Woody riparian buffers have indirect effects on macroinvertebrate assemblages of French rivers, but land use effects are much stronger

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RESEARCH ARTICLE

Woody riparian buffers have indirect effects on macroinvertebrate assemblages of French rivers, but land use effects are much stronger

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Abstract

1. Woody riparian buffers (hereafter, 'woody buffers') are frequently considered as important to mitigate the effects of stressors on streams and rivers. While several individual studies addressing nutrients, pesticides, water temperature and different biotic components support this conjecture, no study has addressed the effects of woody buffers on riverine biota at country-wide scales.
2. We used a comprehensive dataset from sampling sites on 1082 catchments in France, comprising samples of benthic invertebrates, along with data on river size, physico-chemistry, hydromorphology, riparian and catchment land use and woody buffers at sampling sites and upstream.
3. Using partial least square modelling, we delineated the effects of the different environmental variables on two benthic invertebrate metrics, separately for siliceous and calcareous rivers.
4. Overall, models explained 49% (calcareous) and 39% (siliceous) of the variation in benthic invertebrate metrics. Direct effects of woody buffers on benthic invertebrate metrics were marginal, while physico-chemical conditions and catchment land use explained most of the deviance. Direct and indirect effects of woody buffer together covered up to 6% (upstream scale) plus 2% (local scale) of the explained variability.
5. *Synthesis and applications*. In this national-scale study, on 1082 catchments, we investigated the potential of woody buffers to mitigate the effects of catchment-scale and local-scale stressors on macroinvertebrate biodiversity. Our results underline that the establishment of woody buffers is not necessarily a sufficient measure to solve the problem of deteriorating riverine macroinvertebrate communities, especially in catchments prone to intense land use. Nevertheless, two main outcomes included that local woody patches are not sufficient and that woody buffers should be established along longer river stretches. Also, accompanying catchment-scale measures should be promoted to reduce the effects of intense land use and pollution to a level that enables woody buffers to be effective as well.

KEYWORDS
benthic invertebrates, catchment land use, direct and indirect effects, mitigation effect, multiple spatial scale analysis, Partial least square modelling, woody riparian buffers

1 | INTRODUCTION

Rivers are embedded into the surrounding landscape and thus strongly affected by stressors acting upstream or at the catchment scale. The effects of several stressors resulting from catchment land use on riverine biota have been investigated in detail. Stendera et al. (2012) stated that land use, eutrophication and habitat destruction at the catchment scale are the major disturbances on rivers. Changing catchment land use can affect discharge (Buytaert et al., 2006), sediment transport and water quality (Miserendino et al., 2011). However, disentangling the pathways through which catchment land use affects biota remains difficult and catchment land use is frequently considered as an 'overarching stressor' or 'driver' (Death & Collier, 2010; Roth et al., 1996; Sliva & Williams, 2001; Wang et al., 1997; Weigel et al., 2000).

As land use within catchments cannot easily be changed, the riparian zone is often recognised as the most relevant scale for river management, with different measures such as grassy or woody buffers intended to prevent run-off of pesticides, nutrients and fine sediments (Lowrance et al., 1997). Additionally, the shading by woody buffers decreases water temperatures and benefits stenothermic biota (Broadmeadow et al., 2011; Ryan et al., 2013), limits the primary production and the effects of eutrophication (Gulis & Suberkropp, 2003). Furthermore, woody buffers enhance the diversity of riparian and instream habitats through the provision of woody debris (Benke et al., 1984; Wallace et al., 1995) and food sources such as leaves (Cummins et al., 1989; Wallace et al., 1997).

While all riverine organism groups can potentially benefit from woody buffers, the effects on macroinvertebrates' assemblages are supposed to be particularly beneficial. Coarse particulate organic matter (CPOM) provided by riparian trees can serve as food (e.g. leaves) or habitat (e.g. woody debris; Flory & Milner, 1999; Hession et al., 2003; McKie & Cranston, 1998; O'connor, 1991, 1992). Through shading and decreasing water temperature, primary production and periphyton growth are impacted (Bunn et al., 1997, 1999; Mackay & Marsh, 2005), thus changing the availability of food sources for different feeding types. For macroinvertebrate species having an aerial life stage, woody buffers act as terrestrial habitat for reproduction, migration or resting. In particular, sensitive groups such as Ephemeroptera, Plecoptera and Trichoptera (EPT) may benefit from the lower temperatures and thus higher oxygen due to shading effect and from improved water quality due to riparian filtration (Jerves-Cobo et al., 2017).

