Benjamin Kupilas, Brendan G. McKie, Kathrin Januschke, Nikolai Friberg, Daniel Hering.
Stable isotope analysis indicates positive effects of
river restoration on aquatic-terrestrial linkages.
Ecological Indicators. Volume 113, June 2020, 106242. ISSN 1470-160X.

The article has been published in final form by Elsevier at
http://dx.doi.org/10.1016/j.ecolind.2020.106242

Stable isotope analysis indicates positive effects of river restoration on aquatic-terrestrial linkages

Benjamin Kupilas*[1,2,3], Brendan G. McKie[4], Kathrin Januschke[3], Nikolai Friberg[1,5,6], Daniel Hering[3]

[1] Norwegian Institute for Water Research, Gaustadalléen 21, NO-0349 Oslo, Norway

[2] Institute of Landscape Ecology, University of Münster, Heisenbergstr. 2, D-48149 Münster, Germany

[3] Department of Aquatic Ecology, University of Duisburg-Essen, Universitätsstr. 5, D-45141 Essen, Germany

[4] Department of Aquatic Sciences & Assessment, Swedish University of Agricultural Sciences, P.O. Box 7050, SE-75007 Uppsala, Sweden

[5] Freshwater Biological Section, Department of Biology, Universitetsparken 4, 3rd floor, 2100 Copenhagen, Denmark

[6] water@leeds, School of Geography, Leeds LS2 9JT, UK

* Author of correspondence

Email: benjamin.kupilas@niva.no

Abstract

Hydromorphological river restoration can significantly alter habitat configuration and modify invertebrate assemblages of rivers and floodplains. However, the consequences of these changes for ecosystem functioning and aquatic-terrestrial interactions are not known. As a restored shoreline has a more heterogeneous structure compared to a straightened river, restoration is likely to impact aquatic-terrestrial linkages in multiple ways, which might be captured based on biomarker indicators to characterize changes in food web functioning. We conducted a large scale comparative study targeting eleven river restoration projects in central and northern Europe to assess effects of river restoration on trophic patterns across the aquatic-terrestrial interface. We investigated the isotopic composition ($\delta^{13}C$, $\delta^{15}N$) of prey and of invertebrate consumers stratifying between the aquatic, riparian and terrestrial zones. The isotopic distance of riparian arthropods to instream macroinvertebrates and terrestrial arthropods was used as a measure of trophic linkage, and its variation with riparian habitat composition was quantified. Restoration enhanced aquatic-terrestrial linkages, indicated especially by differentiation in the $\delta^{15}N$ isotopic signatures between aquatic, riparian and terrestrial consumers, rather than by $\delta^{13}C$ signatures. The $\delta^{15}N$ isotopic signatures of riparian arthropods revealed a higher relative trophic position in restored sections ($\delta^{15}N_{Restored}$: 8.64‰, $n = 11$) as compared to non-restored sections ($\delta^{15}N_{Degraded}$: 8.05‰, $n = 11$), lending support to the conjecture that restoration increased the proportion of more highly enriched aquatic prey ($\delta^{15}N_{Restored}$: 10.01‰; $\delta^{15}N_{Degraded}$: 10.38‰) while simultaneously reducing the share of lower enriched terrestrial prey ($\delta^{15}N_{Restored}$: 4.88‰; $\delta^{15}N_{Degraded}$: 5.53‰). Riparian habitat diversity and the share of exposed sand and gravel bars were positively related to the strength of aquatic-terrestrial linkages ($R^2 = 0.28$ and $R^2 = 0.31$, respectively), pointing to the importance of habitat diversification in the riparian zone in promoting trophic linkages between river and floodplain. These findings expand our understanding of the multifaceted outcomes of hydromorphological restoration, beyond biodiversity in the aquatic environment. It highlights the need to expand our current set of indicators in order to mechanistic understand restoration effects on ecological networks spanning across boundaries. This knowledge is highly relevant for the large restoration efforts driven by legislative frameworks such as the Water Framework Directive in Europe.

Keywords: *restoration assessment, functional indicators, habitat diversity, food webs, riparian buffer, macroinvertebrates*

1. Introduction

The hydromorphology of most European rivers has been degraded by straightening, damming and removal of riparian vegetation (EEA, 2018). Measures to improve river and floodplain habitat diversity (hereafter referred to as "hydromorphological restoration") are increasingly undertaken to enhance aquatic and riparian biodiversity and ecosystem functioning (e.g., Jähnig et al. 2010, Januschke et al. 2014, Poppe et al. 2016). The assessment of restoration success or failure has mainly focused on hydromorphological features and on the composition of different riverine communities (e.g., Kail et al. 2015, Hasselquist et al. 2018), including fish (e.g., Schmutz et al. 2015, Thomas et al. 2015, Göthe et al. 2019) and macroinvertebrates (e.g., Sundermann et al. 2011, Pilotto et al. 2018), as well as on riparian communities (Göthe et al 2016), while other aspects such as hydro-geochemical processes measured using stable isotopes (Schulte et al. 2011, Mader et al. 2018) and ecosystem functioning has been rarely considered (Kupilas et al. 2017, Frainer et al 2018). In Europe, the focus on instream structural measures is grounded in the Water Framework Directive (WFD), where the deviation of these communities from a reference condition is the center of ecological status assessments (Hering et al. 2010, Friberg 2014). Nevertheless, several studies have revealed that riparian biota is positively affected by restoration, e.g., through increasing species richness and abundance of riparian carabid beetles (Jähnig et al. 2009, Januschke et al. 2014, Januschke & Verdonschot 2016). A major driver of change is the provision of a greater diversity of riparian habitats, such as unvegetated sand and gravel bars, along the river channel.

The use of assemblage composition as an indicator of restoration success, however, has some important limitations, since it does not necessarily reveal pathways between restoration measures and biotic effects, and is only indirectly related to ecosystem functioning. Direct measurements of ecosystem functioning may provide additional and more direct insights into cause-effect-chains between restoration and its effects on an ecosystem level, thus allowing for more targeted restoration planning (Frainer et al. 2018). Furthermore, functional aspects may be more sensitive than classical, community-based parameters. Kupilas et al. (2016) observed changes in the trophic structure of macroinvertebrate communities associated with river restoration, while species richness and diversity of the same communities remained unaffected (Verdonschot et al. 2016). Contrasting responses of functional measurements and community composition have also been observed in the context of environmental impact assessments (e.g., Friberg et al. 2009, McKie & Malmqvist 2009, Niyogi et al. 2013). While functional aspects may complement the monitoring of river restoration measures, and lead to a better mechanistic understanding of restoration effects (Young et al. 2008, 2009, Palmer & Febria 2012, Woodward et al. 2012, Friberg 2014), they are still rarely implemented (Palmer et al. 2014).

The assessment of the success of restoration measures leading to changes in both instream and riparian habitats is particularly challenging, requiring consideration of changes in food web configuration and ecosystem functioning in a broader ecological network crossing habitat boundaries (Truchy et al. 2015, Bruder et al. 2019). Changes in food web architecture (e.g., connectance, trophic complexity, trophic position, trophic niche of consumer groups) can be used to track stressor impacts (Bruder et al. 2019), e.g. the intensity of droughts (Ledger et al. 2013), and ecosystem fragmentation (Layman et al. 2007a). However, the interplay between degradation, restoration and food web properties remains poorly understood.

