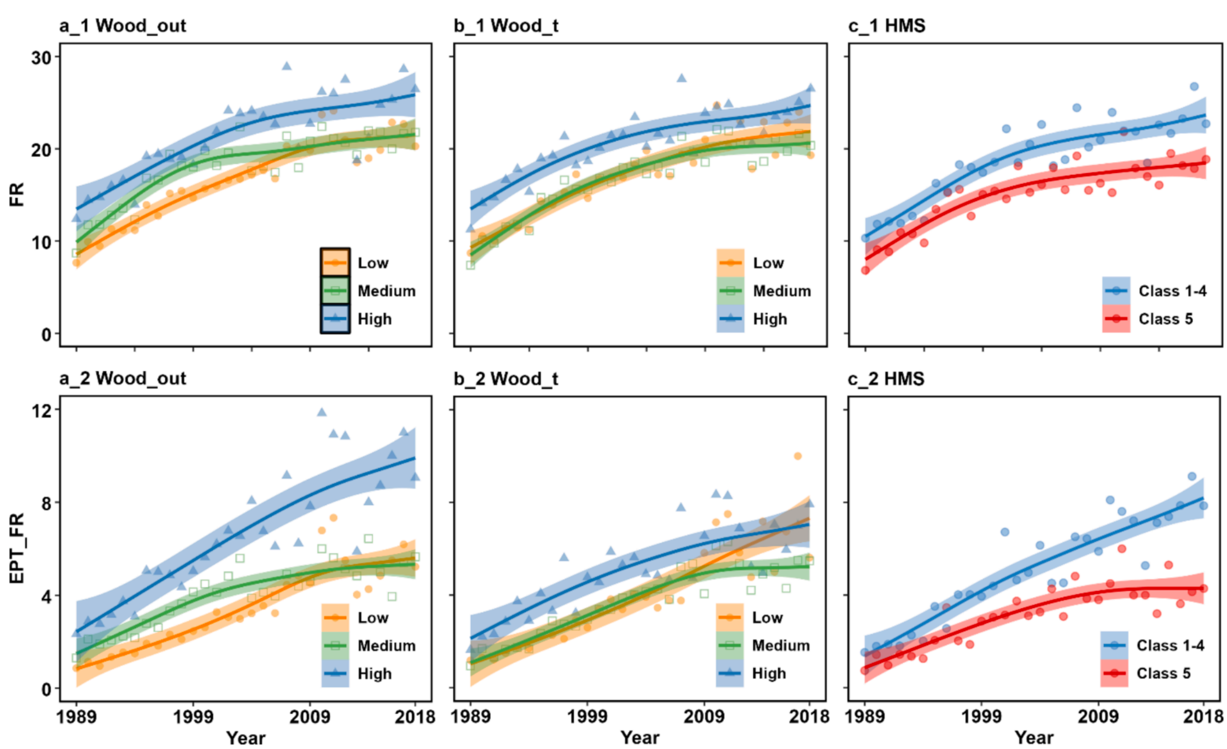

Fig. 3. Temporal trends in the past 30 years (from 1989 to 2018) in biological indicators as related to classes of woodland landcover share and habitat modification; where (a) Wood_out (woodland considered mainly located outside of the urban area), (b) Wood_t (total percentage of woodland) in the upstream catchment, (c) HMS (habitat modification score); and (1) Family richness (FR), (2) Ephemeroptera, Plecoptera and Trichoptera family richness (EPT_FR). The range and number of sites in low, medium, high woodland catergories and HMS classes divisions are presented in Table 5.