Thus, woody buffers may simultaneously mitigate various stressors acting on benthic invertebrates and significantly contribute to enhancing biodiversity. However, despite the multitude of individual studies at the reach scale, the effects of woody buffers on benthic invertebrates have only recently been considered in large-scale analysis by studying the effect of losing woody buffers in tropical regions (Dala-Corte et al., 2020). In Europe, where large parts of the riparian areas have been used for agriculture or converted to build-up area, national or regional scale, including multiple catchments, studies investigating the effects of catchment-scale land use and of the remaining woody riparian buffers on biodiversity are missing. Such an investigation needs to consider several anthropogenic disturbances that act simultaneously, from catchment to site scales, including their interactions (Munns, 2006). Structural equation modelling is increasingly used and has proven efficient in identifying the pathways through which land use impacts the functional structure of fish assemblages, necessary to inform managing decisions at the right level (Leitão et al., 2018). However structuring such models requires many data often not available on a larger regional scale. Thus, finding trade-offs between precise pathways and assessing general relationships at a national scale remain challenging.

Here, we used a large dataset of 1082 sampling sites from French rivers to investigate both the direct and indirect (e.g. through modified river hydromorphology or physico-chemistry) effects of woody buffers on macroinvertebrate metrics with PLS-pm. We related the effects of woody buffers to the effects of a wide array of stressors at the catchment, riparian and local scales. Against their well-documented beneficial effects at the local scale, we expected a strong positive effect of woody buffers on macroinvertebrate metrics, both direct and indirect, in particular on the share of EPT. Furthermore, we aimed to determine if local woody buffers offer a sufficient solution or if continuous afforestation is needed to mitigate human pressures. Calcareous and siliceous rivers differ in their overall nutrient conditions (Krueger & Waters, 1983), siliceous rivers being generally poorer and more sensitive to physico-chemical disturbances (Villeneuve et al., 2018). As several of the pathways relating to catchment land use, as well as woody buffers and biota, depend on physical and chemical conditions within the catchment, we further expected differences in the effects of the different stressors between calcareous and siliceous river types and therefore considered both river types separately.

2 | MATERIALS AND METHODS

2.1 | Data source

The dataset used in this study was extracted from the French nationwide survey network database (RCS, in Naïades) storing standardised macroinvertebrate samples' results for the surveyed sites (short river reach on which macroinvertebrates are sampled). This study, therefore, did not require any ethical approval. We used data recorded between 2007 and 2013, excluded sites in ecoregions with highly specific character, such as the Mediterranean or high mountain regions (all sites considered are located at altitudes below 450 m a.s.l.), and limited the analysis to sites located in small- and medium-sized rivers (Strahler order 1–6). The resulting dataset is composed of 1082 sites (mostly one site per stream), 613 of which are in calcareous rivers and 469 in siliceous rivers (Figure 1).

In the French survey process, macroinvertebrates were sampled according to a standardised protocol (AFNOR, 2009). Twelve sample units were defined per site, based on predefined mesohabitat types, and sampled with a standardised Surber net. Macroinvertebrates were sorted, counted and identified to a predefined taxonomic level, that is, genus level except for Oligochaeta, some Diptera (mainly family), Trichoptera Limnephilidae, Coleoptera Dytiscidae and Hydrophilidae (subfamily). From the resulting taxa lists, the following metrics were calculated: abundance (i.e. share in the community) and diversity (i.e. taxa number) of EPT, and the I2M2 index (Mondy et al., 2012). The multimetric I2M2 index is the official French system to assess the ecological quality of streams for the Water Framework Directive. To avoid rare species effects in raw counts of taxa, we used the average value of the metrics.

