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The key role of increased fine sediment loading in shaping macroinvertebrate communities along a multiple stressor gradient in a Eurasian steppe river (Kharaa River, Mongolia)

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Abstract

Aquatic communities across the Eurasian steppe face increasing anthropogenic pressures due to rapid population growth, catchment-wide land-use changes, and climate change. The particular type, intensity, overlay, and legacy of impacts along longitudinal gradients of Eurasian river networks provide a unique setting to investigate ecological responses in identifiable multiple stressor environments. We studied macroinvertebrate communities along the Kharaa River, Mongolia, which display a distinct, downstream gradient of moderate nutrient enrichment, disturbed bank morphology, reduced riparian vegetation, elevated turbidity, increased fine sediment substrate proportions, and fine sediment intrusion into the hyporheic zone. Within the encountered ranges of physical and chemical environmental factors (TP 0.02–0.09 mg/L, TN 0.33–0.96 mg/L, conductivity 167–322 μS/cm, formazin nephelometric units 0.62–5.43) and hyporheic fine sediment intrusion (0.9–1.6 g dry weight [DW]·L^{-1}·day^{-1}) the population densities and biomass of macroinvertebrates were high (5,313 ± 410 individuals/m^2 and 2,656 ± 152 mg DW/m^2) and notably stable. In contrast, macroinvertebrate community structure showed strong and statistically significant negative linear relationships (Pearson's *r*) with turbidity, that is, for taxa richness ($r = -.83$), Shannon index of diversity ($r = -.89$), Evenness ($r = -.86$), the relative abundance of Ephemeroptera, Plecoptera, and Trichoptera (EPT) individuals ($r = -.93$) and relative biomass of hard substrate colonizers ($r = -.86$). The relative biomasses of fine substrate colonizers, as well as Chironomidae and Oligochaeta (both $r = .76$), were positively correlated with mean turbidity values. In addition, the Proportion of Sediment-sensitive Invertebrates (PSI) methodology was adjusted for local application and the resulting index scores followed a similar pattern, with PSI also being significantly correlated ($r = .66$) with the relative abundance of EPT individuals, the latter being the most sensitive macroinvertebrate community index. We conclude that fine sediment load is the key factor for shaping macroinvertebrate community structure in the multistressor setting of the Kharaa River followed by hydromorphological habitat complexity determined by shear stress,

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substrate, and grain size distributions. We suggest that the implementation of effective regional management strategies aiming at the reduction of fine sediment pollution should be given the highest priority.

KEYWORDS
anthropogenic impact, community metrics, continental climate, riverbank erosion, steppe rivers

1 | INTRODUCTION

Historically, Mongolia's low population density and the traditional nomadic lifestyle have caused minimal impact on the countries pristine landscape. However, over the last few decades, rapid economic development has resulted in significant population growth and urbanization, which has subsequently led to the widespread expansion of agriculture and large increases in livestock densities (Demeusy, 2012; Karthe, Chalov, & Borchardt, 2015; Karthe et al., 2014; Maasri & Gelhaus, 2010; Malsy, Flörke, & Borchardt, 2016; Priess, Schweitzer, Wimmer, Batkhishig, & Mimler, 2011). However, the conversion from natural steppe grasslands and riparian river corridors to crop farmland has elevated the risk of topsoil erosion, depending on the type of agricultural practice (Priess, Schweitzer, Batkhihig, Koschitzki, & Wurbs, 2015; Valentin et al., 2008). Larger herds, with their unrestricted access to rivers and riparian vegetation, have caused extensive riverbank and channel erosion (Hartwig & Borchardt, 2014; Hayford & Gelhaus, 2010), with both processes having a high potential to increase the fine sediment loads in adjacent streams and rivers, resulting in an impairment of ecosystem functioning (Hartwig & Borchardt, 2014), which can also impact aquatic biota. The Kharaa River basin is the second most densely populated catchment in Mongolia (9.4 inhabitants/m^2; Gerelchuluun et al., 2012), making it particularly vulnerable to overexploitation. Since the year 2000, livestock numbers in the Kharaa River basin have approximately doubled (Priess et al., 2015), with estimates of 1.5 million head at present (Hofmann, Tuul, & Enkhtuya, 2016). Most of the grazing is concentrated in the riparian and floodplain zones (Hartwig et al., 2016) but has recently expanded to steeper slopes, further increasing the erosion risk (Priess et al., 2015).

In catchments that are dominated by agriculture and livestock grazing, the aquatic community has to cope with multiple pressures that impact their habitat quality (Dudgeon, 2010; Matthaei & Lange, 2016; Wagenhoff, Townsend, & Matthaei, 2012), with the main stressors being nutrient enrichment, elevated fine sediments and water abstraction for irrigation (Matthaei, Piggott, & Townsend, 2010). Although analytical (Extence, Chadd, England, Naura, & Pickwell, 2017) or experimental approaches (e.g., Elbrecht et al., 2016; Magbanua, Townsend, Hagemann, & Matthaei, 2013; Townsend, Uhlmann, & Matthei, 2008; Wagenhoff et al., 2012) are able to help disentangle the effects that are mediated by different stressors or their interactions, in natural systems, the variety of stressor impacts present and their interactions often result in difficulties in their identification (Wagenhoff, Townsend, Ngaire, & Matthaei, 2011). Furthermore, as described by Murphy et al. (2015) fine sediment input is also a natural process which follows the longitudinal gradient along the river continuum (Vannote, Minshall, Cummins, Sedell, & Cushing, 1980) and thus, assessing the effect of additional (anthropogenic) fine sediment pollution is a challenging task. In developed, industrialized countries, rivers are often channelized or structurally impaired for multiple usages (Allan, 2004; Gergel, Turner, Miller, Melack, & Stanley, 2002) and these have the potential to mask or interact with other stressor impacts (Dunbar et al., 2010; Horsák, Bojková, Zahrádková, Omesová, & Helešic, 2009). The conditions in the middle reaches of the Kharaa River basin, where the river channel typically follows its natural hydromorphological dynamics, is characterized by a relatively low population density, large numbers of unfenced multispecies herds, and extensive agricultural areas with low fertilizer application (Hofmann et al., 2016). A longitudinal gradient of human-induced impacts has been identified in the region, thus making it an appropriate study area for investigating the potential effects of multiple stressors and their hierarchies on the resident aquatic macroinvertebrate fauna.