An important component of food webs in riverine landscapes that is likely to be affected by both instream and riparian restoration is the flow of materials, carbon and nutrients from land to water and vice versa. Previous studies have documented increased retention of terrestrial leaf litter in rivers following habitat restoration (Lepori et al. 2005, Flores et al. 2011), and an increased usage and uptake of terrestrially derived C into aquatic food webs (Kupilas et al. 2016, Frainer et al. 2018). However, less research attention has been given to the effects of riverine restoration on terrestrial food webs and the flow of energy and nutrients from water to land. In particular, rivers can be an important source of energy and nutrients for riparian biota such as predaceous ground beetles and spiders, through consumption of the emerging adults of aquatic insects and drifting aquatic organisms accumulating along the shoreline (Hering & Plachter 1997, Collier et al. 2002, Paetzold et al. 2005). Since the flux of biomass between the river and its riparian zone is determined by habitat structure (Baxter et al. 2005, Paetzold et al. 2005, Burdon & Harding 2008, Carlson et al. 2016), hydromorphological restoration may promote food web connectivity. Specifically, a restored heterogeneous shoreline structure, with a shallow river profile and without bank fixations, may enable riparian arthropods to stay close to the river channel and to more effectively prey on both the adult stages of aquatic organisms, and surface drifting aquatic organisms washed ashore.

To assess effects of hydromorphological restoration on trophic connectivity between water and land, we conducted a large-scale comparative study targeting eleven river restoration projects in central and northern Europe. We analyzed stable isotopes (δ^{13}C and δ^{15}N) for invertebrate taxa collected in three spatially-explicit zones: in the stream channel (instream macroinvertebrates), within a one meter strip along the shoreline (hereafter referred to as “riparian arthropods”), and in less dynamic, higher elevated habitats adjacent to the riparian zone (hereafter referred to as “terrestrial arthropods”). Our overall aim was to use stable isotopes as indicators of connectance between rivers and their riparian zones and to elucidate how restoration interventions influenced this link.

We used stable isotope composition of carbon and nitrogen (δ^{13}C, δ^{15}N) and trophic fractionation, i.e. the enrichment or depletion in δ^{13}C and δ^{15}N between diet and consumer, to elucidate food web responses to restoration. The trophic fractionation of δ^{13}C is low, changing only 0-1‰ from source to consumer and the fractionation of δ^{15}N is usually about 3‰ (Post 2002, Brauns et al. 2018). Based on this isotopic shift between prey and predator, δ^{15}N is generally used to characterize the trophic position of a consumer in a food web and δ^{13}C can be used to identify the ultimate carbon sources for an organism (Post 2002). Rather than an exhaustive quantification of different potential basal resources in the aquatic and terrestrial habitats, our analyses focussed on detecting shifts in the position of the organisms in isotope space (i.e., a δ^{13}C-δ^{15}N biplot where species are plotted based on their stable isotope signatures; Layman et al. 2007b). A special focus was on the position of riparian arthropods in isotope space following restoration to explore their potential as an indicator of restoration effects. We calculated the relative position of riparian arthropods to instream macroinvertebrates and to terrestrial arthropods in isotope space as a measure of trophic linkage. Our hypotheses were: (i) Isotopic signatures of riparian arthropods in restored reaches show evidence for an increased trophic linkage between river and land; i.e., increased distance to terrestrial arthropods reflecting a smaller share of terrestrial prey, and higher similarity to instream macroinvertebrates reflecting an increased use of aquatic resources. (ii) Riparian habitat diversity and the presence of unvegetated side bars are positively related to the strength of aquatic-terrestrial linkages as reflected by isotopic distance.

2. Methods

2.1 Study sites

We investigated the isotopic composition of consumers in aquatic, riparian and terrestrial habitats associated with eleven restoration projects conducted across central and northern Europe (Fig. 1, Table 1, Muhar et al. 2016), encompassing both medium-sized lowland rivers and medium-sized mountain rivers (mean discharge: 10 to 60 m^3/s). Along each river, we selected a representative sampling reach at the downstream end of a restored river section (R) and compared it to a non-restored, hydromorphological degraded “control section” (D) located upstream of the restored section. Both sections within each river had previously been similar to one another, prior to application of the restoration measures (Hering et al. 2015, Muhar et al. 2016). As the distance between restored and degraded river sections was small compared to overall river size (2.8 km, n = 11), background shifts in isotopic composition between the sections (e.g. arising from differences in geology or vegetation) unrelated to the restoration are unlikely. Detailed information about the restoration measures and environmental characteristics of the rivers is given by Muhar et al. (2016).

2.2 Sample collection, preparation and laboratory analysis

Study reaches were sampled in summer 2012 and 2013 (Table 1). At each sampling reach, invertebrates were collected in three spatially-explicit zones to obtain an overview of the isotopic signatures across the aquatic- terrestrial interface (Fig. 2): instream macroinvertebrates, riparian arthropods and terrestrial arthropods. Restored and degraded sections were always sampled in the same field campaign. From the instream habitats, we collected individuals of the dominant instream macroinvertebrate taxa representing different functional feeding groups (FFG; grazer, shredder, collector, predator; Appendix 1), to infer isotopic signals of potential aquatic food sources of riparian arthropods. For insect taxa we targeted late-instar larvae, reflecting the isotopic composition of an aquatic insect at the time close to emergence, and thus most closely represent the composition of the adult stage prone to predation by riparian arthropods (Paetzold et al. 2005). For hololimnic species larger individuals were targeted. The sampling of instream macroinvertebrates is described in more detail by Kupilas et al. (2016). Multiple individuals of each species were pooled to get sufficient biomass for a sample, and where possible, enough for technical replication.

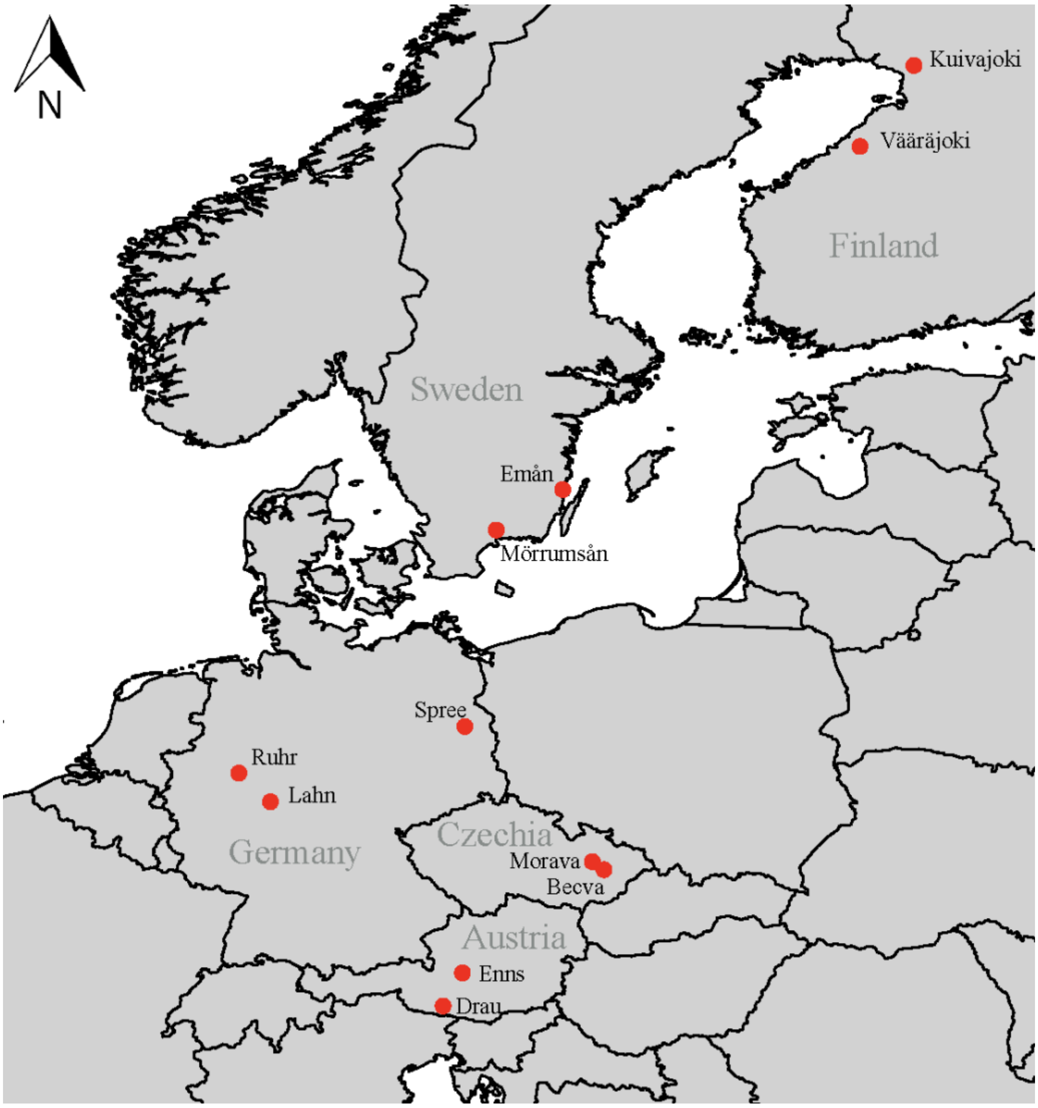

Fig. 1: Location of the restored sections.