For each site, several environmental data were compiled. The woody buffers were extracted from BD TOPO® (IGN) at two scales: The woody buffer at the local scale corresponds to the share of woody vegetation within an area of 30-m width and 500-m length (i.e. 250-m upstream and 250-m downstream of the studied site). The woody buffer at the upstream scale corresponds to the share of woody vegetation within an area of 30-m width and 5,000-m length upstream of the studied site, including tributaries. The 30-m width is a commonly used buffer for the riparian forest (Van Looy et al., 2013).

Land use data were extracted from the 2006 Corine Land Cover database (European Environment Agency, 2007). We used five pooled categories: urban areas (i.e. urban elements and roads), wetlands (i.e. lakes, ponds and rivers), croplands, grasslands and forests. For each study site, we computed the land use at two scales: to assess the site-scale riparian land use (hereafter local land use) possibly affecting sites' physical and chemical characteristics (Allan et al., 1997), we used a 30-m radius buffer around the sampling site; at the catchment scale, the land use within the subcatchment from river source to the sampling site was calculated.

Physico-chemical data were obtained from the French surveillance network RCS. We considered the monthly measurements of concentrations (mg/L) of suspended matters, ammonium, nitrite, nitrate, phosphorus and dissolved oxygen. We calculated the average concentrations over the 11 months preceding the macroinvertebrates sampling.

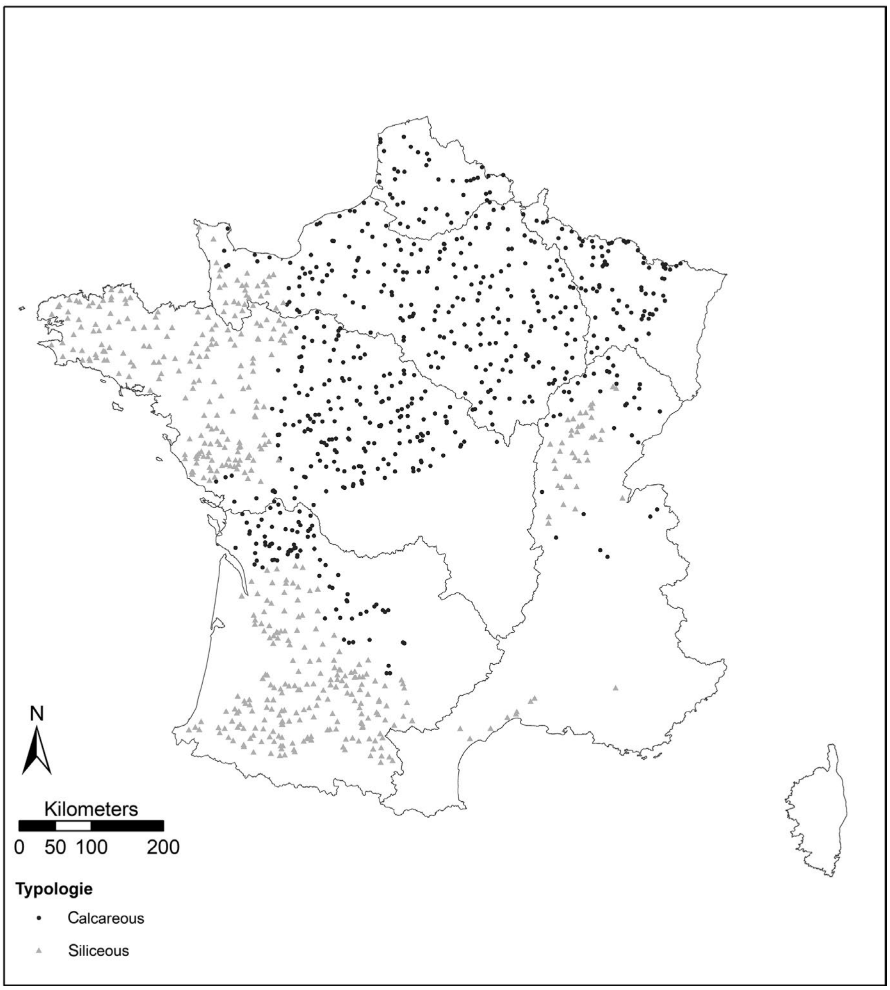

FIGURE 1 Map of the studied sites in France

We considered hydromorphological variables potentially affecting the hydromorphological functioning of the river: straightness rate of the watercourse, the number of crossings (e.g. bridges), the mean number of dams and weirs per kilometre and the number of pumping facilities per catchment surface unit (km²). There is no database on individual hydromorphological modification or impact on every river; therefore, all of these variables are considered as proxies (e.g. crossings are usually protected with embankments) for these modifications and were calculated from the BD TOPO® (3D vector description of the elements of the territory and of its infrastructures, of metric precision, exploitable on scales ranging from 1:5000 to 1:50000; IGN).