The increased fine sediment input from both point and nonpoint sources is known to have a multitude of consequences on macroinvertebrate communities in both direct and/or indirect ways (Jones et al., 2012; Wood & Armitage, 1997). Responses range from increased drift (e.g., Culp, Wrona, & Davies, 1986; Larsen & Ormerod, 2010a; Matthaei, Weller, Kelly, & Townsend, 2006) and reduced trait diversity (Larsen & Ormerod, 2010b) to reduced taxa richness and/or density (e.g., Kaller & Hartman, 2004; Milner & Piorkowski, 2004; Quinn, Williamson, Smith, & Vickers, 1992; Wantzen, 2006; Yule, Boyero, & Marchant, 2010). In particular, EPT organisms are often reported to be sensitive to increased fine sediment loads in rivers (Angradi, 1999; Bertaso, Spies, Kotzian, & Flores, 2015; Bryce, Lomnicky, & Kaufmann, 2010; Burdon, McIntosh, & Harding, 2013; Freeman & Schorr, 2004; Larsen, Vaughan, & Ormerod, 2009; Mebane, 2001). This fine sediment can directly impact habitat quality and ultimately result in significant changes in the community composition (Larsen et al., 2009). Different case studies focusing on the impacts of fine sediment input caused by mining or construction activities have also reported a decrease in macroinvertebrate abundances and taxa richness (Cline, Short, & Ward, 1982; Milner & Piorkowski, 2004; Quinn, Davies-Colley, Hickey, Vickers, & Ryan, 1992; Wagener & LaPerriere, 1985) and declines in fine sediment specific metrics (Extence et al., 2013). Similar land-use mediated influences on macroinvertebrate communities have also been reported (e.g., Braccia & Voshell, 2006; Harding, Young, Hayes, Shearer, & Stark, 1999; Matthaei et al., 2006; Quinn, Cooper, Davies-Colley, Rutherford, & Williamson, 1997). For instance, the results of Quinn et al. (1997) indicated increased total density while the density of Ephemeroptera, Plecoptera, and Trichoptera (EPT) and the quantitative macroinvertebrate community index was decreased at pasture dominated sites characterized by increased fine sediment loads compared to native forested sites. Other studies, aiming to identify the impacts of catchment urbanization on macroinvertebrate assemblages, have reported increased nutrients, electrical conductivity and turbidity, which, in turn, negatively impact biotic indices such as taxa richness or EPT richness (Roy, Rosemond, Paul, Leigh, & Wallace, 2003). Additionally, strong negative responses in EPT-related metrics to increased deposited inorganic fine sediment resulting from reduced habitat availability have been reported (e.g., Burdon et al., 2013; Larsen, Pace, & Ormerod, 2011; Mathers, Rice, & Wood, 2017; Pollard & Yuan, 2010; Zweig & Rabeni, 2001). Burdon et al. (2013) suggested a critical threshold of 13–20% for surficial sediments, whereas, Shearer and Young (2011) observed that pastured sites had a lower macroinvertebrate community index due to saprobic pollution, compared to sites in native forest areas. However, in contrast, macroinvertebrate community metrics from headwater streams in the United States did not differ (except the percentage of clingers) between low, medium, and high sedimentation categories caused by historical timber harvest activities (Longing, Voshell, Dolloff, & Roghair, 2010).

The aims of the present study were to determine (a) whether macroinvertebrate structural and functional metrics indicate stressor effects on the resident macroinvertebrate communities along an environmental gradient in the middle reach of the Kharaa River, (b) if there is evidence that such effects are a result of single rather than multiple environmental stressors, and (c) if such effects are related to fine sediment (organic and/or inorganic particles) migration and deposition into the upper sediment layers. As a consequence, important ecosystem functioning may have been impacted and thus specific river management recommendations are urgently needed to address these issues with a holistic approach by incorporating them into a river basin management plan within the framework of integrated water resource management in the Kharaa River basin in the near future (Karthe, Heldt, Houdret, & Borchardt, 2015).

2 | MATERIALS AND METHODS

2.1 | Study site

The Kharaa River basin is situated in northern Mongolia, approximately 60 km north of the capital Ulaanbaatar (Figure 1). The Kharaa River is a fourth-order stream, which originates in the western

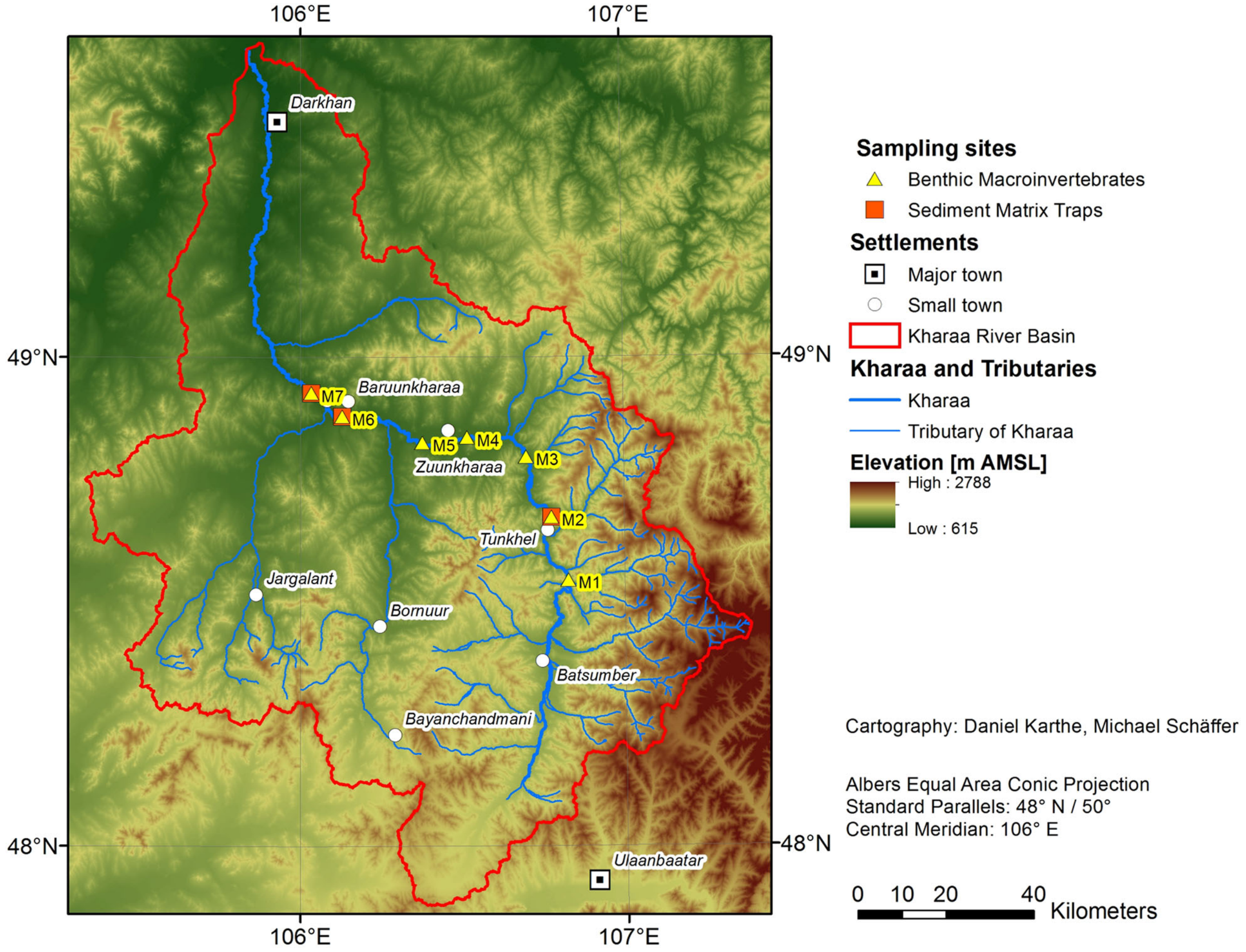

FIGURE 1 Map of the Kharaa River basin. The location of the sampling sites for the macroinvertebrate communities (yellow triangles) and fine sediment infiltration rate (red squares) are displayed

Khentii Mountains (>2,600 m a.s.l.) and flows in a north-westerly direction until converging with the Orkhon River (654 m a.s.l.). The size of the basin is approximately 15,000 km^2 and the length of the main river channel is 362 km. The annual average air temperature in the basin is −0.4°C (Törnros & Menzel, 2010). Between June 2009 and May 2010 the mean water temperature in the middle region was 5.3 ± 1.1°C (± standard deviation [SD]; five sites; 30-min interval; EBI 85-A, Ebro Electronic GmbH & Co. KG, Ingolstadt, Germany). The long-term annual discharge (1990–2008) at the confluence with the Orkhon River was approximately 12 m^3/s. As the river is usually frozen from November to March each year, there is minimal discharge during these winter months and thus the local aquatic communities must endure harsh climatic conditions as a consequence (Avlyush, Schäffer, & Borchardt, 2013; Karthe, Chalov, et al., 2015). Reference should be made to (Hofmann et al., 2015, 2016; Hofmann, Hürdler, Ibisch, Schaeffer, & Borchardt, 2011) for a more detailed description of the catchment. The middle regions of the Kharaa River main channel are characterized by a longitudinal gradient in land-use intensity which is mainly caused by the geomorphological structure of the floodplain but also due to the presence of larger settlements (Hartwig et al., 2016; Hofmann et al., 2011; Priess et al., 2011, 2015; Schweitzer & Priess, 2009). In the upper river reaches, the valley is relatively narrow with small villages, sparse nomadic camps, and moderately intense livestock grazing. Close to the town of Zuunkharaa (Figure 1), the river valley opens into a wider floodplain where agricultural activities increase including widespread grain and vegetable production surrounding the townships. Dispersed nomadic families also reside here with increased herd sizes of mixed livestock species consisting of mostly, sheep, goats, cattle, and horses.