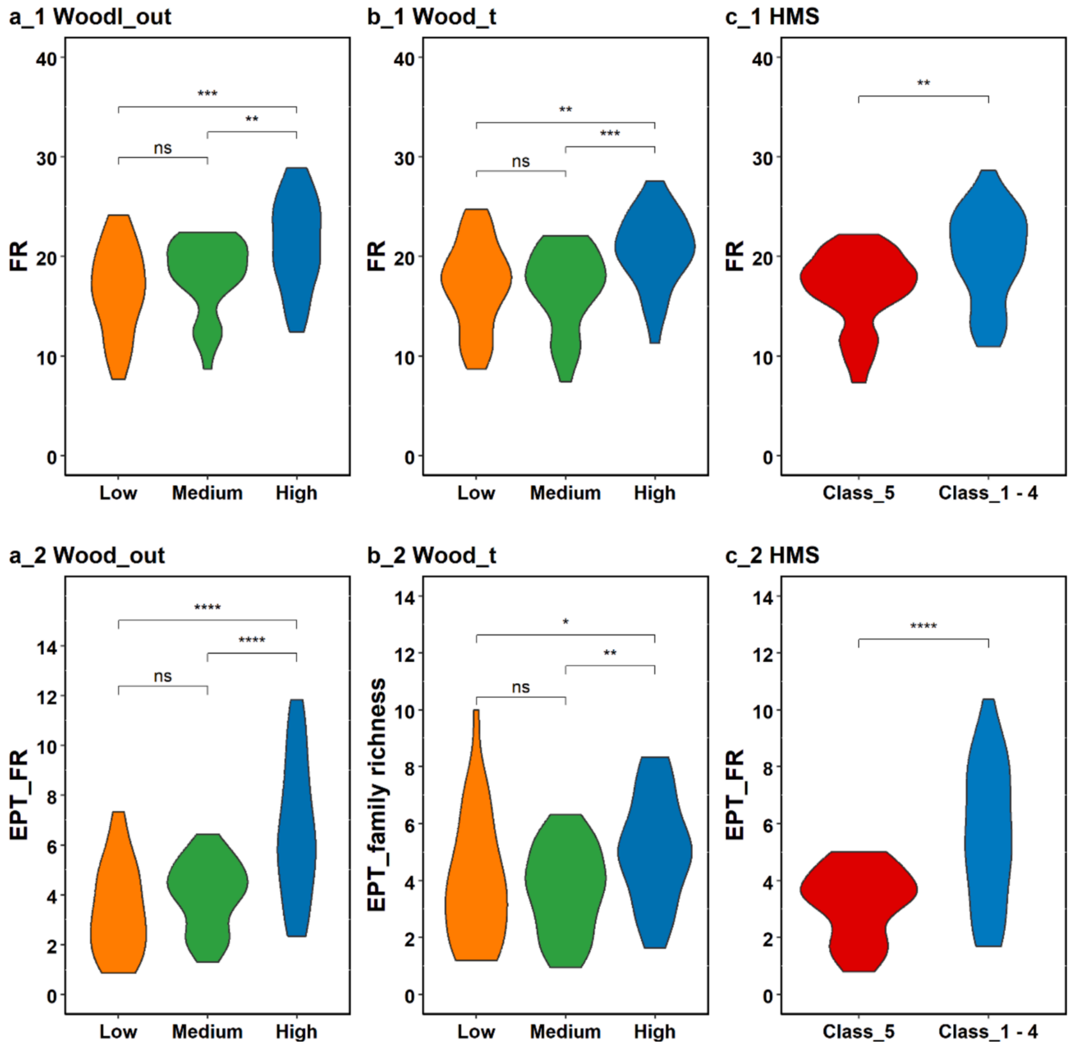

Fig. 4. A representation of whether the different selected groups for the two macroinvertebrate indices (1) FR (family richness) and (2) EPT_FR (Ephemeroptera, Plecoptera and Trichoptera family richness) from Fig. 2 are significantly different from one another with respect to two types of woodland: (a) Wood_out (woodland considered mainly located outside of the urban area) and (b) Wood_t (total percentage of woodland) in the upstream catchment, and (c) HMS (habitat modification score) in the past 30 years (from 1989 to 2018). The range and site number of low, medium, high and HMS classes division are presented in Table 5. We use the following convention for symbols indicating statistical significance: ns: $p > 0.05$, *: $p <= 0.05$, **: $p <= 0.01$, ***: $p <= 0.001$, ****: $p <= 0.0001$).

of evidence is weighted towards North America (10) and Europe (10) with the remaining studies in Oceania (6), Asia (5) and South America (4). Experimental studies (QE) comprised 6 of the 34 studies, all others being observational (QO). Four partially-overlapping categories of evidence were identified: (1) catchment scale work or findings related to woodland percentage of the upstream catchment, (2) riparian scale work or findings focusing on woodland coverage in the riparian buffer zone (3) studies of impacts of tree coverage detected located inside of urban area and (4) studies of the large portion of preservation forest outside of urban area. Information pertaining to the criteria (Tables 1 and 2) together with other details were answered for establishing aspects of urban forestry benefit in quantitative terms. A summary of the key details of the final articles can be found in the appendix (Table S1 and S2).