In addition to the pressure data, we included Strahler order and the subcatchment size upstream of the sampling site into the analysis.

2.2 | Data analysis

Different methods have emerged recently to study the relative stressor effects on macroinvertebrate communities (Damanik-Ambarita et al., 2018), among which partial least square path modelling (PLS-pm; Wold, 1982, see Appendix S1 in Supporting Information for a short description) has proven efficient to consider the hierarchy of scales in linking land use to environmental variables and eventually to biodiversity (Riseng et al., 2011), and to classify the importance of links and interactions between these groups of variables (Lange et al., 2014). PLS models were computed in the XLSTAT software (v. 2019.2.1, https://www.xlstat.com).

Based on this method, we developed models (Figure 2) linking the latent variables of (a) land use at the catchment scale, (b) land use at the local scale, (c) share of woody buffers at the upstream scale, (d) share of woody buffers at the local scale, (e) physico-chemical conditions, (f) hydromorphological alterations and (g) the river's characteristics to macroinvertebrate metrics.

These latent variables represent the main factors proven to have effects on macroinvertebrates' communities. Land use and local land use are usually considered as 'overarching stressors' (Death & Collier, 2010) as they drive different stressors such as increased run-off (Buytaert et al., 2006), sediment inputs and water quality deterioration (Miserendino et al., 2011). Urban cover and cropland particularly generate an overall degradation of biotic integrity indices (Marzin et al., 2013). Woody buffers are hypothesized to have positive effects on stream ecology by controlling water warming and dissolved oxygen concentration through shading effects, or to limiting suspended matters and nutrients incomes. They also provide food and habitats for macroinvertebrates. The alteration of hydromorphological processes at the reach scale directly effects macroinvertebrates' communities by degrading their physical habitats (Dahm et al., 2013; Lamouroux et al., 2004). Lastly, the physico-chemical parameters have a strong direct effect, especially on sensitive taxa, such as EPT (Dahm et al., 2013). Catchment size and Strahler index were used as natural landscape predictors of the biodiversity metrics.

Interactions between these different stressors were considered, introducing indirect effects for the different latent variables when data were available to inform the underlying mechanisms. Catchment land use and local land use explain a part of the observed variations of all the other latent variables (e.g. woody buffer structure depends on agricultural practices, part of the hydromorphological alterations is related to crossing protection, water quality is highly related to land use at the catchment scale) and are therefore considered to have indirect effects on macroinvertebrates through all the other variables. Woody buffers are hypothesised to explain a part of the physico-chemical variables' variations, due to retention effects (Gericke et al., 2020), and of the hydromorphological conditions, due to riparian stabilization. Last hydromorphological conditions influence the physico-chemical conditions, as a modification of the stream morphology can modify the residence time of substances, the self-purification capacity of streams and other internal processes (Baker et al., 2012). All of the necessary data to describe the underlying mechanisms were not available in regional/national-scale databases. Therefore, we maintained the remaining undocumented pathways as the direct pathways. The statistical inference of the PLS-pm allowed then to differentiate the weights of the different pathways. Separate models were run for the two metrics (I2M2 and abundance diversity of EPT) and for calcareous and siliceous rivers. In contrast to I2M2 as a single variable, abundance diversity of EPT final node is built as a latent variable, therefore constructed from the two manifest variables: the abundance and the diversity of EPT. As the different sites belong to different catchments, we considered these as spatially uncorrelated.