2.2 | Field sampling

Between September 2006 and May 2010, macroinvertebrate samples were collected from seven sites along the Kharaa River mid-region (M1–M7; Figure 1). To cover annual variability, yearly spring and autumn samples were taken, except site M2 (only in 2009 and spring 2010), site M5 (only in autumn 2006 and 2008 and spring 2007), and site M7 (not in autumn 2007 and spring 2008) due to logistic reasons. To validate the results from these sampling programs, further samples were collected during the ice-free period between April and October in 2007, 2008, and 2009, at sites M1, M3, and M6. A multihabitat sampling approach (Haase et al., 2004) was used on all occasions and kick nets with an open frame of 25 × 25 cm (sample area 0.0625 m^2) and a 500-μm aperture was employed. Benthic substrates were visually mapped and macroinvertebrates sampled, according to their spatial percental occurrence, to cover all existing instream microhabitats (20 sample units in total and 1.25 m^2, respectively). Every unit was sampled for approximately a 30-s period. This semiquantitative sampling approach was assumed to best reflect the local macroinvertebrate community composition, while comparability was ensured. Sample units were combined, preserved with 96% ethanol, and transported to the laboratory for analysis. To quantify the fine sediment load that has infiltrated the upper layer of the river substrate, sediment matrix traps were installed for the period between May and September 2009 (summer) and again between September 2009 and May 2010 (winter). Three sites were chosen, one in the upper middle region (Site M2) and two in the lower middle region (Site M6 and M7; Figure 1). The traps were composed of two cylindrical baskets (diameters, 15 and 20 cm; height, 22 cm) made of stainless steel mesh material (aperture, 5 mm) after Sear (1993) and Seydell, Ibisch, and Zanke (2009). The sediment matrix consisted of particles removed on-site, with a grain size between 25 and 63 mm, which did not have a detectable biofilm layer. Three replicates were installed per site in hydraulically comparable locations of riffle or glide topographies. Riffles or glides in gravel-bed rivers are naturally well connected with surface water flow, and therefore, have been assumed to best reflect sediment dynamics while displaying the strongest effect size. To minimize the interactions between the traps while covering natural hydraulic variabilities, a side-by-side arrangement perpendicular to the river current was chosen. As both vertical and horizontal particle intrusion into the sediment matrix occurred at the sample locations, not only was the sediment migration via the surface water column captured but also surrounding sediment coming from pore water. In this way, the results included the net fine sediment intrusion over a specific time period from recently mobilized particles (vertical path) and, historically, in interstice deposited particles (horizontal path) from floodplain or catchment erosion processes as well as in-stream processes. This methodology was selected instead of continuous turbidity measurements because it allowed for a time-integrating in situ estimation of the fine sediment net intrusion in the benthic zone, while providing an indication of the local sediment history, and as a consequence, a metric for sediment deposition which is stronger related to invertebrate community metrics than turbidity (Turley, Bilotta, Extence, & Brazier, 2014).

Additional environmental data were acquired to describe the characteristics of the sampling sites (Table 1). During the macroinvertebrate sampling, physical–chemical parameters including water temperature, pH, oxygen, electrical conductivity (EC), and turbidity were measured on-site using MULTI® 350i and TURB® 430 IR (WTW, Weilheim, Germany). Due to the strong circadian dynamics of the first three parameters and the methodologically induced differences in measuring times during the day, only EC and turbidity were included in the analyses. Mean turbidity values (±standard error [SE]) were calculated for each sampling site depending on sampling effort (range: $3 \le n \le 8$). These measurements were related to the total environmental turbidity gradient of the study area. For this purpose, continuous turbidity measurements (15-min interval) from two monitoring stations in the Kharaa River main channel were taken between 7 June and 17 July, 2012 (41-day period), covering both low and high discharge periods due to the beginning of the summer rainfall period (Karthe et al., 2014). The monitoring stations were located 45 km upstream from the sampling site M1 (GPS: N 48.41322°; E 106.93521°) and close to sampling site M7 (1.36 km upstream; GPS: N 48.91165°; E 106.075033°). Daily mean turbidity values were calculated based on continuous interval data and

TABLE 1 Environmental characteristics (mean ± SE, *n* in brackets) of the sites in the middle region of the Kharaa River from upstream (M1) to downstream (M7)

Site		M1	M2	M3	M4	M5	M6	M7
GPS location	N	48.54406°	48.67167°	48.80335°	48.83460°	48.82686°	48.87986°	48.91589°
	E	106.82719°	106.77667°	106.82719°	106.50909°	106.37836°	106.12990°	106.0604°
Outlet distance (km)		296.7	276.6	252.2	227.3	213.9	181.1	170.2
Elevation (m)		1,048	944	915	865	840	804	787
River width (m)		16.8 ± 0.7 (10)	21.7 ± 1.1 (10)	25.3 ± 1.4 (10)	19.7 ± 0.7 (10)	30.8 ± 0.6 (10)	25.9 ± 1.0 (10)	24.5 ± 1.8 (10)
River depth (m)		0.30 ± 0.03 (58)	0.30 ± 0.02 (68)	0.30 ± 0.02 (78)	0.32 ± 0.03 (67)	0.33 ± 0.02 (93)	0.43 ± 0.03 (66)	0.35 ± 0.02 (74)
Dominant benthic substrates[a]		Blocks and boulders	Blocks and boulders	Boulders and cobbles	Boulders and cobbles	Cobbles and coarse pebbles	Cobbles and coarse pebbles	Cobbles and coarse pebbles
Fine substrates cover <2 mm (%)		8.7 ± 1.6 (7)	9.5 ± 3.8 (3)	12.3 ± 1.3 (8)	9.7 ± 1.1 (6)	11.8 ± 0.0 (3)	11.3 ± 3.0 (8)	16.7 ± 2.2 (7)
D_{50} (mm)[b]		198.8	192.7	116.2	61.4	34.0	32.1	24.5
D_{60}/D_{10}[c]		2.3	3.8	7.4	3.4	6.5	5.5	5.1
Shear stress (N/m^2)[d]		4.91	3.86	2.81	2.53	2.10	4.28	4.93
Energy slope (m/m)[d]		0.0035	0.0032	0.0027	0.0028	0.0015	0.0009	0.0010
Wooden riparian vegetation (%)		41%	52%	21%	21%	0%	26%	0%
Riverbank damage (%)[e]		10%	19%	12%	17%	91%	69%	91%
Turbidity (FNU)		1.94 ± 1.0 (7)	0.62 ± 0.2 (3)	1.22 ± 0.4 (8)	1.55 ± 0.6 (6)	1.74 ± 0.8 (4)	2.68 ± 1.5 (7)	5.43 ± 1.6 (7)
Conductivity (μS/cm)		176 ± 23 (7)	180 ± 31 (3)	203 ± 15 (10)	210 ± 17 (8)	223 ± 16 (6)	287 ± 14 (11)	322 ± 19 (10)
TN (mg/L)		0.50 ± 0.05 (4)	0.46 ± 0.05 (2)	0.38 ± 0.1 (6)	0.49 ± 0.07 (6)	0.48 ± 0.07 (5)	0.33 ± 0.04 (7)	0.96 ± 0.18 (6)
TP (mg/L)		0.03 ± 0.01 (4)	0.02 ± 0.003 (2)	0.02 ± 0.003 (6)	0.02 ± 0.002 (6)	0.02 ± 0.001 (5)	0.03 ± 0.002 (7)	0.09 ± 0.03 (6)

Abbreviations: FNU, formazin nephelometric unit; TN, total nitrogen; TP, total phosphorus.