3.1.2. Bibliometric analysis

Catchment scale has 10 studies considering woodland inside (7 positive, two uncertain and one unknown) and 10 studies considering woodland outside of the urban area. In general, the answer to Q1 (Is the share of woodland positively correlated with aquatic macroinvertebrate biodiversity?) is yes, but not always. There were 20 of 37 studies showing significant positive correlation between woodlands and aquatic invertebrate biodiversity. The answer for Q2 (Is it important for woodland to be located inside of the urban area to confirm a positive correlation?) is no. Evidence for supporting aquatic invertebrate biodiversity was found in the cases of both inside and outside woodland. There are 5 out of 10 studies showing a significant positive contribution of trees outside of the urban area. There are also 15 of 27 studies confirming the benefits of trees inside of cities. The majority of studies affirmed the benefits to aquatic water quality and ecological status both at the catchment and riparian scale. There was little substantial difference between riparian (8/17) and catchment (12/20) studies. However, relationships defined as negative, uncertain, and unknown together comprise almost half of the findings. The “uncertain” studies reflect benefits tailing off at high woodland level, and that extra influences from habitat modification and use of a variety of bioindicators may result in confounding conclusions (Table 4).

3.2. Biodiversity trend examination in English urban centres

3.2.1. Summary of the results from screening data and general information

There is a wide gradient of woodland cover (in terms of woodland outside and woodland total variables) for the selected 143 sites. The woodland outside varies from 0 to 60 %. From north to south, all regions

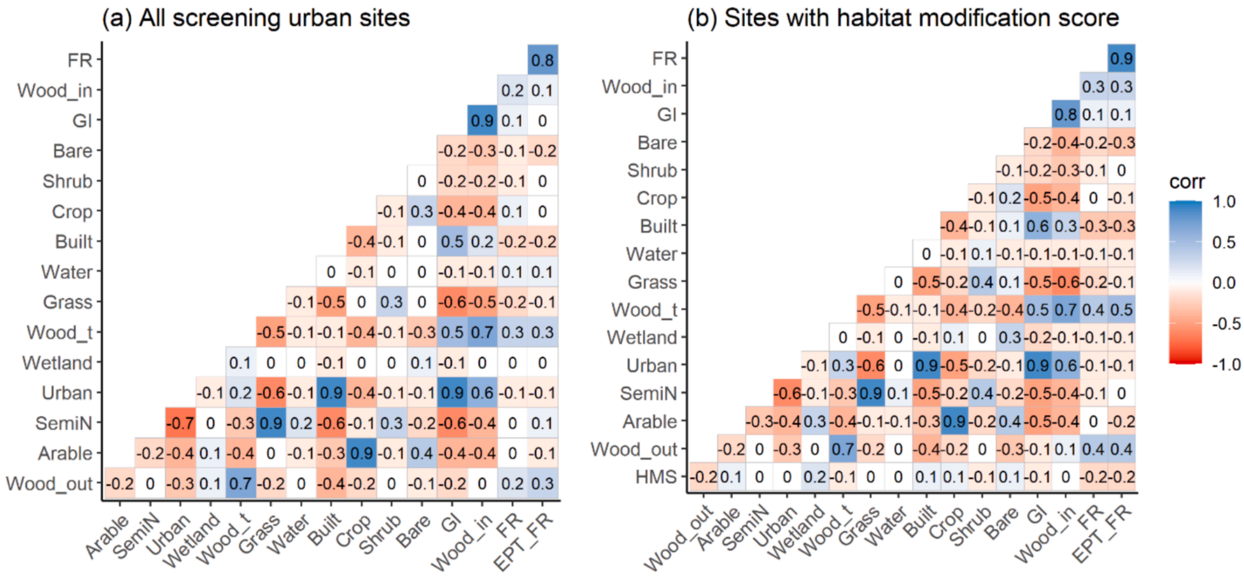

Fig. 5. Symmetric correlation matrix plot for the associations between physical characteristics, land cover parameters and richness indicators. The colors represent the degree of pairwise correlation (Spearman's rank correlation coefficient). FR represents family richness. EPT_FR represents Ephemeroptera, Plecoptera and Trichoptera family richness. The full name and explanation of land cover parameters can be found in Table 3, HMS represent habitat modification score.

contained basins with very low tree coverage (Fig. 1 a). The woodland total varies from 10 to 70 %. Greater woodland total coverage can be found in the Thames (TH) than in the Midlands (MI) region (Fig. 1 b). Some sites with low woodland outside of the urban area are showing greater woodland total coverage in Thames, however sites with medium to high level woodland outside is showing less woodland total (Fig. 2 a & b). Nearly half of the sites (43 of 92, Table 5) which included river habitat modification survey belong to Class_5, indicating severely modified status (Fig. 2 c). Another 23 sites lie in Class_4 which is also significantly modified. Rivers with high woodland are not always less habitat modified, and vice versa (Fig. 2). Some sites have been less modified but have less woodland coverage. A few sites located in the Thames region have a severe habitat modification (in Class_5) despite having woodland total coverage above 44 %.