3 | RESULTS

The models well explained the variability of the two macroinvertebrate metrics (Table 1). Validation index values ranged from 49% (calcareous rivers; I2M2) to 21% (siliceous rivers; abundance diversity of EPT), with the other two models having a validation index of nearly 40% (siliceous; I2M2: 39%/calcareous; abundance diversity of EPT: 39%). All the Q^2 values were positive, indicating a good predictive capability.

The by far most important direct influence on both metrics was posed by the physico-chemical conditions (35%–60%) and by catchment land use (23%–37%; Table 1), followed by hydromorphology (3%–17%). Physico-chemistry was a particularly good predictor for I2M2 in siliceous rivers (60%), while the effects of catchment land use were most pronounced for EPT in siliceous rivers (37%). Direct effects by woody buffers were generally minor, with both the effects of upstream woody buffers and of local woody buffers, ranging between 1% and 4%. Effects were most pronounced for EPT in calcareous rivers (4% each for local and upstream woody buffers).

In contrast to the direct effects, catchment land use was generally more important than physico-chemical conditions for the

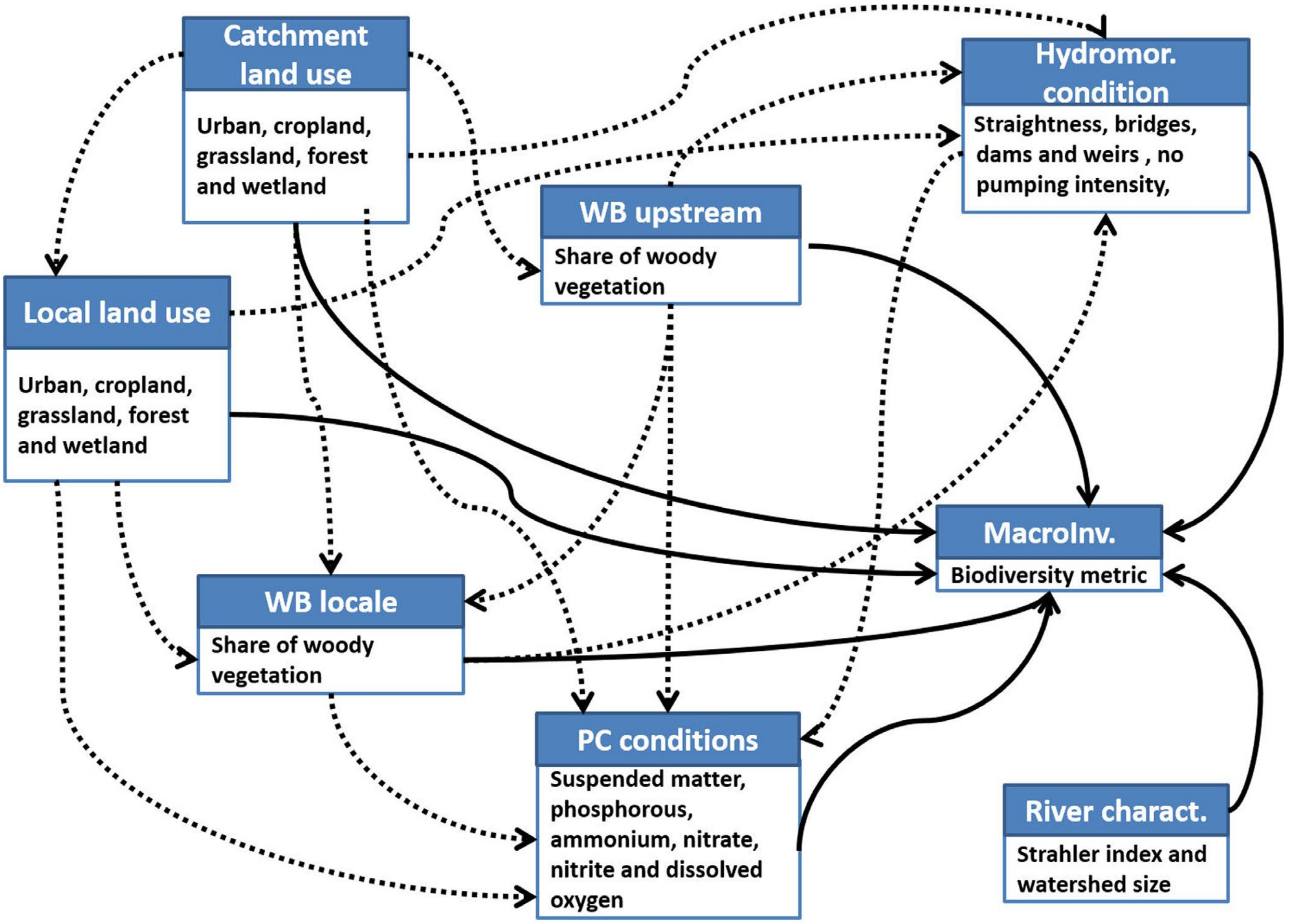

FIGURE 2 Design of the multiscale and multi-stressors structural model. Each latent variable is represented by a coloured box and each direct effect from this latent variable to another is represented by a solid arrow. Indirect effects on the biological response variables are represented by dotted arrows. Each latent variable is a linear combination of the manifest variables listed in the box frame

total effects (direct and indirect effects). For all four models, the total effect of land use ranged between 34% and 48%, while the total effect of physico-chemical conditions dropped to 23%–34%. Hydromorphological conditions remained in the same order of magnitude (5%–15%) than for the direct effects. The total effects of woody buffers ranged between 1% and 6% (woody buffers upstream), and between 1% and 2% (woody buffers local). As for the direct effects, the total effects of woody buffers were strongest for EPT in calcareous rivers (6% each for upstream woody buffers, 2% for local woody buffers).

4 | DISCUSSION

4.1 | General effects of woody buffers on macroinvertebrates