[a] River bottom substrate was characterized using Wentworth (1922) scale.

[b] Grain size where 50% of the substrate grains are smaller.

[c] Grain uniformity coefficient (Vukovic & Soro, 1992).

[d] Data source: Berner, 2007 (Average shear stress weighted per microhabitat occurrence).

[e] Riverbank damage was defined as broken banks due to trampling livestock and/or direct anthropogenic influence, for example, nearby roads or river crossings.

were plotted cumulatively. Median values were used as estimates for the total environmental turbidity gradient of the study reach. River bottom substrate composition was mapped during macroinvertebrate sampling procedures at each site. The 50% cumulative percentile grain size value (D_{50}) and the grain uniformity coefficient D_{60}/D_{10} (Vukovic & Soro, 1992) were estimated by fitting Weibull distributions (implemented in R package "stats," R Development Core Team) to the river bottom substrate data to characterize substrate composition and to identify colmation effects. Furthermore, hydromorphological data from Berner (2007) was supplemented with personal observations in terms of mean river width, mean water depth, bank erosion intensity, and bank vegetation coverage to estimate the overall bank erosion risk. Riverbanks were mapped along a 2-km stretch per site. Mean bottom shear stress (τ) was estimated by using FST (Fliesswasserstammtisch) hemisphere data (Statzner & Müller, 1989) and mean energy slope (S_e) by using surveying data from Berner (2007). Mean total nitrogen and mean total phosphorus were calculated from surface water samples for each site ($2 \le n \le 7$) to estimate the nutrient status (Hofmann et al., 2018). To estimate the anthropogenic pressures, classified SPOT and Landsat TM data for land-use and land coverage (Priess et al., 2015; Schweitzer, 2012) were used and adapted to the sampling site's subcatchments.

2.3 | Sample and data processing

The benthic invertebrates were identified to the lowest possible taxonomic level, using Russian keys and classification books which included the adjacent regions (Tsalolikhin, 1994), counted and the total body length was measured under a stereomicroscope (precision 0.1 mm). For taxa sampled in high abundances, only a length measurement was recorded from meaningful aliquots, which resulted in a measuring ratio of 36% of all individuals. The invertebrate biomass was estimated using length–mass relationships (Benke, Huryn, Smock, & Wallace, 1999; Burgherr & Meyer, 1997; Meyer, 1989; own unpublished data). Furthermore, functional (feeding, habitat, and locomotion types), structural, and diversity macroinvertebrate community metrics have been derived from the taxonomic data. To help determine the fine sediment impact on macroinvertebrate communities, a set of nine metrics were selected: taxa richness (number of taxa), Shannon index of diversity (*H*; Shannon & Weaver, 1949), Evenness (*E*; Magurran, 1988), relative density of EPT individuals (density % EPT), total benthic density (individuals/m^2), density of Chironomidae (Chiro density; chironomid individuals/m^2), relative biomass of Chironomidae and Oligochaeta (Biomass % Chiro/Oligo; Chironomid and Oligochaete biomass relative to total biomass), relative biomass of fine substrate (sand and mud) colonizers (Biomass % FS Colonizer) and relative biomass of hard substrate (coarse pebbles to boulders) colonizers (Biomass % HS Colonizer). Although other studies have reported relatedness to fine sediment pollution (e.g., Burdon et al., 2013), some of these metrics have the potential to also indicate other stressor responses. Therefore, the Proportion of Sediment-sensitive Invertebrates (PSI, ψ) was additionally calculated, using the approach of Extence et al. (2013). For this reason, fine sediment-sensitive rating values (FSSR) have been adapted to the benthic macroinvertebrate taxa from the Kharaa River by using genus and species data given by Extence et al. (2013) completed by expert knowledge (see Table S4). Individuals of the groups Chironomidae and Oligochaeta were excluded because of the low identification level for chironomids in our data and individual number uncertainties in oligochaetes due to fragmentation as a result of ethanol storage and transportation.

After the recovery of the sediment matrix traps, the samples were transported to the Central Geological Laboratory in Ulaanbaatar for analysis. The samples were dried (105°C, 24 hr) and the grain size fractions smaller than 250 µm were unified and defined as fine sediment in the context of this study. The net rate of fine sediment intrusion (NIR_{fs}) was calculated using the following formula:

$$\mathrm{NIR}_{\mathrm{fs}}[\mathrm{g}\cdot\mathrm{L}^{-1}\cdot\mathrm{d}^{-1}] \;=\; \frac{m_{\mathrm{fs}}[\mathrm{g}]}{V_{\mathrm{trap}}[\mathrm{L}]\;\cdot\;t_{\mathrm{inc}}[\mathrm{d}]},$$

with m_{fs} being the mass of fine sediment with grain sizes smaller than 250 µm in grams, V_{trap} being the volume of the inner basket of the trap in liters and t_{inc} being the incubation time in days. To estimate the organic portion of this fine sediment fraction, particulate organic carbon (POC) and particulate nitrogen (PN) were measured using a carbon/nitrogen/sulphur analyzer (vario EL; Elementar Analysensysteme GmbH, Germany) according to the method described by Hartwig and Borchardt (2014).

2.4 | Statistical analyses

Nonmetric multidimensional scaling (nMDS) using Bray–Curtis dissimilarity was performed to visualize taxonomic data. The data set was standardized using Wisconsin standardization and was fourth-root transformed (Faith, Minchin, & Belbin, 1987; Legendre & Gallagher, 2001). Significant environmental factors were identified using environmental fitting (10^6 permutations; R package "vegan;" Oksanen et al., 2017). Macroinvertebrate community metrics have been calculated afterward to identify fine sediment-related differences between the sampling sites. The calculated metrics, as well as the PSI, were tested to determine the difference between sampling sites by applying an rmANOVA (repeated measures analysis of variance) and a least significant difference test with Bonferroni adjustment of *p* values. Prerequisites for statistics were tested using Fligner–Killeen test and Shapiro–Wilk test to determine the data's homogeneity of variance and normal distribution. Data transformations were identified by the Box–Cox method (Box & Cox, 1964) and calculated as follows: relative density of EPT individuals: $y' = y^{0.9}$; relative biomass of hard substrate colonizer: $y' = y^{1.3}$; total density, relative biomass of fine substrate colonizer and relative biomass of Chironomidae and Oligochaeta: $y' = y^{0.3}$, density of Chironomidae: $y' = y^{0.2}$ and PSI: $y' = y^2$.

Linear regression analyses (Pearson's *r*) were performed between macroinvertebrate metric means and the mean of turbidity measures at each site. Although linear models may suffer from some weaknesses in explaining the relationships between fine sediment pollution and biotic response variables, they have been applied due to their robustness.

Differences between the net rate of fine sediment intrusion and the fine sediment organic matter content (POC, PN) of the sites were tested with a one-way ANOVA and a multiple comparison test (Tukey's honestly significant difference) for both incubation periods, during summer and winter. All graphics and statistical analyses were computed by using open-source R (Version 3.4.1, http://www.R-project.org; R Development Core Team, 2010).