3.2.2. FR and EPT_FR trends according to the different percentage of woodland and local HMS

The richness trends in the past 30 years show overall consistent improvements (Fig. 3). Both bioindicators had a significant positive relationship with year ($p < 0.001$, Table S3), the increase rate of EPT_FR is higher than FR over the observed 30 years (Table S3). The proportion of woodland has a positive influence on the presence of the richness of macroinvertebrates (FR and EPT_FR, Fig. 5 and Table S3). From 1989 to 2018 there was an increase in diversity of around 10 to 20 families for all sites regardless of woodland share. Throughout the time period, the FR in sites having greater woodland percentage was larger than for sites with less woodland sites. This is apparent for both woodland outside and woodland total attributes (Fig. 5). The smaller sub-group of EPT_FR is continuing to improve over time in most cases (from around 2 to 6 families). However, there is a marked preference of the more sensitive macroinvertebrates (EPT_FR) for sites with higher wood_out, instead of wood_t (Fig. 3 a & b). The Wilcoxon test (Fig. 4a & b) shows there to be significant differences in macroinvertebrate biodiversity between the high woodland category and the other (medium and low) categories. The difference between low and medium groups is not statistically significant. Similar results are also observed in tests only covering data for a recent 5 year period (2014–2018, Fig. S2), demonstrating that any long-term changes in land-use since 1990 have not affected the relationship between woodland and macroinvertebrate biodiversity.

The arrival of new families in urban rivers is reflected in improvements from 1989 to 2018 in both low and high HMS classes (Fig. 3 c). However, the improvement in the severely modified sites (Class 5) has notably slowed recently and has nearly ceased. In addition, even more recently, a strikingly negative influence on the presence of the more sensitive macroinvertebrates (EPT_FR) is apparent for Class 5. The differences between low and high modified rivers have grown over time and with a significantly difference (Fig. 4 c). For both richness indicators, they have statistical strongly negative relationship with HMS (correlation coefficient = -0.2, $p < 0.05$, Fig. 5 b).

3.2.3. The key land cover parameters related to macroinvertebrate family richness

Macroinvertebrate diversity richness variables are more strongly correlated with woodland variables than any of the other variables (Fig. 5). The most strongly negatively correlated variables are **urban or built**. Apart from the high correlation coefficient between two biotic indices, the most highly positively correlated pairs of variables are: (i) grass (LCM_2020) and semiN (seminatural, LCM_2015), (ii) crop (LCM_2020) and arable (LCM_2015), (iii) built (LCM 2020) and urban (LCM 2015). In addition, GI (green infrastructure, derivative land cover) are highly related to both urban and wood_in (Woodland inside, derivative land cover). Wood_in and wood_out (woodland outside, LCM_2015) are correlated with wood_t (woodland total, LCM_2020), respectively. HMS are negatively correlated with Wood_out and wetland (Fig. 5 b).

The importance of the physical characteristics (including altitude and slope gradient) of the sampling sites together with the catchment land cover parameters based on the Random Forest model were ranked (Fig. 6). The top predictors for the macroinvertebrates bioindicators include Wood_t, Built, Wood_out and Bare land cover. The community general taxonomic richness was also closely associated with the slope gradient (Fig. 6 a). Importantly, the category of woodland land cover comes out stronger than grass and semi-natural and wetland. This implies that of non-urban land cover, woodland was more beneficial than the other types. The wood_t was a stronger explanatory variable than wood_out, in particular in the analysis of the sub-set of sites for which habitat modification scores were available (Fig. 6 c & d). Built and bare land gave strong negative effects to the taxonomic richness (Table S3