Table 1: Overview of restored study reaches based on data by Muhar et al. (2016).

Site name	FI_R1	SE_R1	DM_R1	CZ_R1	AT_R1	FI_R2	SE_R2	DL_R2	DM_R2	CZ_R2	AT_R2
Country	Finland	Sweden	Germany	Czech Republic	Austria	Finland	Sweden	Germany	Germany	Czech Republic	Austria
River name	Vääräjoki	Emån	Ruhr	Becva	Drau	Kuivajoki	Mörrumsån	Spree	Lahn	Morava	Enns
River type	Gravel-bed	Gravel-bed	Gravel-bed	Gravel-bed	Gravel-bed	Gravel-bed	Gravel-bed	Sand-bed	Gravel-bed	Gravel-bed	Gravel-bed
Latitude (N)	64.054433	57.149095	51.44093	49.4968975	46.75454	65.6860429	56.336005	52.377747	50.86588	49.6570728	47.42112
Longitude (E)	24.2206639	16.441897	7.96223	17.5211533	13.309393	25.6349874	14.700237	13.878897	8.79088	17.2179975	13.816094
Altitude (m a.s.l.)	60	10	153	232	570	74	87	35	191	218	692
Catchment geology	organic	siliceous	siliceous	siliceous	siliceous	organic	siliceous	siliceous	siliceous	siliceous	calcareous/ siliceous
Mean discharge (m³/s)	9.9	29.3	15.2	16.6	62.6	12.8	12	14	12	17.7	21.5
Stream order	4	6	3	7	7	4	6	6	3	7	5
Ecoregion	Fenno-scandian shield	Fenno-scandian shield	Central Highlands	Hungarian lowlands	Alps	Fenno-scandian shield	Fenno-scandian shield	Central plains	Central Highlands	Hungarian lowlands	Alps
Restoration Length (km)	1.4	0.9	0.75	0.45	1.9	0.4	3.3	0.95	0.24	0.22	0.6
Restoration date	1997-2006	2006-2011	2008	1997	2002-2003	2002-2006	2003-2012	2005	2000	1997	2003-2004
Main restoration action	instream measures	Hydro RivCon (dam removal, naturalise flow regime, fishway construction, salmonid spawning gravel and boulder additions)	riverbed widening	riverbed widening	riverbed widening; (partial removal of bank fixation; initiation of secondary channel; reconnection of one sidearm)	instream measures	Hydro RivCon (increased flow, fishway construction and salmonid spawning gravel additions)	remeandering	riverbed widening	riverbed widening	riverbed widening (partial removal of bank fixation; initiation of one secondary channel)
Time of sampling	August 2012	August 2013	June 2013	September 2012	July 2013	August 2012	August 2013	July 2013	July 2013	September 2012	July 2013

The non-aquatic consumers (*a priori* defined as "riparian" and "terrestrial") either comprised predaceous ground beetles or spiders and were sampled in two separate zones along the study reaches. The first "riparian" zone comprised a one meter strip along the shoreline, representing a zone subject to highly variable hydrological dynamics, and consequently colonized by invertebrates well-adapted to those conditions (e.g., small and flat ground beetles), while the second "terrestrial" zone comprised embankments >1m from the shoreline characterized by less variable hydrological dynamics, and both higher elevated and more densely vegetated than the riparian zone, and often colonized by larger taxa with less specialized habitat preferences (compare Sadler et al. 2004, van Looy et al. 2005, Kedzior et al. 2016). Riparian and terrestrial arthropods were both collected at randomly chosen locations of the study reach using exhausters and forceps. Each sample of riparian and terrestrial arthropods consisted of several individuals to constitute a bulk sample (Appendix 2).

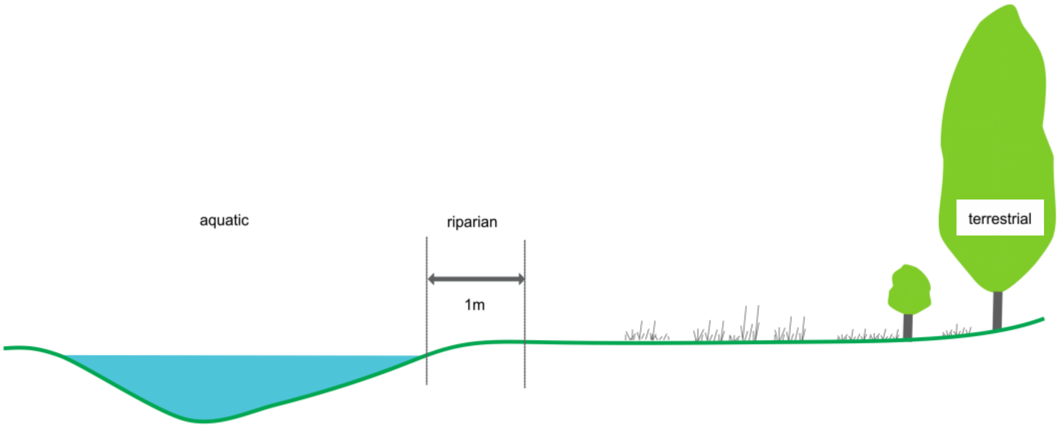

Fig. 2: Schematic overview of aquatic, riparian, and terrestrial habitats sampled at each study reach.

Instream macroinvertebrates, riparian arthropods, and terrestrial arthropods were presorted in the field, counted and kept separate from one another. The samples were transported to the laboratory in a cool box. In the laboratory, specimens were kept individually for 12 to 24 hours to allow for gut evacuation (instream macroinvertebrates were hold in filtered and aerated stream water). Afterwards, the specimens were identified to the lowest level possible (mostly species or genus; Appendix 1 and 2). To prepare samples for stable isotope analysis, we freeze-dried the samples to remove water, and then ground them with mortar and pestle to obtain a homogenized composite sample- Multiple individuals were pooled to get sufficient biomass for a sample, and where possible, enough for technical replication. Depending on the amount of sample material, up to four replicates of each bulk sample from each river section were loaded into tin capsules (~800 µg).

Content of carbon and nitrogen and stable isotopes of carbon and nitrogen were analysed with an elemental analyser (CE Instruments EA 1110 CHNS, Carlo Erba, Milan, Italy) connected via a ConflowIV interface to a Thermo Finnigan MAT 253 isotope ratio mass spectrometer (both Thermo Fischer, Bremen, Germany) at University of Duisburg-Essen's Stable Isotope Facility (Instrumental Analytical Chemistry). Data from the stable isotope analysis are expressed as relative difference between ratios of samples and standards (VPDB for $\delta^{13}C$ and atmospheric nitrogen for $\delta^{15}N$) as described by the equation:

$\delta^{13}C, \delta^{15}N = [(R_{sample}/R_{standard}) - 1] \times 1000$, where $R = {}^{13}C/{}^{12}C$ or ${}^{15}N/{}^{14}N$.