3 | RESULTS

3.1 | Macroinvertebrate community metrics

The macroinvertebrate communities examined in the middle reaches of the Kharaa River were characterized by high total densities (5,313 ± 410 individuals/m^2, $n = 68$) and total biomasses (2,656 ± 152 mg dry weight/m^2, $n = 68$, both mean ± SE). The comparison of the macroinvertebrate communities using structural and functional metrics indicated changes in community composition, biodiversity, and habitat complexity from upstream (M1) to downstream (M7) sites (Figure 2). These changes were characterized by significantly decreased taxa richness, Shannon diversity, Evenness, the relative density of EPT individuals and the relative biomass of hard substrate colonizers. In contrast, densities of chironomids and the relative biomass of chironomids and oligochaetes were significantly increased at site M7 compared to M1. The total densities and the relative biomass of fine substrate colonizers did not show significant differences between the seven sites. Most of the metrics followed linear trends in a longitudinal direction resulting in significantly increased or decreased values at site M7. This suggested a gradient in the quality of environmental parameters for the macroinvertebrate communities along the river continuum, although the interseasonal variation was particularly high, as indicated by the results of the rmANOVA.

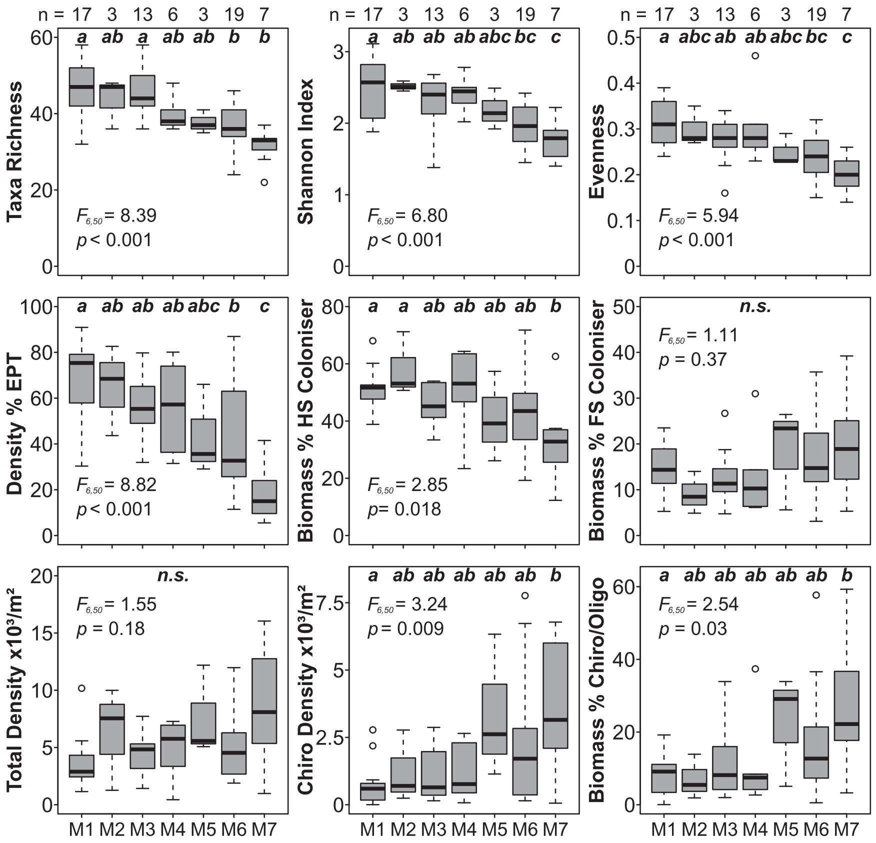

FIGURE 2 Boxplot (median, 25/75 percentile, 1.5× interpercentile range, outliers) of macroinvertebrate metrics of the sites M1 to M7 in the middle Kharaa River along a longitudinal gradient; significant differences between sites grouped by letters "*abc*," "*ns*" (nonsignificant; LSD test with Bonferroni correction), sample number (*n*) is indicated above the plots; results from rmANOVA for differences between the sites are given in each plot. LSD, least significant difference; rmANOVA, repeated measures analysis of variance

3.2 | Macroinvertebrate community composition related to environmental factors

The environmental data from sites M1 to M7 displayed multiple longitudinal changes along the middle section of the Kharaa River (Table 1). Along natural gradients representing the river continuum, namely elevation, distance to outlet, mean river width, mean energy slope, or benthic substrate dominant grain size (D_{50} value), factors indicating more intense human activities also appeared to be aligned. Impairment of riparian wooden vegetation (trees and bushes) coincided with increased bank damage, mean turbidity, mean electrical conductivity, wheat production, and fallow land, with the latter two both indicating increasing large-scale agriculture, from an upstream to downstream direction.

The nMDS results demonstrated that the taxonomic composition of the sampling sites represented a longitudinal gradient along the river continuum as related to the factors mentioned above with a subregional clustering (Figure 3a). Furthermore, most other (anthropogenic) factors considered, were found to be either positively or negatively significant along this gradient. Mean turbidity, mean electrical conductivity, bank damage, and substrate D_{60}/D_{10} ratio were orientated in a downstream direction in accordance with mean river width and, to a lesser extent mean river depth, further suggesting an increased soil and fine sediment input or in-stream migration, respectively, in the downstream part of the Kharaa River middle region (Figure 3b). In contrast, riparian wooden vegetation did decrease in a downstream direction, culminating in its complete disappearance at site M5 and M7, and resulting in higher proportions co-occurring with higher elevation, outlet distance and benthic substrate grain size (Figure 3b and Table 1). In comparison to the analysis of the land-use and land coverage data using the environmental fitting method, the results indicated that mixed forest and potato cultivation (small-scale agriculture) were more related to the upstream subregions than wheat cultivation, fallow, settlements, and floodplain vegetation, which increased downstream (Figure 3c). Apart from these longitudinally oriented gradients, nutrient parameters such as total nitrogen and total phosphorus, as well as the percentage of fine river bottom substrate, followed a different orientation indicating the specific importance of these factors at the most downstream site M7. Even though there was an indication for increased fine sediment fractions at the most downstream sampling site, a quantitative statement regarding the composition of the fine particle-matrix in between the dominate grain size was not possible based on the applied mapping approach.

The regression analyses between the mean of each macroinvertebrate metric and the mean turbidity values at each site of the Kharaa River middle reaches resulted in negative linear relationships for taxa richness ($r = -.83$, $p = .03$, $R^2 = 0.57$), Shannon Index of Diversity ($r = -.89$, $p = .01$, $R^2 = 0.72$), Evenness ($r = -.86$, $p = .021$, $R^2 = 0.63$), relative abundance of EPT individuals ($r = -.93$, $p < .01$, $R^2 = 0.74$) and relative biomass of hard substrate colonizers ($r = -.86$, $p = .02$, $R^2 = 0.63$). Relative biomass of fine substrate colonizers