We expected strong positive direct and indirect effects of woody buffers on macroinvertebrate metrics. This was not confirmed. In line with the large catchment analysis from Burdon et al. (2020) showing a positive but weak link between woody riparian integrity and macroinvertebrates communities' integrity, the effects of woody buffers were smaller than expected, with the effects of the upstream woody buffers slightly exceeding the effects of local woody buffers. However, the effects of catchment land use and of physico-chemistry superimpose the effects of woody buffers greatly. Thus, our results somehow contradict the majority of local-scale studies on the effects of woody buffers on macroinvertebrate communities (Couceiro et al., 2007; Iñiguez-Armijos et al., 2014; Lorion & Kennedy, 2009; Nessimian et al., 2008; Rios & Bailey, 2006). At the local scale, there is overwhelming evidence that reducing the width of woody buffers promotes generalists over specialists, such as EPT (Braun et al., 2018; Li & Dudgeon, 2008; Mc Conigley et al., 2017; Tomanova et al., 2006). The reasons for the weak effects of woody buffers in our study remain controversial. Potentially, we could have omitted an important explanatory factor when building the PLS model or have implemented unsuited relationships between the woody buffers' latent variables and the other latent variables. We consider this as unlikely, as the structure has been designed to be in line with the above-cited references. However, a reach-scale study

TABLE 1 Results of PLS model for I2M2 and abundance diversity of EPT for calcareous and siliceous rivers. The first line provides the R^2 of the individual models; other lines show the direct and total effects of the different latent variables on I2M2 and abundance diversity of EPT. Values are percentages of explained variance

	I2M2		Abundance diversity of EPT	
	Calcareous rivers	Siliceous rivers	Calcareous rivers	Siliceous rivers
Validation of the structural model, R^2	49	39	39	21
Direct effect of the latent variables				
Land use (catchment)	24	27	23	37
Land use (local)	7	8	5	< 1
Woody buffers (upstream)	1	< 1	4	< 1
Woody buffers (local)	1	< 1	4	1
Physico-chemical conditions	44	60	35	38
Hydromorphological alterations	16	3	17	13
River's characteristics	7	1	12	11
Total effect of the latent variables				
Land use (catchment)	37	48	33	44
Land use (local)	8	9	6	2
Woody buffers (upstream)	2	1	6	2
Woody buffers (local)	1	1	3	2
Physico-chemical conditions	29	34	23	25
Hydromorphological alterations	15	5	16	13
River's characteristics	7	2	12	11