The analytical precision over all measurements (standard deviation from 791 in-house standards) was 0.08‰ for $\delta^{13}C$ and 0.19‰ for $\delta^{15}N$.

2.3 Data analysis

We displayed the isotopic composition of each study reach in $\delta^{13}C$-$\delta^{15}N$-isotope space (Appendix 3). For instream macroinvertebrate communities, we computed the area of a convex hull drawn around all species in isotope space to indicate the isotopic niches occupied by the communities. For further analyses, we calculated mean isotopic values of each community (separately for $\delta^{13}C$ and $\delta^{15}N$; for number of taxa used *cf.* Appendix 1 and 3), reflecting the average isotopic signature of each river; the arithmetic mean of a community is similar to its centroid in isotope space. We used multiple Wilcoxon Matched pair tests (Fowler et al. 1998) between the three organism groups (instream macroinvertebrates, riparian and terrestrial arthropods) to explore the trophic organization across the aquatic-terrestrial interface for the total population of restored and degraded sections (n=22).

To characterize shifts in the position of riparian organisms in isotope space following restoration, we calculated two metrics based on the relative position of groups to each other in the $\delta^{13}C$-$\delta^{15}N$-isotope space: the distance of riparian arthropods to terrestrial arthropods, calculated as riparian arthropods minus terrestrial arthropods; and the distance of riparian arthropods to instream macroinvertebrates, calculated as riparian arthropods minus instream macroinvertebrates. This was done for each investigated section and separately for $\delta^{13}C$ and $\delta^{15}N$. Both metrics provide a measure of the trophic linkage between riparian arthropods and the terrestrial and aquatic system considering trophic fractionation. To quantify the restoration effect, we then compared the isotopic distances of riparian arthropods to terrestrial arthropods and to instream macroinvertebrates between restored and corresponding degraded reaches using Wilcoxon Matched pair tests.

To explore the relationship between riparian habitat composition and the strength of trophic linkages, we extracted data on riparian habitats adjacent to our study reaches compiled by Poppe et al. (2016). Briefly, for each study reach riparian habitats were recorded along ten equidistant transects vertical to flow directions covering the entire floodplain area. The length of each riparian habitat feature was measured and their extent as a proportion of total habitat area was computed. We calculated riparian habitat diversity (Shannon-Wiener Index) based on the habitat composition at each study reach and correlated the resulting habitat diversity to the trophic linkage metrics (i.e. isotopic distances). In addition, the proportion of exposed side bars as key habitats for ground-dwelling riparian arthropods was correlated to the trophic linkage metrics. All statistical analyses were performed in R (Version 3.2.2, http://www.r-project.org/).

3. Results

3.1 Isotopic signatures across the aquatic-terrestrial interface

Isotopic composition of instream macroinvertebrates and terrestrial arthropods revealed a clear differentiation between the aquatic and fully terrestrial taxa (Wilcoxon Matched pair test, $\delta^{15}N$: $P < 0.001$, $\delta^{13}C$: $P < 0.001$, n=22, Fig. 3, Appendix 3), with riparian arthropods taking an intermediate position (Fig. 3). Instream macroinvertebrates were significantly more enriched in $\delta^{15}N$ compared to the terrestrial arthropods, as indicated by the median pairwise isotopic distance between the two groups (+3.7‰; n = 22; equivalent to one trophic level). Riparian arthropods were generally more similar in their δ^{15}N isotopic signatures to instream macroinvertebrates then to terrestrial arthropods (Wilcoxon Matched pair test, δ^{15}N: $P < 0.001$, n=22, Fig. 3 b), indicating a larger proportion of more highly δ^{15}N enriched aquatic prey in their diet. Considering trophic fractionation, the δ^{15}N isotopic signatures of riparian arthropods reflected a mixed diet with a significant proportion of aquatic insects and hence, an intermediate position in isotope space.

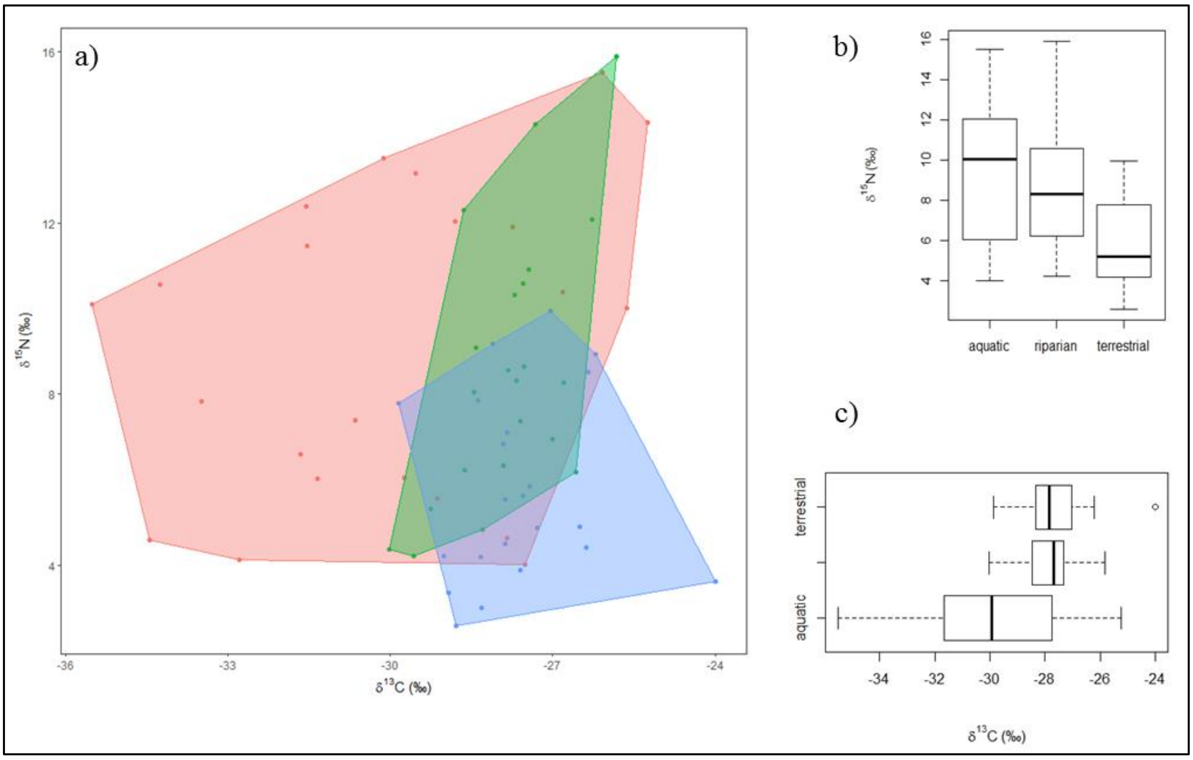

Fig. 3: Trophic organization across the aquatic-terrestrial interface as indicated by mean stable isotope composition (δ^{15}N, δ^{13}C) of invertebrates collected in aquatic, riparian and terrestrial habitats across all study reaches (n=22): a) general distribution of instream macroinvertebrates (red), riparian arthropods (green) and terrestrial arthropods (blue) in isotope space, and pairwise comparison of b) δ^{15}N and c) δ^{13}C isotopic signatures between instream macroinvertebrates, riparian and terrestrial arthropods (Median; Box: 25–75%; Whisker: Min–Max excluding outliers, ○ = Outliers).

Differences in the δ^{13}C signatures were less clear than for δ^{15}N, and indicating substantial overlap in resources across the aquatic-terrestrial interface for the majority of study reaches (compare Fig. 3 c, Appendix 3). Carbon isotope values for instream macroinvertebrates ranged widely, as expected if aquatic invertebrates rely on both aquatic and terrestrial C sources. The δ^{13}C isotopic signatures of riparian arthropods were generally more similar to those of terrestrial arthropods than to those of instream macroinvertebrates (Wilcoxon Matched pair test, δ^{13}C: $P < 0.001$, n=22, Fig. 3 c). Considering trophic fractionation of δ^{13}C, the median of pairwise calculated distances between riparian arthropods and instream macroinvertebrates across all study reaches was still within the range of one trophic level (+1.5‰, n = 22). Overall, there were large differences between study reaches: riparian arthropods were more closely linked to the aquatic habitat in Austria, Germany (mountain) and partly in the Czech Republic and Finland. The majority of study reaches in Sweden, Finland and Germany (lowland) displayed more pronounced differences between riparian arthropods and instream macroinvertebrates (Appendix 3).