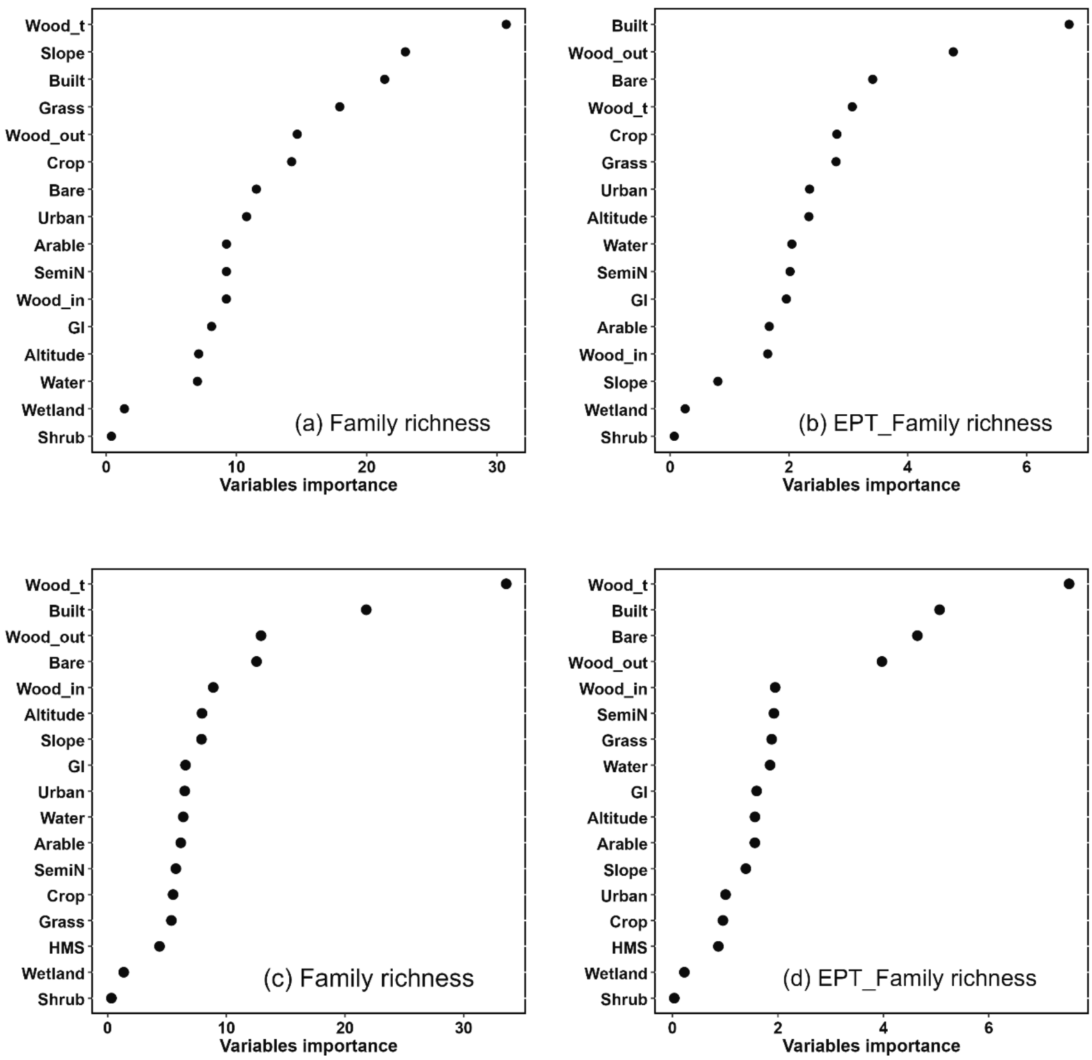

Fig. 6. Random Forest analysis for ranking the importance of parameters. (a) and (b) for the total 143 sites, (c) and (d) for the 92 sites with HMS (Habitat modification score). Full name and explanation for the abbreviations of land cover parameters can be found in Table 3.

Table 4
Summary of the number of reviewed studies by answering the research questions in this study. Column with header of 'Catchment' and 'Riparian' relate to the first research question (Q1), 'Inside' and 'Outside' relate to the second question (Q2).

	Catchment	Riparian	Inside	Outside
Positive	12	8	15	5
Negative	1	2	2	1
Uncertain	5	6	8	3
Unknown	2	1	2	1

and Fig S3). We also tested the responses from the top three predictors by the partial dependence plots and regression model (Fig. S3 and Table S3). These two analyses quantify the expected changes in macroinvertebrate diversity arising from change in the top three predictors.