often uses dedicated observed explanatory variables that do not exist as national-scale databases. Thus, in our model, we included the indirect pathways that were possible to populate with existing databases (e.g. physical and chemical local variables result from land use and woody buffer). The remaining effects not accessible in indirect pathways (e.g. not observed temperature, connectivity, hydrology) could not simply be ignored and were summarised as the remaining direct effects between catchment-scale land use or woody buffers and macroinvertebrates. By construction, this gives more explanatory weight to the highest level of latent variable in the hierarchy. A second option is that the variability of conditions in the spatially broadly distributed dataset has masked the effects of woody buffers. However, the variability of conditions was not reflected in the Strahler order and the sub-catchment size, both of which had only minor effects on the targeted metrics. A third possible explanation is that the gradient in the share of woody buffers might have been too short for significant effects on macroinvertebrates. In other words, the woody buffers present along the vast majority of river sections might not have been sufficiently broad or have covered a sufficiently long river stretch to show large effects on the benthic fauna. This conjecture is in line with several studies highlighting the relevant buffer width required for effects on rivers; for example, a meta-analysis of 222 studies recommends a width of 100 m for high land-use intensity, 70 m for moderate intensity and 40 m for low intensity (Hansen et al., 2010). Fourth, we have not introduced potential legacy effects into the models, due to the lack of historical land use datasets at this very large scale. Legacy effects potentially limit the explanatory power of current catchment and riparian land use, in line with results from Greenwood et al. (2012). Some currently forested catchments in France were not forested in the 1950s (Koerner et al., 2000), which may still affect recent aquatic biota as observed by Harding et al. (1998). This is most frequently relevant for siliceous hilltops (e.g. Brittany), and siliceous plains (e.g. the Landes), providing a possible rationale for the smaller effects of riparian buffers in for siliceous rivers. Fifth, we considered the extent of woody riparian buffers but ignored woody buffer quality and functioning. Beneficial effects of woody riparian buffers on the retention of nutrients, on fine sediments and pesticides and on water temperatures were mainly reported by reach-scale or experimental studies on well-functioning woody buffers that did not consider or even actively excluded confounding factors (Dosskey, 2001; Feld et al., 2018). However, it is well known that preferential flow or drainages bypassing the woody buffers limit retention effects (Dorioz et al., 2006; Dosskey, 2001; Polyakov et al., 2005). As a consequence, the overall effects of woody buffers at the catchment scale, that inevitably include woody buffers of varying quality and limited functionality, are much lower compared to reach-scale or experimental studies (Hill, 2019). Finally, recent afforestation often involved coniferous trees (Koerner et al., 2000) with potential acidification effect and detrimental effect on aquatic communities (Harriman et al., 2003; Ormerod et al., 1989) that can obstruct the recovery of invertebrates' communities (Malcolm et al., 2014). As land use did not differentiate between deciduous and coniferous trees, we were not able to consider this potential confounding effect. Despite these various limiting factors, we detected small positive effects of riparian forest on aquatic invertebrates' communities and on specific sensitive taxa, comforting the overall potential of riparian buffers as managing measure.

4.2 | Riparian buffers can mitigate a small proportion of catchment-scale land use impacts

The overarching effect of catchment land use on macroinvertebrates, as resulting from our analysis, echoes many studies determining the ecological functioning of rivers by hierarchical ordination of possible pressures (e.g. Allan, 2004; Poff et al., 1997; Roth et al., 1996; Thorp, 2014; Wasson et al., 2002). Concerning EPT, effects at the catchment scale are often more important than effects at the local scale (Burt et al., 2010; Miserendino et al., 2011). High shares of grassland, forest and wetland favour EPT taxa, while high shares of cropland and urban area are detrimental. Numerous studies have shown that land use pressures like agriculture and urbanization have a negative impact on water quality at the reach scale (Allan, 2004; Hering et al., 2013; Lorenz & Feld, 2013; Robinson et al., 2014), for example, through reducing oxygen contents (Ding et al., 2017). In contrast, forested catchment has a positive effect. Death and Collier (2010) showed that rivers having a catchment covered with 40%–60% of forests conserved 80% of freshwater macroinvertebrate diversity. The catchment-scale forest has also an impact on local water temperature and Dohet et al. (2015) showed that some cold stenothermic Trichoptera species were only detected in forested catchments. Finally, forest can reduce the loadings of suspended matters like fine sediments, a benefit to sensitive EPT taxa (Feld, 2013). Nevertheless, our results show that even though land use effect remains clearly dominant on explaining the observed biodiversity, implementing riparian buffers should have a positive effect on both the general quality index and specialised taxa.