3.2 Restoration effect

The $\delta^{15}N$-distance of riparian arthropods to terrestrial arthropods revealed differences between restored and degraded sites (Wilcoxon Matched pair test, $P < 0.05$, n = 11, Fig. 4 a): The $\delta^{15}N$ isotopic signatures of riparian arthropods differed more from those of terrestrial arthropods in restored reaches than in degraded reaches. Accordingly, riparian arthropods in restored reaches have a relatively higher trophic position than in degraded river reaches (as reflected by higher $\delta^{15}N$, Table 2), suggesting an increased proportion of higher $\delta^{15}N$ enriched aquatic prey in the diet of riparian consumers and thus enhanced trophic linkages following restoration. This pattern is further supported by the pairwise comparison between restored and degraded reaches using the $\delta^{15}N$-distance of riparian arthropods to instream macroinvertebrates: although the comparison showed a minor effect (Wilcoxon Matched pair test, $P = 0.08$, n = 11), the findings suggest a closer relation between aquatic and riparian biota in restored reaches (Fig.4 b). No clear pattern regarding effects of restoration emerged using $\delta^{13}C$-distances of riparian arthropods to terrestrial arthropods and instream macroinvertebrates.

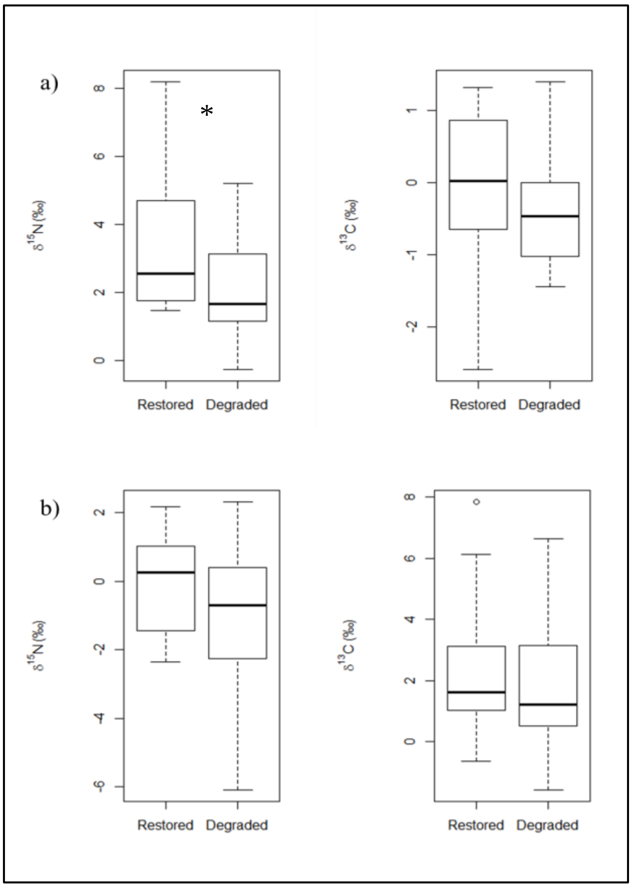

Fig. 4: Pairwise comparison of the isotopic distances of riparian arthropods to a) terrestrial arthropods and b) instream macroinvertebrates between restored and corresponding degraded study reaches (Median; Box: 25–75%; Whisker: Min–Max excluding outliers, ○ = Outliers): Significant differences (*P* < 0.05) between pairs are indicated with ***.**

Table 2: Median $\delta^{13}C$ and $\delta^{15}N$ values of consumers in aquatic, riparian and terrestrial habitats separately for restored (R) and degraded (D) study reaches.

	aquatic		**riparian**		**terrestrial**		
	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$	n
R	-30.12	10.01	-27.52	8.64	-27.87	4.88	11
D	-29.53	10.38	-27.82	8.05	-27.84	5.53	11

3.3 Relationship between riparian habitat composition and trophic linkage

There was a positive, though weak, relationship between riparian habitat diversity and our trophic linkage metrics as well as between the proportion of unvegetated side bars and trophic linkage metrics (Fig. 5). We limited our analysis to $\delta^{15}N$-distance of riparian arthropods to terrestrial arthropods that displayed the most pronounced differences between restored and degraded sites.

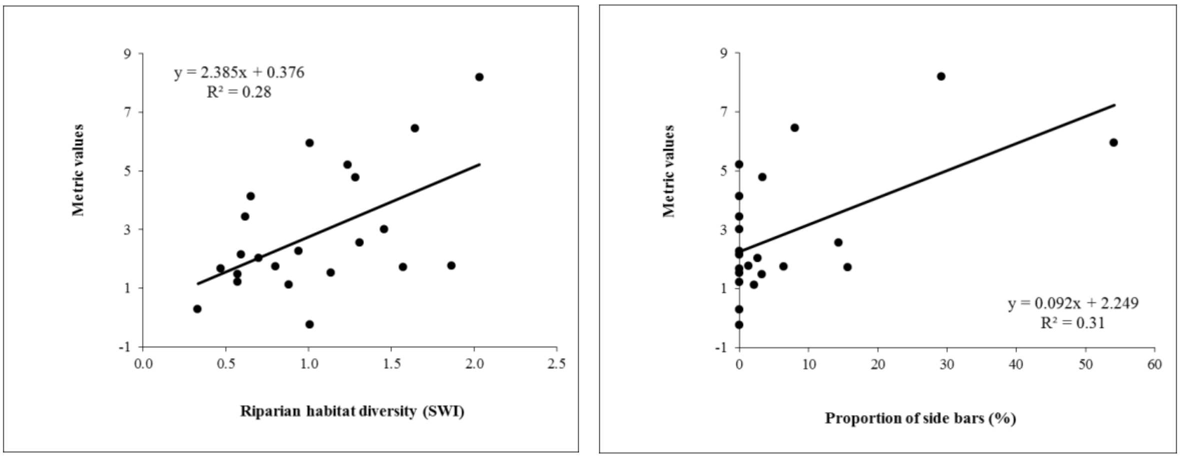

Fig. 5: Relationship between metric values ($\delta^{15}N$-distance of riparian arthropods to terrestrial arthropods in isotope space) and a) diversity of riparian habitats (Shannon-Wiener Index) and b) proportion of unvegetated side bars.

4. Discussion

Our findings reveal that restoration measures targeting riverine habitats affect not only instream food webs (Kupilas et al. 2016), but also trophic linkages between stream food webs and riparian consumers. Hypothesis (i) that hydromorphological restoration favours enhanced aquatic-terrestrial linkages was confirmed across all eleven projects, supported especially by differentiation in the $\delta^{15}N$ isotopic signatures between aquatic, riparian and terrestrial consumers, rather than by $\delta^{13}C$ signatures. Riparian $\delta^{15}N$ signatures revealed a higher trophic position relative to other terrestrial consumers following restoration, indicating decreased use of terrestrial and increased use of aquatic prey. We further observed that the strength of aquatic-terrestrial linkages (as reflected by isotopic distance) is positively related to riparian habitat diversity, pointing to the importance of habitat diversification in the riparian zone in promoting trophic linkages between river and floodplain (confirming hypothesis ii). In general, these findings suggest that hydromorphological restoration results in enhanced trophic linkages between river and riparian zone, attributable especially to the provision of open sand and gravel bars, and to the general diversification of riparian habitats.