4. Discussion

The statistical analysis was based on a database of 4226 samples from England covering 143 sites over a 30 years (1989 to 2018) period. The sites covered some of the most densely urban areas of England including the cities of London, Manchester, Birmingham and Southampton. The extent and scale of this study makes the analysis potentially more powerful than what is currently available. The longest investigated period from the literature review covered 7 years of observations (two studies). One study was focusing on one site in Kentucky (United States of America) (Hawley et al., 2016). The other from Canada included 133

Table 5
Sum of number of the sites (Num_site) in each division (Wood_out for woodland outside of the urban or crop land area, Wood_t for total woodland cover, HMS_Class for the class of habitat modification score).

	Wood_out Range (%)	Num_site	Wood_t Range	Num_site	HMS_Class Range	Num_site
Low	0.0–8.5	81	9.9–27.6	45	1–4	46
Medium	8.6–19.3	37	27.7–43.7	63		
High	19.4–60.4	26	43.8–70.2	35	5	43

sites but only covered locations surrounding the Toronto region (Wallace et al., 2013). Besides, we found only two studies (from South Korea: (Park et al., 2021a; Park et al., 2021b) covering a national-wide scale of investigation (of three years duration from 2016 to 2018 in this case)).

The findings from the literature review and the statistical analysis are in agreement. Addressing the research questions Q1 and Q2 respectively, sections 4.1 and 4.2 cover the beneficial aspects of woodland influence on biodiversity. Section 4.3 discusses notable temporal changes occurring through the 30-year period examined. The fourth sub-section identifies other key land cover influences on aquatic biodiversity, draws out more general implications and makes recommendations for management of NBS.

4.1. The importance of woodland

Although both the *meta*-analysis and our statistical analysis did not come up with an absolute affirmative answer to Q1, we found robust evidence of the benefit of woodlands to local macroinvertebrate biodiversity.

The searching and screening process in the literature review highlighted evidence which had been collected in environmental situations and scales where NBS could potentially play a significant role in determining macroinvertebrate diversity. In this context we determined whether or not evidence for woodland benefits were identified. These may or may not represent woodlands defined as NBS. From the literature review, more than half of the studies showed a significant positive impact on aquatic macroinvertebrate community by various bioindicators, considering land cover either in the riparian zone, in the wider catchment or in both (Table S1). The evidence points in the direction of the beneficial value of woodlands in urban settings across various biological aspects, including taxonomic and functional diversity, as well as abundance and the ratio of sensitive and rare species (Table S1 & S2).

The English case-study findings are in accordance with the positive support from the literature review regarding Q1. The overall evidence from both bioindicators (general community FR and sensitive groups EPT_FR) is that catchments with high woodland had higher levels of biodiversity throughout the 30-year time period than catchments with lower woodland percentages (Figs. 2 & 3). Use of the two land cover maps revealed these findings to be apparent for both woodland types (Wood_out and Wood_t). In addition, woodlands are more important than semi-natural, grassland and wetland land cover (Fig. 5). It implies that the presence of trees in urban green spaces improves local aquatic biodiversity. The river habitat survey identifies the riparian condition, when highly modified, can cap further recovery (Fig. 2). This brake on recovery is particularly clear for EPT_FR over the past 30 years. Less modified rivers, likely with good riparian vegetation condition, hold an ongoing potential for recovery.

The studies of similar scale and extent as our study have reached similar conclusions to ours. Park et al. (2021a, b) which looked into catchment scale for 754 sites during 3 years found positive relationship of forest to benthic macroinvertebrates index (BMI). Walllace et al. (2013) studied 133 sites for 7 years and also indicate a positive relationship between BMI and forest landcover percentage. BMI (Barbour, 1999) represents the health condition of a habitat from the bioassessment of macroinvertebrate composition metric. The higher the BMI score, the better the river ecological status.

4.2. Does woodland inside or outside the city make a difference?

From the literature review, 8 of 17 studies suggested a positive impact from woodland land cover, but this also included the contribution of the riparian woodlands standing outside of the urbanized area. For studies at the catchment scale, half of them (9 of 18) considered woodlands inside of the urban area, and 5 of these 9 concluded that aquatic macroinvertebrates biodiversity was positively influenced by woodland. The remaining four are uncertain or undetectable; none showed negative relationships between woodland and aquatic biodiversity. The other half of the 18 studies consider woodlands outside of the city zone, and of these 5 confirm the positive contribution of woodland to aquatic biodiversity.