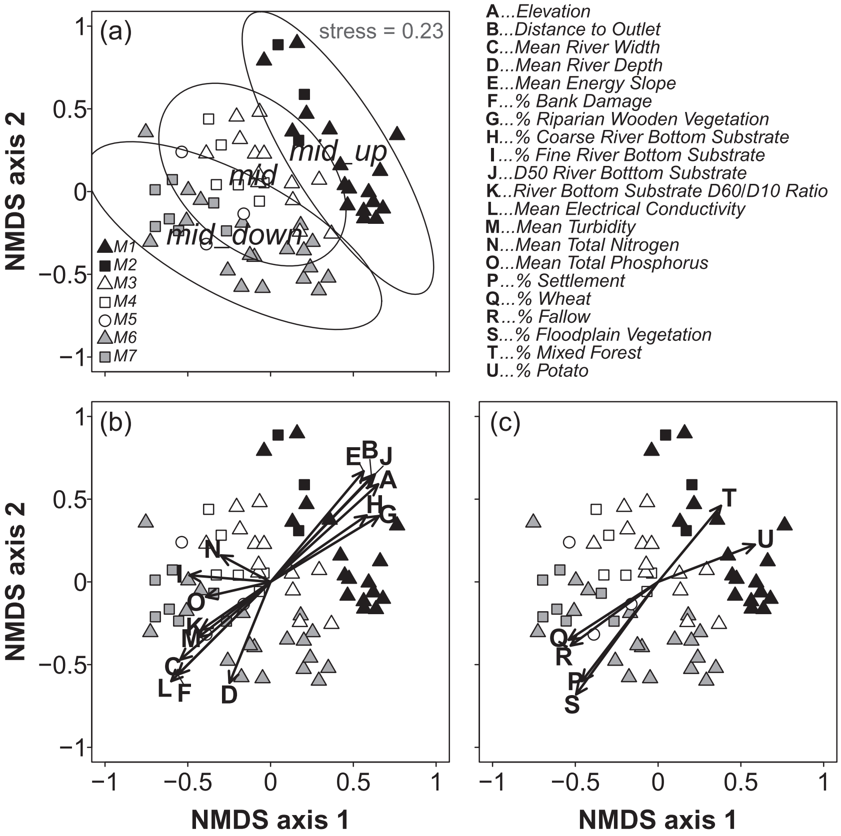

FIGURE 3 Nonmetric multidimensional scaling (nMDS) based on Bray–Curtis dissimilarities between macroinvertebrate taxonomic composition from the seven sampling sites (M1–M7, legend see plot (a)) in the Kharaa middle region with (a) 95% confidence intervals (ellipsoids) of subregions middle upstream (mid_up), middle (mid), and middle downstream (mid_down), (b) in relation to environmental and hydromorphological variables, and (c) in relation to classified land cover data derived from remote sensing variables (arrows; only significant [$p < .05$] were added to the nMDS plot and labeled with capitalized Arabic characters; description is given in the figure)

($r = .76$, $p = .036$, $R^2 = 0.54$) and relative biomass of Chironomidae and Oligochaeta ($r = .76$, $p = .029$, $R^2 = 0.57$) were positively correlated to mean turbidity values. The other metrics also displayed positive relationships to mean turbidity, although the linear regression was not statistically significant (total density: $r = .59$, $p = .16$, $R^2 = 0.22$; density of Chironomidae: $r = .64$, $p = .08$, $R^2 = 0.40$). These results indicated an impact of suspended fine sediments on the macroinvertebrate community structure and to a lesser extent on habitat complexity by shifting from EPT dominance to increased proportions of fine sediment colonizers, like Chironomidae and Oligochaeta, and an associated loss of biodiversity. The calculation of the PSI further supported the hypothesis of fine sediment impairment at the lower Kharaa sampling sites (M5 to M7), which had significantly less sediment-sensitive individuals than the other upstream sites (*rm*ANOVA; $p < .001$, $F_{6,50} = 18.9$) and were classified as moderately sedimented. The PSI values in our study were correlated to the Percentage of EPT individuals metric (Pearson's $r = .65$, $p < .001$, $n = 68$). This demonstrated the sensitivity of the latter to sediment pollution in the Kharaa River.

The range of turbidity measurements from the macroinvertebrate sampling campaigns (0.69–5.43 FNU [formazin nephelometric unit]) was approximately three times lower upstream and six times lower downstream of the study reach compared to the estimated total environmental turbidity gradient from continuous measurements (median: 2.4 FNU upstream, 34.6 FNU downstream). These measurements covered both low and high flow conditions. It became obvious that macroinvertebrate samples and thus, also turbidity measurements, were taken from seldom occurring conditions (15% of the observations) at the lower range of the environmental turbidity gradient.

3.3 | Fine sediment intrusion

The analysis of fine sediments (< 250 μm) at the three sites in the middle region of the Kharaa River, during both the summer and winter periods, indicated an increased fine sediment net intrusion into the upper layers of the river bed at the most downstream site M7 compared to the upstream site M2 (summer: $F_{2,6} = 38.73$, $p < .001$; winter: $F_{2,6} = 5.93$, $p = .038$). During the summer period, the mean net intrusion rate ($\mathrm{NIR}_{\mathrm{fs}}$) indicated an increased deposition of fine sediments at site M7 by close to five times compared to site M2, and still, more than three times compared to site M6 (Figure 4a). During the winter period, the deposition of fine sediments was lower and increased by four times at site *M7* compared to site M2 and close to two times compared to site M6 (Figure 4b). The $\mathrm{NIR}_{\mathrm{fs}}$ measurements over the winter period corresponded very well to the mean of the turbidity measurements during the field expeditions and the macroinvertebrate samplings ($r = .999$, $p = .03$; Figure 4b,c). This was not the case during the summer period ($p = .2$) where fine sediment deposition into the interstitial space on the river substrate at site M7 was further increased by other factors explainable by the intermittent turbidity measurements (Figure 4a,c). Although the amount of infiltrated fine sediments at the three sites followed a

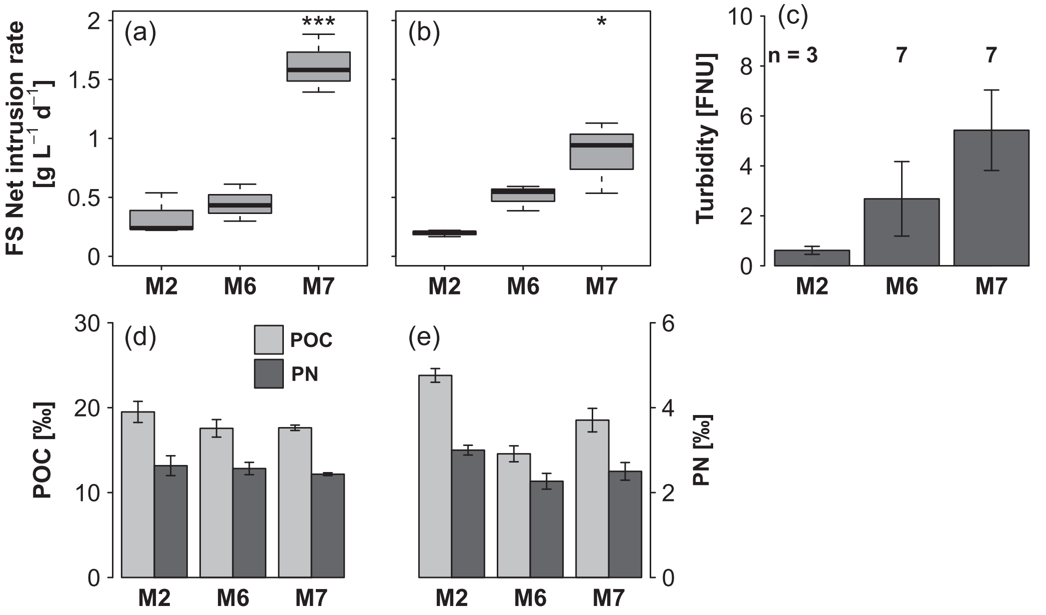

FIGURE 4 Fine sediment net intrusion rate at the three sites in the mid-region of the Kharaa River during (a) the vegetation period from May to September 2009 and (b) the winter from September 2009 to May 2010 in comparison to (c) turbidity measurements, and (d, e) the fine sediment portions of particulate organic carbon (POC) and particulate nitrogen (PN) for both incubation periods, respectively. Boxes are indicating median, 25/75 quartile, minimum and maximum (whiskers), significant differences marked with asterisks (one-way analysis of variance); bars are indicating means ± standard error

clear longitudinal pattern, the estimation of their organic portions did not. Although no differences in the contents of PN ($F = 0.41$, $p = .7$) or POC ($F = 1.33$, $p = .3$) occurred between the sites during the summer period (Figure 4d), the POC content was slightly increased at site M2 compared to both downstream sites (M6, M7) during the winter period ($F = 18.6$, $p = .003$), whereas the PN content was not ($F = 4.62$, $p = .06$; Figure 4e).