4.1 Isotopic signatures across the aquatic-terrestrial interface

We found a clear separation between instream macroinvertebrates and predaceous terrestrial arthropods using stable isotopes ($\delta^{13}C$, $\delta^{15}N$). $\delta^{15}N$ signatures revealed that aquatic communities were approximately one trophic level higher than fully terrestrial arthropods across all 22 study reaches. Riparian consumers also occupy a higher trophic position than terrestrial arthropods, indicating a significant proportion of $\delta^{15}N$ enriched emerging aquatic insects and other stranded aquatic organisms in their diet. Aquatic biomass consumed by riparian arthropods is likely to be transferred further through terrestrial food webs given their importance for terrestrial consumers at higher trophic levels (Jackson & Fisher 1986), although a fraction might also be transferred back into aquatic food webs when riparian consumers fall to the water surface (Baxter et al. 2005). Our large-scale comparison, therefore, supports the role of riparian arthropods as a linkage between river and floodplain biota (Baxter et al. 2005, Paetzold et al. 2005).

4.2 Restoration effect and influence of riparian habitat composition on trophic linkage

Our findings expand our understanding of the multifaceted outcomes of hydromorphological restoration, beyond the aquatic environment. In addition to previous findings that restoration promotes riparian habitat diversification (e.g., Jähnig et al. 2010, Januschke et al. 2011, Poppe et al. 2016), riparian plant diversity (Hasselquist et al. 2018) and riparian arthropod assemblages (e.g., Jähnig et al. 2009, Januschke et al. 2014), our results provide evidence that hydromorphological restoration promotes trophic connectivity between river and floodplain. Aquatic-terrestrial linkages are essential for sustaining biodiversity and ecosystem functioning in riverine landscapes (Nakano & Murakami 2001, Tockner & Stanford 2001, Tockner et al. 2008) and the reciprocal flow of matter between streams and their adjacent riparian zones underpins landscape integrity (Baxter et al. 2005). In particular, emerging adult aquatic insects represent an important prey subsidy for a wide range of riparian consumers such as arthropods, birds, lizards, and bats (Baxter et al. 2005, Burdon and Harding 2008). Our findings indicated a significantly smaller share of terrestrial prey in the diet of riparian arthropods following restoration and suggested a modest increase of aquatic prey. This effect is largely inferred from the $\delta^{15}N$ isotopic signatures of riparian arthropods, rather than changes in $\delta^{13}C$ signatures, as $\delta^{15}N$ signatures revealed a higher relative trophic position of riparian biota following restoration. In terms of $\delta^{13}C$ isotopic signals we observed almost no changes, though $\delta^{13}C$ was originally expected to be a better indicator of changes in resource use (Collier et al. 2002, Post 2002).

Our findings suggest that there was no considerable shift in the use of ultimate carbon resources following restoration and that δ^{15}N patterns were more consistent for describing trophic linkages of riparian arthropods.

Overall, patterns of δ^{13}C across the aquatic-terrestrial interface were inconsistent between river reaches and were independent of their restored or degraded state: in some regions, the sections showed large differences between terrestrial and aquatic δ^{13}C, while others reflected an overlap in δ^{13}C signatures (Appendix 3). These findings suggest that differences in δ^{13}C isotopic signatures between water and land were dictated by regional environmental characteristics and regional differences in community composition rather than restoration measures. One possible reason for a δ^{13}C-overlap across the aquatic-terrestrial interface is the utilization of terrestrial carbon (leaves, wood) by instream invertebrates. Even aquatic biofilms are often "contaminated" with terrestrial carbon (trapped particles, bacteria growing in the biofilm, uptake of DOC of terrestrial origin). Hence, grazing or shredding instream macroinvertebrates may reflect isotopic signatures initially derived from terrestrial carbon instead of aquatic carbon so that riparian consumers can receive terrestrial C both primarily or secondarily, i.e. by consuming aquatic prey that has fed on terrestrial C in the aquatic environment. The use of another isotope (deuterium, δ^{2}H) has recently been highlighted as an application to explicitly determine between allochthonous and autochthonous nutrient sources (Vander Zanden et al. 2016).). In future studies, the use of deuterium isotopes should be considered in order to more clearly differentiate the usage of allochthonous vs. autochthonous resources in linked stream-riparian food webs.

Riparian arthropod predation is concentrated along the shoreline and habitat structure of the riparian zone determines not only composition of riparian arthropod assemblages but also aquatic insect emergence and the accumulation of surface drifting organisms (Hering & Plachter 1997, Hering 1998, Paetzold et al. 2005, Carlson et al. 2016). Open sand and gravel bars are major drivers of aquatic-terrestrial transfers as the boundary between river and shore is open for cross-habitat movements (Paetzold et al. 2005). Furthermore, aquatic insects leaving the water for emergence are particularly vulnerable to predation on open bars providing a minimum of shelter (Hering & Plachter 1997). In line with this, we found a positive relationship between the provision of such habitats and the strength of aquatic-terrestrial linkages. However, we further highlighted that overall riparian habitat diversity is important for the strength of trophic linkages between river and floodplain. Different pathways for aquatic biomass to enter the riparian zone are made available by a diverse shoreline: spaces between stones for insect emergence, small lentic zones prone for stranding of aquatic organisms, and wet soils in which midge larvae (Chironomidae), a preferred prey of small ground beetles of the genus *Bembidion*, dwell (Hering 1998). Moreover, the high share of aquatic prey may simply be explained by the lack of terrestrial prey, which is much more abundant in vegetated zones and by the lack of shelter for emerging aquatic insects. Finally, hydromorphological restoration can affect the composition and dispersal of instream macroinvertebrates and shifts in the adult trait composition of the aquatic invertebrate assemblages can have substantial impact on the subsidy of stream invertebrates to terrestrial food webs (Carlson et al. 2016, McKie et al. 2018).

Our findings provide evidence for an enhanced stream-riparian linkage following restoration. As hydromorphological restoration typically enhances riparian arthropod abundances and species richness in the riparian zone (Günther & Assmann 2005, Lambeets et al. 2008, Jähnig et al. 2009, Januschke & Verdonschot 2016), we can assume that the quantitative energy flow into the terrestrial food web is also increased (i.e., more riparian predators are consuming more aquatic prey). This is in line with numbers of arthropods caught in our study reaches: the three reaches with highest δ^{15}N-distance between riparian arthropods and terrestrial arthropods (indicating a smaller share of terrestrial prey in the diet of riparian consumers) also revealed higher abundances of riparian arthropods in restored compared to degraded reaches. This also applies for the expected increase in aquatic insect biomass as a result of restoration, which can serve as potential prey for riparian predators. Hering & Plachter (1997) and Burdon & Harding (2008) showed positive associations between aquatic insect biomass and riparian predator densities.

4.3 Conclusion

Although hydromorphological restoration primarily addresses biodiversity of aquatic and floodplain habitats, our study highlights that restoration can also affect ecological networks spanning across boundaries. Aquatic-terrestrial connectivity was enhanced following restoration, as revealed by the isotopic signatures of invertebrate in aquatic, riparian and terrestrial habitats. Our findings expand our understanding of the manifold outcomes of river restoration and reveal the necessity to expand our set of indicators used to assess restoration measures. Developing a predictive understanding of ecological responses to environmental change requires a set of structural and functional indicators. Future evaluation of hydromorphological restoration measures should incorporate indicators for food web configuration crossing habitat boundaries to facilitate a mechanistic understanding of ecological responses. Biomarkers including stable isotopes and poly-unsaturated fatty acids can be used to describe the trophic connectivity between stream and riparian food webs. We also saw that riparian habitat diversity is a key factor for promoting trophic linkages between water and land as it enhances the pathways for aquatic biomass entering the riparian zone. From a management perspective, the riparian zone should be more explicitly incorporated into future restoration planning because it acts as the interface for aquatic-terrestrial transfer, provides habitat for various organism groups and provides a wide range of ecosystem services (e.g., flood protection). Sustaining biodiversity becomes increasingly relevant during times of global species decline where freshwaters and floodplains are disproportionately contributing to global biodiversity.