For the English analysis, both woodland total and woodland outside had positive temporal trends with biodiversity (Fig. 2), woodland total was generally a more powerful indicator (Fig. 5 a, c, d), which demonstrated the importance of woodland within the urban area to support richness. Because the woodland total shows stronger relationship than woodland outside to FR, and since the woodland inside is also always highly correlated with woodland total (Fig. 4), it seems that the woodland inside is the most beneficial to local macroinvertebrate diversity. The high woodland percentage groups showed significant difference from the low and medium level of woodland percentage (Fig. 3). The contribution of urban and agricultural tree cover outside forests has been largely overlooked (Liu et al., 2023). Liu et al. also mentioned that, tree cover inside urban areas is not only valuable for national carbon stock, systematic identification of their location could also form an integral part of monitoring and planning schemes related to biodiversity, microclimate, habitats, and hydrological cycles. On the other hand, the peripheral basin (woodland outside of urban area) is also critical for maintaining good ecological status. These woodlands can be important for protecting the aquatic species and can provide periodic or permanent refugia in deteriorating environmental conditions (Bylak et al., 2018).

4.3. Temporal change in bioindicators

The 143 English sites show improvement in biodiversity indicators over time (Table S3). The temporal changes in FR are greater than the difference in FR between low and high woodland (Fig. 2 a_1 & b_1). As the statistical analysis in this study did not include sites with wastewater influence, the known improvements in sewage treatment over the 30-year period (Whelan et al., 2022) are not affecting temporal trends in biodiversity here. Nevertheless, it is notable that diffuse urban pollution (as illustrated for example by stream water dissolved lead concentrations, reflecting reduced air pollution and road runoff contamination alone) has markedly decreased throughout the 1988–2018 period and this will likely have some beneficial effect. Dissolved lead concentrations in a subset of 15 of the 143 urban sites have typically declined from 40.75 μg/L in 1988 to 18.95 μg/L in 2003 and remained fairly constant thereafter (with an average of 8.29 μg/L and not exceed 23.26 μg/L) (Fig. S4). This declining trend closely follows the improving trends seen in FR and EPT_FR (Fig. 2).

In recent years the improvement has been levelling off (Fig. 2). This indicates that a limit to further improvement in FR is being approached. We postulate that there are three aspects which may be limiting further improvement. These are: (i) high levels of woodland prevent species dispersion (ii) severe habitat modification may prevent further improvement regardless of there being high woodland cover (iii) highest feasible biodiversity levels are already being approached. Evidence from the literature review supports evidence that some or all of these factors may be important.

Whilst we are seeing a levelling off of improvements in biodiversity in recent years, the upper limit of the 95 % confidence interval level for the entire population of 1515 sites (36 for FR and 15 for EPT, Qu et al., 2023) is still considerably higher than typical current levels in the 143 selected sites (Fig. 2). This suggests that future improvements in urban river environments are still achievable. Logically this might be deemed achievable through further tree planting, but too much riparian woodland can be a problem. A substantial proportion of papers reported the uncertain, insignificant, even negative influence of woodland land cover. One study (Thornhill et al., 2017) pointed out a potential biodiversity decline when riparian shading rose above 75 %. In addition, (Walsh et al., 2007) suggested difficulties in species dispersal under high woodland conditions might contribute to decreasing biodiversity. This is understandable due to establishment of physical barriers, the fostering of potential predators and disadvantageous microclimate alterations arising from presence of dense woodland (Ramey and Richardson, 2017; O'Malley et al., 2020; Bollinger et al., 2023). In addition, riparian woodland comprising monoculture forestry with possible fertilizer application may likely impair development of macroinvertebrate communities (Palik et al., 2020). Short-rotation woody crops with the aim of producing a constant yield of merchantable wood, have often led to low tree species diversity, and damaged the water quality (Griffiths et al., 2019). Although only 5 studies contained information about tree species, these suggest it is important to plant diverse trees combined with other types of green infrastructure in urbanizing catchments as part of efforts to develop NBS that can provide multiple environmental and societal benefits.

4.4. Other important factors influencing local macroinvertebrate diversity

The built or impermeable land cover showed mainly negative influences from both literature review (Liao et al., 2020) and our statistical analysis. High percentage of built land cover is problematic because it is largely impermeable and can lead to rapid pollution pathways to rivers and a more extreme hydrological regime entailing disruptive drought and flood events. This can lead to receiving aquatic environments experiencing intermittently high pollution concentrations and damaging sediment fluxes. These potentially stress wildlife. However, confounding evidence may be apparent whereby better biodiversity (high score of FR and EPT_FR) in sites with high built land cover is probably due to the specific location of the built land. If the riparian area is preserved (i.e., woodland or grassland semi-natural) then this is beneficial for FR and any harm from built land is less apparent.