4 | DISCUSSION

4.1 | General changes of community metrics along the sampling gradient

The macroinvertebrate community along the Kharaa River middle region showed a substantial shift in structure, diversity and to a lesser extent in habitat preferences at the most downstream site (M7). Although the hydromorphological river bed characteristics at all sites give reason to expect rheophilic dominated invertebrate communities; the community metrics indicated a shift from EPT and hard substrate colonizer dominance to increased biomass proportions of fine substrate colonizers and decreased proportions of sediment-sensitive individuals, and thus, ecologically significant fine sediment pollution at this site. However, the increasing trend in relative biomass of fine substrate colonizers was not statistically significant, even if biomass proportions of chironomids and oligochaetes (both closely related to fine sediment habitats) were significantly increased. It is assumed that the higher individual biomass of other fine substrate colonizing taxa, especially those larger in body size, compared to chironomids and oligochaetes, was most likely the reason for the missing overall fine sediment colonizer's biomass effect. Larvae of larger insect taxa characterized by fine substrate preferences (esp. psammophilous Ephemeroptera, e.g., *Ephemera orientalis*) occurred in higher abundances also at the upstream sites of the Kharaa River middle region and may have masked such potential longitudinal effects resulting from the increasing chironomid and oligochaete densities. Following the decreasing elevation gradient along the natural continuum of the river, which also implies decreasing sediment transport energy, shrinking proportions of hard substrate colonizers and increasing proportions of fine substrate colonizers was expected. However, even if such natural longitudinal changes in hydromorphological aspects, can to a certain extent, explain the observed macroinvertebrate colonization pattern, it is very unlikely that this was the main environmental factor causing the situation in the downstream study region, as the bed characteristics and hydraulic conditions at the two downstream sites (M6 and M7) are also similar (Table 1; Hartwig & Borchardt, 2014).

4.2 | Relevance of natural changes in environmental factors for explaining the gradient

In spite of the evidence that the macroinvertebrate community was influenced by environmental stressors, the taxonomic composition and metrics of the macroinvertebrate communities in relation to the environmental data revealed a clear longitudinal gradient, which was elucidated by morphologic and geographic environmental factors (Vannote et al., 1980). This was expected, given the longitudinal design of the present study, but it has to be considered that the study reach was within a single biocoenotic region (Berner, 2007) and not extended to the whole catchment which ensured better comparability between sampling sites. Furthermore, other factors also related to fine sediment pollution were aligned to this natural gradient. The relative occurrence of wooden riparian bank vegetation decreased from upstream to downstream, whereas the frequency of a disturbed bank morphology increased. This coincided with an increase in electrical conductivity and turbidity as well as in the grain uniformity coefficient (D_{60}/D_{10} ratio) indicating increased fine sediment mobilization and deposition and is in accordance with bank stabilizing and sediment retaining functions of riparian vegetation buffer stripes (Tal, Gran, Murray, Paola, & Hicks, 2004). Furthermore, the tributaries in the mid-down reaches of the Kharaa River were identified as being the main sources of fine sediments from riverbank erosion in the whole catchment (56%; Theuring, Collins, & Rode, 2015), which regularly transport high loads of fine sediments into the Kharaa River main channel, especially during high discharge events (Hartwig, Theuring, Rode, & Borchardt, 2012; Karthe et al., 2014; Theuring et al., 2015). This additional sediment load over a long period may have resulted in exceeding the ecological tolerance of many invertebrate species and subsequently lowered the habitat suitability (Richards & Bacon, 1994), thus indicating an initial fine sediment accumulation threshold (Kaller & Hartman, 2004) for altering macroinvertebrate communities. In comparison to the results from Burdon et al. (2013), the benthic substrate composition at this most downstream sampling site (16.7 ± 2.2%; macroinvertebrate's microhabitat mapping data) was within the threshold range of 13–20% surficial sediment <2 mm, whereas at all other sites it remained below this threshold. In agreement with Burdon et al. (2013), strong influences on EPT taxa were also detected in the present study with further evidence for this threshold being derived. Toxic effects from heavy metals cannot be excluded completely as it is known that there were mining sources at different tributaries along the Kharaa River middle region (Hofmann, Venohr, Behrendt, & Opitz, 2010). But such effects were very unlikely to explain the observed macroinvertebrate community pattern as heavy metal sediment contents along the Kharaa River main channel were slightly elevated only locally and did not show a longitudinal gradient (Kaus et al., 2016).

4.3 | Effects of fine sediment on benthic macroinvertebrates

In agreement with other studies (Angradi, 1999; Bertaso et al., 2015; Bryce et al., 2010; Burdon et al., 2013; Freeman & Schorr, 2004; Larsen et al., 2009; Mebane, 2001) the relative density of EPT individuals was the most sensitive metric to increased fine sediment pollution in our results. This was also illustrated by a large portion of the reduction in the overall taxa richness at *M7* being traceable to a reduction in EPT taxa richness, as both metrics were well correlated to each other (Pearson's $r = 0.93$, $p < 0.001$, $n = 68$). As EPT organisms also include species that are not sensitive to fine sediment and are known for being sensitive to also other environmental stressors, we additionally calculated the PSI for comparison. Both, the percentage of EPT individuals and the PSI were significantly correlated and followed a similar pattern. Moreover, due to their widespread crawling locomotory type, the habitat preferences of EPT species are most closely related to stable lithal (stony or rocky) or phytal (mosses, macrophytes or submerged parts of terrestrial plants) substrates, their oxygen demand is typically high, and their habitat niche tolerances low. The deposition of higher loads of fine sediment can alter the suitability of habitats for EPT colonization, due to the increased substrate instability, which can create a higher risk of being displaced by accidental (catastrophic) drift for the individuals present. Furthermore, food availability or quality may be lowered, especially for grazing and passive filter-feeding species, which ultimately results in lower individual fitness. Wood and Armitage (1997) identified the following key impacts of fine sediment pollution on benthic invertebrates (a) benthic habitat suitability due to substrate composition alterations, (b) increased drift resulting from (fine) sediment deposition or substrate instability, (c) affected respiration or low oxygen concentrations due to fine sediment deposition, and (d) impaired feeding activity. Although we cannot quantify the individual effect of these four mechanisms from our data, all four can be expected to play a role in shaping the macroinvertebrate communities in the Kharaa River middle region. Considering the harsh climatic conditions in Mongolia, particularly during the long and cold winters, when rivers are covered by ice, partly down to the sediment surface (Avlyush et al., 2013; Batima, Batnasan, & Bolormaa, 2004), mechanisms (a), (c), and (d) appear to be highly relevant for the survival of macroinvertebrates. The hyporheic interstitial zones in gravel-bed rivers provide refuges not only during the ice cover period but also during floods when the risk of catastrophic drift increases correspondingly to the shear stress in benthic habitats (Stubbington, 2012). The increased deposition of fine sediments can either directly impair the vital function of this hyporheic compartment by physical clogging, or have indirect effects, by lowering the oxygen availability, which ultimately results in decreased habitat quality for benthic macroinvertebrates. Both processes have been detected at site M7 in the study of Hartwig and Borchardt (2014) and, therefore, can be assumed to be the major factors influencing the habitat quality and therefore the macroinvertebrate community composition at this site. This was evident due to the shift from EPT dominance to chironomids' and oligochaetes' dominance and significantly lowered PSI scores (M7: 48.5 ± 10.5, $n = 7$; M1: 67.5 ± 3.6, $n = 17$; mean ± SD).