Acknowledgements

This study results from the EU-funded project REFORM (REstoring rivers FOR effective catchment Management), European Union’s Seventh Programme for research, technological development and demonstration under Grant Agreement No. 282656. We acknowledge a PhD fellowship of the German Environment Foundation (Deutsche Bundesstiftung Umwelt, DBU) to B.K. This. Study was supported by NIVA strategic research funds and the Biodiversa project CROSSLINK (BiodivERsA3-2015-49). We are grateful to many colleagues who spent their time sampling in the field and preparing samples and to the staff of the stable isotope facility for analyzing the samples. We would also like to thank two anonymous reviewers, whose helpful comments improved an earlier version of the manuscript.

References

Baxter, C.V., Fausch, K.D. & Saunders, W.C. (2005) Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones. Freshwater Biology, 50, 201–220.

Brauns, M., Boëchat, I.G., de Carvalho, A.P., Graeber, D., Gücker, B., Mehner, T. & von Schiller, D. (2018) Consumer-resource stoichiometry as predictor of trophic discrimination ($\Delta^{13}C$, $\Delta^{15}N$) in aquatic invertebrates. Freshwater Biology, 63, 1240–1249.

Bruder, A., Frainer, A., Rota, T. & Primicerio, R. (2019) The Importance of Ecological Networks in Multiple-Stressor Research and Management. Frontiers in Ecological Science, 7, art59.

Burdon, F.J. & Harding, J.S. (2008) The linkage between riparian predators and aquatic insects across a stream-resource spectrum. Freshwater Biology, 53, 330–346.

Carlson, P.E., McKie, B.G., Sandin, L. & Johnson, R.K. (2016) Strong land-use effects on the dispersal patterns of adult stream insects: implications for transfers of aquatic subsidies to terrestrial consumers. Freshwater Biology, 61, 848-861.

Collier, K.J., Bury, S. & Gibbs, M. (2002) A stable isotope study of linkages between stream and terrestrial food webs through spider predation. Freshwater Biology, 47, 1651–1659.

EEA (European Environment Agency) (2012) European Waters – Assessment of Status and Pressures. EEA 426 Report No. 8, EEA, Copenhagen. 96 pp.

Flores, L., Larranaga, A., Diez, J. & Elosegi, A. (2011) Experimental wood addition in streams: effects on organic matter storage and breakdown. Freshwater Biology, 56, 2156–2167.

Fowler, J., Cohen, L., & Jarvis, P. (1998) Practical statistics for field biology. John Wiley & Sons, Chichester.

Friberg, N., Dybkjær, J.B., Olafsson, J.S., Gislason, G.M., Larsen, S.E. & Lauridsen, T.L. (2009) Relationships between structure and function in streams contrasting in temperature. Freshwater Biology, 54, 2051-2068.

Friberg, N. (2014) Impacts and indicators of change in lotic ecosystems. Wires Water, 1, 513-531.

Frainer, A., Polvi, L.E., Jansson, R. & McKie, B.G. (2018) Enhanced ecosystem functioning following stream restoration: The roles of habitat heterogeneity and invertebrate species traits. Journal of Applied Ecology, 55, 377-385.

Göthe, E., Timmermann, A., Januschke, K. & Baattrup-Pedersen, A. (2016) Structural and functional responses of floodplain vegetation to stream ecosystem restoration. Hydrobiologia, 769, 79-92.

Göthe, E., Degerman, E., Sandin, L., Segersten, J. Tamario, C. & McKie, B.G. (2019) Flow restoration and the impacts of multiple stressors on fish communities in regulated rivers. Journal of Applied Ecology, 56, 1687-1702.

Günther, J. & Assmann, T. (2005) Restoration ecology meets carabidology: effects of floodplain restitution on ground beetles (Coleoptera, Carabidae). Biodiversity and Conservation, 14, 1583–1606.

Hasselquist, E. M., Polvi, L. E., Kahlert, M., Nilsson, C., Sandberg. L. & McKie, B.G. (2018) Contrasting Responses among Aquatic Organism Groups to Changes in Geomorphic Complexity Along a Gradient of Stream Habitat Restoration: Implications for Restoration Planning and Assessment. Water 10, 1465.

Hering, D. (1998) Riparian beetles (Coleoptera) along a small stream in the Oregon Coast Range and their interactions with the aquatic environment. Coleopteran Bulletin, 52, 161-170.

Hering, D. & Plachter, H. (1997) Riparian ground beetles (Coeloptera, Carabidae) preying on aquatic invertebrates: a feeding strategy in alpine floodplains. Oecologia, 111, 261–270.

Hering, D., Borja, A., Carstensen, J., Carvalho, L., Elliott, M., Feld, C.K., Heiskanen, A.S., Johnson, R.K., Moe, J., Pont, D., Solheim, A.L. & Van de Bound, W. (2010) The European Water Framework Directive at the age of 10: A critical review of the achievements with recommendations for the future. Science of The Total Environment, 408, 4007–4019.

Hering, D., Aroviita, J., Baattrup-Pedersen, A., Brabec, K., Buijse, T., Ecke, F., Friberg, N., Gielczewski, M., Januschke, K., Köhler, J., Kupilas, B., Lorenz, A., Muhar, S., Paillex, A., Poppe, M., Schmidt, T., Schmutz, S., Vermaat, P.J., Verdonschot P. F. M., Verdonschot, R., Wolter, C. & Kail, J. (2015) Contrasting the roles of section length and instream habitat enhancement for river restoration success: a field study on 20 European restoration projects. Journal of Applied Ecology, 52, 1518-1527.

Jähnig, S.C., Brunzel, S., Gacek, S., Lorenz, A.W. & Hering, D. (2009) Effects of re-braiding measures on hydromorphology, floodplain vegetation, ground beetles and benthic invertebrates in mountain rivers. Journal of Applied Ecology, 46, 406–416.

Jähnig, S.C., Brabec, K., Buffagni, A., Erba, S., Lorenz, A.W., Ofenböck, T., Verdonschot, P.F.M. & Hering, D. (2010) A comparative analysis of restoration measures and their effects on hydromorphology and benthic invertebrates in 26 central and southern European rivers. Journal of Applied Ecology, 47, 671–680.

Jackson, J.K. & Fisher, S.G. (1986) Secondary production, emergence, and export of aquatic insects of a Sonoran desert stream. Ecology, 67, 629–638.

Januschke, K., Brunzel, S., Haase, P. & Hering, D. (2011) Effects of stream restorations on riparian mesohabitats, vegetation and carabid beetles. Biodiversity and Conservation, 20, 3147–3164.

Januschke, K., Jähnig, S.C., Lorenz, A.W. & Hering, D. (2014) Mountain river restoration measures and their success(ion): effects on river morphology, local species pool, and functional composition of three organism groups. Ecological Indicators, 38, 243–255.

Januschke, K. & Verdonschot, R.C.M. (2016) Effects of river restoration on riparian ground beetles (Coleoptera: Carabidae) in Europe. Hydrobiologia, 769, 93-104.

Kail, J., Brabec, K., Poppe, M. & Januschke, K. (2015) The effect of river restoration on fish, macroinvertebrates and aquatic macrophytes: A meta-analysis. Ecological Indicators, *58*, 311–321.

Kędzior, R., Skalski, T. & Radecki-Pawlik, A. (2016) The effect of channel restoration on ground beetle communities in the floodplain of a channelized mountain stream. Periodicum Biologorum, 118, 171–184.

Kupilas, B., Friberg, N., McKie, B.G., Jochmann, M.A., Lorenz, A.W. & Hering, D. (2016) River restoration and the trophic structure of benthic invertebrate communities across 16 European restoration projects. Hydrobiologia, 769, 105-120.

Kupilas, B., Hering, D., Lorenz, A.W., Knuth, C. & Gücker, B. (2017) Hydromorphological restoration stimulates river ecosystem metabolism. Biogeosciences, 14, 1989-2002.