Built and sparse land cover appears to be the biggest obstacle for pollution sensitive species (EPT_FR) in urban rivers (Fig. S3 & Table S3). Bare ground, despite only ever comprising a small share in sites in the English case study, contributed a disproportionally negative effect on macroinvertebrates (Fig. S3). This land cover sub-type could be important not just in urban settings (Bylak et al., 2022b; Maloney and Feminella, 2006; Park et al., 2011). Arising harmful effects of bare ground are due to the high input of sediments, and high turbidity (from bare unconsolidated soil on building sites) that could be released as well as possible legacy pollution in reclaimed industrial land. Additionally, the sparse land cover category comprise lands with exposed soil, sand, or rocks and never have more than 10 % vegetated cover during the year (Zanaga et al., 2021), characteristics which do not themselves generally provide good habitats for wildlife. A proportion of macroinvertebrates (such as genera *Simulium*, *Leuctra*, *Ephemera*, *Polycentropus*, *Ischnura, eta.*) have four life stages. Individuals undergo complete metamorphosis linking both aquatic with terrestrial habitats. Therefore, bare ground located in riparian zones indicates especially severely modified habitats that potentially adversely affect habitat quality and the survival rate of these species. Bare ground has been found problematic for a range of biotic communities including macroinvertebrates in rapidly developing countries or areas (Bylak et al., 2022b). Freshwater macroinvertebrates taxonomic richness in areas where there is still high pollution (as had been the case in England before 1990) will likely benefit greatly from tree planting initiatives.

Aside from land cover categories, local physical attributes (slope and altitude) emerge as strong explanatory variables (Fig. 5). The significance embodies the local ecological preferences of macroinvertebrates, which involve local hydro-climatic and geological features preference (Shah et al., 2015). Different communities are found under different types of natural conditions. RIVPACS (River InVertebrate Prediction And Classification System), a well-established scheme, reflects this and predicts similar communities exist wherever environmental conditions are the same (Wright et al., 1998). In the absence or removal of stress, RIVPACS predicts a differentiation across physical patterns, alongside local hydro-climatic and geological factors. In the present English study, the latitude gradient is strong and reflects a number of the key factors that control macroinvertebrate communities directly (Qu et al., 2023). In summary, land cover and location attributes are powerful because they represent integration of a wide range of factors that are strong indicators for the pattern of macroinvertebrate communities. The benefits of woodland to aquatic biota, not merely for macroinvertebrates but phytoplankton as well, cannot be overlooked and are worthy of further investigation (Qu et al., 2022).

5. Conclusion

The international literature points to the positive effects of woodlands on water quality and aquatic macroinvertebrate diversity from the majority of studies, although the biotic response to woodland is often found to be uncertain. Examination of 30 years of data for English urban areas shows woodlands inside and outside of urban areas assist biodiversity recovery and conservation. The increasing trend of aquatic macroinvertebrate richness is probably associated with a reduction in chemical pollution, However, although a minority of the literature suggested uncertain or negative effects, adding more woodland can provide a 50 % further beneficial effect in urban areas. The English study confirms findings on the negative effects of built or other impermeable land cover types on local macroinvertebrate diversity. Sparse land is also found to be clearly detrimental for biotic diversity. These harmful effects are exacerbated when located in riparian zones where they result in severely modified river habitats.

The method is potentially applicable in other countries, as satellite data of the types used here are available worldwide. The ESA data is particularly valuable as it includes a representation of sparse land. Findings from our literature review suggest further analysis regarding of tree species and woodland biodiversity would be valuable to distinguish their different contribution. The Random Forest model developed is suitable for ranking importance of factors but is not readily suitable for prediction and interaction effects. Potential interaction effects from multiple stressors may also affect the final conclusion and might be identified from statistical modelling of a data set covering additional sites for example covering known gradients of wastewater stress. A next step would be to develop a predictive machine learning algorithms (e.g., convolutional neural network combined with long short-term memory for richness prediction (Cha et al., 2021; Lee and Rezaie, 2021), that can be used to test scenarios of land cover change.

CRediT authorship contribution statement

Yueming Qu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Michael Hutchins:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization. **Alice Fitch:** Writing – review & editing, Methodology, Data curation. **Andrew C. Johnson:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2024.105251.

Data availability

Data will be made available on request.

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