4.4 | Sediment alterations by fine sediment intrusion—seasonal and methodical discussion

The increased net intrusion rate of fine sediment (<250 μm) at the sampling site (M7) supported the hypothesis of increased fine sediment pollution in these reaches of the Kharaa River. This increase was higher over the summer (vegetation) period when 70% of the precipitation occurs compared to the winter period when rivers are covered by ice for several months, which results in relatively stable discharge conditions (Avlyush et al., 2013; Karthe, Heldt, et al., 2015). Flood and storm events were reported to be major causes for sediment mobilization and remobilization processes in Mongolia (Chalov et al., 2015; Pietroń, Jarsjö, Romanchenko, & Chalov, 2015) and, therefore, can explain the stronger increase of fine sediments during this period. As the chemical analyses of the fine sediment fraction indicated, organic particles did not reflect the fine sediment gradient. This suggests that they were less important in explaining the macroinvertebrate community pattern. The higher density of wooden riparian vegetation upstream in the study region could have led to the assumption of higher organic matter due to leaf litter input. However, this was not the case during the summer and only tended to occur during the winter sampling period, where POC was slightly increased at the most upstream site. Higher rates in nutrient turnover during the hot summer conditions could explain this difference, but this cannot be stated from the data and, therefore, has to remain speculative. Although other studies mostly focused on an upper grain size limit of 2 mm (e.g., Burdon et al., 2013; Jones, Growns, Arnold, McCall, & Bowes, 2015; von Bertrab, Krein, Stendera, & Hering, 2013) it appeared to be meaningful to focus on a smaller grain size limit in the Kharaa River middle region. Sand 0.125–2 mm; Wentworth, 1922) was a considerable natural component of riverine sediments along the studied region (Hartwig & Borchardt, 2014) and, therefore, particles <250 μm were expected to be more ecologically relevant in terms of potential clogging of habitats for resident macroinvertebrate organisms. Due to the long incubation period of several months and to enable both, vertical and horizontal intrusions, the sediment matrix trap method allows for time-integrating analysis. Thus, the NIR_{fs} values from the 1-year incubation period in this study can be expected to be representative of the situation in the Kharaa River study reach in the past. This was a specific attempt to not only cover current river bed erosion/deposition processes but also historical processes that are likely to have influenced benthic habitats and the contemporary macroinvertebrate community composition. It cannot be fully excluded that horizontal intrusion processes may have been significant or overlaid vertical transport and the sediment matrix traps used in the current study enhanced fine particle trapping when compared to the surrounding sediment. Therefore, the values from this study may overestimate the vertical intrusion, although the intrusion rates are comparable to other studies using similar methodologies (Seydell et al., 2009).

4.5 | Effects of anthropogenic stressors on fine sediment pollution

The longitudinal land-use type and land-use intensity pattern in the Kharaa catchment described by Schweitzer and Priess (2009), Hofmann et al. (2011), and Priess et al. (2011, 2015) were reflected in the results of the multivariate analysis where hydromorphological deficits, such as riverbank damage and a progressive decline of the larger riparian vegetation such as bushes and trees were aligned in an upstream–downstream direction in association with an increasing area of large-scale agriculture, human settlements, and floodplain vegetation as related to wider valley morphologies. The negative impacts of livestock on riverbank stability and macroinvertebrate communities are well reported (e.g., Quinn, Davies-Colley, et al., 1992; Raymond & Vondracek, 2011). Thus, considering that livestock is allowed to graze unrestrained in Mongolia, it is very likely that the observed hydromorphological deficits were caused by the constant feeding activity adjacent to the river channel. Therefore, the direct impact of livestock trampling riverbank soil, along with the indirect impact by overgrazing the riparian vegetation (personal observations), both have severely impaired the riverbank stability in the region (Hartwig et al., 2016). An increased load of fine sediment entering the river course is an obvious consequence of this riverbank deterioration (Theuring, Rode, Behrens, Kirchner, & Jha, 2013). Hartwig and Borchardt (2014) have shown that hyporheic zones in the downstream parts of the Kharaa middle region were impaired by significantly increased total suspended solids (TSS) and physical clogging (M7 in the present study). These results were supported by occasional turbidity measurements taken in parallel to the macroinvertebrate samples in our study. However, it should be noted that these measurements cannot fully reflect the complete range of the turbidity gradient in the Kharaa River. Special consideration should be given to the fact that macroinvertebrates were only sampled during wadeable low- and mid-flow conditions when the river was characterized by lower turbidity. In contrast, most sediment mobilization and remobilization primarily occur during short high-flow events (Chalov et al., 2015; Pietroń et al., 2015). Although, as indicated by the relationships between macroinvertebrate community metrics and the mean turbidity values, it can be assumed that these measurements reflected the local turbidity gradient, albeit on a lower level.

4.6 | Effects of nutrients and EC on benthic macroinvertebrates

Increasing nutrient concentrations were reported along the Kharaa River with maximum values measured at the Kharaa–Orkhon confluence (total nitrogen and total phosphorus; Hofmann et al., 2011). Eutrophic conditions due to increased nutrient input induce high respiratory rates and oxygen demands. This can potentially result in a macroinvertebrate colonization pattern similar to the pattern observed during the current investigations. However, despite slightly increased nutrient concentrations in the Kharaa mid-region, Hartwig and Borchardt (2014) measured decreasing periphyton biomass and gross primary production with community respiration remaining comparable in the downstream site (M7) compared to the next upstream site (M6). This was attributed to light limitations caused by high loads of TSS and altered habitat availability due to increased fine particle deposition on the benthic substrate.

Furthermore, the measured total nitrogen and total phosphorus concentrations were consistently low and, therefore, the ecological consequences can be assumed to be less relevant. Thus, the share of saprobically caused alterations in the macroinvertebrate community pattern can be expected to be minimal. This was supported by the fact that larger stoneflies (*Agnetina* sp., Perlidae), or different species of Perlodidae (*Isoperla* spp., *Skwala* sp., *Diura* sp.) and Chloroperlidae (*Triznaka* sp.), as well as mayflies of the genus *Epeorus* (*E. [Belovius] pellucidus*), which generally showed very small saprobic tolerances (Rosenberg & Resh, 1993) have been sampled from all sites (including M7) of the study area, at least at low densities. Although other studies have reported EC as being closely related to biological degradation (Vander Laan, Hawkins, Olson, & Hill, 2013), in the present study, it was also closely related to the longitudinal gradient, the mean turbidity, and the bank damage. Although, separating the possible effects of EC on macroinvertebrate communities from the effects of fine sediment was not possible during the current research, soil intrusion from bank erosion could be identified as the main source of the EC gradient, due to very low fertilizer use in the local agriculture (Hofmann et al., 2015) and due to also low population density in the region (Hofmann et al., 2011). Furthermore, the ecological consequences of this relatively small EC gradient ($\Delta EC_{mean} = 146\,\mu S/cm$), which occurs on a relatively low level ($EC_{max} = 383\,\mu S/cm$) can be assumed to have little effect in relation to the more severe habitat impairing effects of increased fine sediment intrusion. This conclusion is supported by the results of another study that focused on the ecological consequences of EC on macroinvertebrates (Kefford, 1998).

5 | CONCLUSION

Although it cannot be excluded completely that other natural and/or anthropogenic environmental factors could have been causal in shaping the macroinvertebrate community pattern in the Kharaa River middle region, from the current results, it is evident that the increased fine sediment pollution was one of the most important driving factors. This is especially true in the lower parts of the Kharaa River middle region and supports our original hypothesis that stated that macroinvertebrate communities were locally impaired by fine sediment pollution. These main sources of fine sediments in the Kharaa River basin, as identified using sediment isotope fingerprinting, have been determined to be riverbank erosion and to a lesser extent upland erosion processes (Theuring et al., 2013). Therefore, the urgent need for the implementation of riverbank stabilizing and livestock management measures, as well as further fine sediment-related monitoring along the course of the Kharaa River middle region, is unquestionable. These management recommendations and threshold values for ecologically critical fine sediment loadings are likely transferable and should be considered essential to mitigate the adverse impacts of sediment pollution on the aquatic environment in other intensively grazed regions and basins of the Eurasian steppe belt.

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SUPPORTING INFORMATION

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

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