Lambeets, K., Hendrickx, F., Vanacker, S., Van Looy, K., Maelfait, J.-P. & Bonte, D. (2008) Assemblage structure and conservation value of spiders and carabid beetles from restored lowland river banks. Biodiversity and Conservation, 17, 3133-3148.

Lambeets, K., Vandegehuchte, M.L., Maelfait, J.-P. & Bonte, D. (2009) Integrating environmental conditions and functional life-history traits for riparian arthropod conservation planning. Biological Conservation, 142, 625–637.

Layman, C.A., Quattrochi, J.P., Peyer, C.M. & Allgeier, J.E. (2007a) Niche width collapse in a resilient top predator following ecosystem fragmentation. Ecology Letters, 10, 937- 944.

Layman, C.A., Arrington, D.A., Montana, C.G. & Post, D.M. (2007b) Can stable isotope ratios provide for community- wide measures of trophic structure? Ecology, 88, 42–48.

Ledger, M.E., Brown, L.E., Edwards, F.K., Milner, A.M. & Woodward, G. (2013) Drought alters the structure and functioning of complex food webs. Nature Climate Change, 3, 223-227.

Lepori, F., Palm, D. & Malmqvist, B. (2005) Effects of stream restoration on ecosystem functioning: detritus retentiveness and decomposition. Journal of Applied Ecology, 42, 228–238.

Mader, M., Roberts, A.M., Porst, D., Schmidt, C., Trauth, N., van Geldern, R. & Barth, J.A.C. (2018) River recharge versus O2 supply from the unsaturated zone in shallow riparian groundwater: A case study from the Selke River (Germany). Science of the Total Environment, 634, 374-381.

McKie, B.G. & Malmqvist, B. (2009) Assessing ecosystem functioning in streams affected by forest management: increased leaf decomposition occurs without changes to the composition of benthic assemblages. Freshwater Biology, 54, 2086-2100.

McKie, B.G., Sandin, L., Carlson, P.E. & Johnson, R.K. (2018) Species traits reveal effects of land use, season and habitat on the potential subsidy of stream invertebrates to terrestrial food webs. Aquatic Sciences, 80:15.

Muhar, S., Januschke, K., Kail, J., Poppe, M., Hering, D. & Buijse, A.D. (2016) Evaluating good-practice cases for river restoration across Europe: context, methodological framework, selected results and recommendations. Hydrobiologia, 769, 3-19.

Nakano, S., & Murakami, M. (2001) Reciprocal subsidies: Dynamic interdependence between terrestrial and aquatic food webs. Proceedings of the National Academy of Sciences, 98, 166-170.

Niyogi, D.K., Harding, J.S. & Simon, K.S. (2013) Organic matter breakdown as a measure of stream health in New Zealand streams affected by acid mine drainage. Ecological Indicators, 24, 510–517.

Paetzold, A., Schubert, C.J. & Tockner, K. (2005) Aquatic Terrestrial Linkages Along a Braided-River: Riparian Arthropods Feeding on Aquatic Insects. Ecosystems, 8, 748-759.

Palmer, M.A. & Febria, C.M. (2012) The Heartbeat of Ecosystems, Science, 336, 1393- 1394.

Palmer, M.A., Hondula, K.L. & Koch, B.J. (2014) Ecological restoration of streams and rivers: shifting strategies and shifting goals. Annual Review of Ecology, Evolution, and Systematics, 45, 247–269.

Pilotto, F., Nilsson, C., Polvi, L.E. & McKie, B.G. (2018) First signs of macroinvertebrate recovery following enhanced restoration of boreal streams used for timber floating. Ecological Applications, 28, 587-597.

Poppe, M., Kail, J., Aroviita, J., Stelmaszczyk, M., Giełczewski, M. & Muhar, S. (2016) Assessing restoration effects on hydromorphology in European mid-sized rivers by key hydromorphological parameters. Hydrobiologia, 769, 21-40.

Post, D.M. (2002) Using stable isotopes to estimate trophic position: models, methods and assumptions. Ecology, 83, 703–718.

Sadler, J., Bell, D. & Fowles, A. (2004) The hydroecological controls and conservation value of beetles on exposed riverine sediments in England and Wales. Biological Conservation, 118, 41–56.

Schmutz, S., Jurajda, P., Kaufmann, S., Lorenz, A.W., Muhar, S., Paillex, A., Poppe, M. & Wolter, C. (2015) Response of fish assemblages to hydromorphological restoration in central and northern European rivers. Hydrobiologia, 769, 67-78.

Schulte, P., van Geldern, R., Freitag, H., Karim, A., Négrel, P., Petelet-Giraud, E., Probst, A., Probst, J.L., Telmer, K., Veizer, J. & Barth, J.A.C. (2011) Applications of stable water and carbon isotopes in watershed research: Weathering, carbon cycling, and water balances. Earth-Science Reviews, 109, 20-31.

Sundermann, A., Antons, C., Cron, N., Lorenz, A.W., Hering, D. & Haase, P. (2011) Hydromorphological restoration of running waters: Effects on benthic invertebrate assemblages. Freshwater Biology, 56, 1689–1702.

Thomas, G., Lorenz, A.W., Sundermann, A., Haase, P., Peter, A. & Stoll, S. (2015) Fish community responses and the temporal dynamics of recovery following river habitat restorations in Europe, Freshwater Science, 34, 975–990.

Tockner, K. & Stanford, J.A. (2002) Riverine flood plains: present state and future trends. Environmental Conservation, 29, 308–330.

Tockner, K., Bunn, S.E., Gordon, C., Naiman, R.J., Quinn, G.P. & Stanford, J.A. (2008) Flood plains: critically threatened ecosystems. In Aquatic Ecosystems, Trends and Global Prospects, Polunin NVC (ed). Cambridge University Press: New York; 45–61.

Truchy, A., Angeler, D.G., Sponseller, R.A., Johnson, R.K. & McKie, B.G. (2015) Linking biodiversity, ecosystem functioning and services, and ecological resilience: towards an integrative framework for improved management. Advances in Ecological Research, 53, 55-96.

Vander Zanden, H.B., Soto, D.X., Bowen, G.J. & Hobson, K.A. (2016) Expanding the Isotopic Toolbox: Applications of Hydrogen and Oxygen Stable Isotope Ratios to Food Web Studies. Frontiers in Ecology and Evolution, 4, art20.

Van Looy, K., Vanacker, S., Jochems, H., de Blust, G. & Dufrêne, M. (2005) Ground beetle habitat templets and riverbank integrity. River Research and Applications, 21, 1133–1146.

Verdonschot, R.C.M., Kail, J., McKie, B.G. & Verdonschot, P.F.M. (2016) The role of benthic microhabitats in determining the effects of hydromorphological river restoration on macroinvertebrates. Hydrobiologia, 769, 55-66.

Woodward, G., Gessner, M.O., Giller, P.S., Gulis, V., Hladyz, S., Lecerf, A., Malmqvist, B., McKie, B.G., Tiegs, S.D., Cariss, H., Dobson, M., Elosegi, A., Ferreira, V., Graça, M.A.S., Fleituch, T., Lacoursiere, J.O., Nistorescu, M., Pozo, J., Risnoveanu, G., Schindler, M., Vadineanu, A., Vought, L.B.M. & Chauvet, E. (2012) Continental- Scale Effects of Nutrient Pollution on Stream Ecosystem Functioning. Science, 336, 1438-1440.

Young, R.G., Matthaei, C.D. & Townsend, C.R. (2008) Organic matter breakdown and ecosystem metabolism: functional indicators for assessing river ecosystem health. Journal of the North American Benthological Society, 27, 605-625.

Young, R.G. & Collier, K.J. (2009) Contrasting responses to catchment modification among a range of functional and structural indicators of river ecosystem health. Freshwater Biology, 54, 2155–2170.