4.3 | An ideally continuous woody riparian corridor has higher positive effects and longer buffer stretches should be implemented

We observed that the total effect of upstream woody buffer cover is more important than the effect of local woody buffers. Several beneficial effects of woody buffers are likely to act only on longer river stretches, while the effects of very local buffers might be superimposed by the stressors acting upstream. Orlinskiy et al. (2015) found that upstream woody buffers limited the effects of pollution on downstream freshwater macroinvertebrate populations. Likewise, upstream woody buffers have an impact on the water temperature downstream and a 100-m section of woody buffers can reduce temperature by up to 1°C compared to an open river (Kristensen et al., 2013). Thus, it appears that managing woody buffers at the catchment scale and maintaining or enabling a large proportion of wood cover in the 30-m corridor over longer upstream stretches (ideally a full cover), limiting the impact of pollution and preventing its spread (Osborne & Kovacic, 1993), is preferable for macroinvertebrates, rather than local woody buffers in unforested upstream reaches.

4.4 | Riparian buffers are more efficient for calcareous river types

We expected differences in the effects of woody buffers (as well as in the effects of stressors) between river types. This expectation was confirmed. Catchment land use and physico-chemistry had the highest total effects on both I2M2 and EPT for siliceous rivers. These results are in line with Villeneuve et al. (2018), who observed similar differences between calcareous and siliceous rivers. Calcareous and siliceous rivers differ fundamentally in ecological functioning and the effects of pressures. Calcareous rivers are more productive (Hill & Webster, 1982). Conversely, a lower primary production evokes a lower secondary production for siliceous rivers (Cross et al., 2006). This often results in more nutrient-poor conditions in siliceous rivers, which are therefore more vulnerable to physico-chemical disturbances while calcareous rivers with a higher primary production and a more stable secondary production are more resistant to physico-chemical disturbances (Villeneuve et al., 2018). In this study, the total effects of local and upstream woody buffers were higher for calcareous rivers, especially for EPT diversity but remained rather low at this broad scale. Our results underline that woody buffers are not able to mitigate catchment disturbances, especially for the most sensitive siliceous river ecosystem, which should therefore be managed at the catchment scale to reduce the overall upstream impacts. Woody buffers have a higher potential to mitigate impacts in calcareous rivers, and the establishment of woody riparian corridors should therefore be prioritized in calcareous regions.

4.5 | Conclusion and management summary

Our results indicate that the establishment of local woody buffers is not necessarily a sufficient measure to solve the problem of deteriorating riverine macroinvertebrate communities, at least not at large (i.e. country-wide) scales and in intensively used agricultural landscapes. If macroinvertebrate communities are strongly affected by pollution or by intense catchment land use, the establishment of local woody buffers is likely to have minor effects. This does not preclude, however, that woody buffers may be beneficial for macroinvertebrates at the local scale, as there is an overwhelming support in the literature for this conjecture.

Therefore, our study identified two main rules in order to enhance the local effects of woody buffers on macroinvertebrates biodiversity: (1) Effects of upstream woody buffers are larger than those of local woody buffers, and woody buffers should be established continuously along longer stretches of rivers. (2) The establishment of woody buffers needs to be accompanied by measures targeting the effects of intense land use and of pollution, to decrease them below a level that continuous woody buffers can mitigate, especially for the most sensitive siliceous river ecosystems.

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CONFLICT OF INTEREST

None of the authors have a conflict of interest.

AUTHORS' CONTRIBUTIONS

All authors jointly conceptualised the study. M.L.G. compiled and analysed the data with support from M.P. and J.P. The manuscript was written by M.L.G., with support of J.P. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

Data available via the data INRAE repository https://doi.org/10.15454/QY4UVN (Piffady, 2020).

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