The impact of deposited fine sediment on benthic macroinvertebrates in small headwater streams in Luxembourg

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"The principle of all things is water;
all comes from water,
and to water all returns."

Thales of Miletus

Moim rodzicom

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Glossary and Abbreviations

Biplot	an ordination diagram which simultaneously plots species and sample/environmental scores. Only relevant for ordination techniques such as CCA, RDA, DCA, CA, and PCA.
C/N ratio	Proportion of Carbon to Nitrogen in a substance; here sediments. It is a measurement of nitrogen limitation consumed by microbial composition.
CCA	Canonical Correspondence Analysis is a direct gradient ordination method assuming species distribution to be unimodal.
CPOM	Coarse Particulate Organic Matter (e.g., leaf litter, branches or wood debris) accumulated on the channel.
DCA	Detrended Correspondence Analysis is an eigenvalue-based ordination technique derived from CCA. DCA performs detrending to counteract the arch effect (a defect from a CA), and rescale the ordination axes. DCA is used here primarily to identify the gradient length of species data sets in order to correctly apply linear (RDA) or unimodal (CCA) ordination techniques.
DOC	Dissolved Organic Carbon is here as a part of suspended particles in water.
Eigenvalue	a central concept in linear algebra, measure the strength of an ordination axis.
EPT Taxa	describes a group of aquatic insects' larvae which includes the species orders: Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies).
FPOM	Fine Particulate Organic Matter (detritus = animal and plant remnants), which originated from the decomposition of coarse particulate organic matter.
Habitat fragmentation	describes a discontinuity of landscape and the habitats of organisms caused by natural geographical barriers (e.g., mountains, isle) and anthropogenic activity (e.g., deforestation, urban development, road networks). As a consequence, it can induce the genetic isolation of species and frequently their extinction.

In-stream variables	combine here the environmental parameters characterised by a stream channel (morphometric properties, substrate) and physicochemical conditions.
Interstitial spaces	describes the gaps between the coarse-grained texture of a streambed; here it represents the spaces between gravel, cobble, and boulder in the streambed.
Microhabitats	are the mineral (e.g., stony, pebbles, sand, mud) and organic (e.g., CPOM, wood trunks, periphyton) substrates on the streambed, which are very significant to aquatic organisms.
Patch-Sampling	a defined spot or area of a streambed where samples were collected and measured in the field.
Periphyton	biofilm containing microalgae, bacteria and detritus attached to the surface of substrates in the flowing waters. It provides benthic invertebrates with essential food sources.
Pool	is a section of a stream- or riverbed, characterised by decreased flow velocity and as a sinking area for sediment and organic particles.
pRDA / pCCA	partial RDA / partial CCA are methods of variation partitioning, meaning that the effects of covariables are factored out or nullified.
RDA	Redundancy Analysis is direct gradient ordination analyses assuming that species have a linear distribution to a linear relationship to environmental variables.
Riffle	is a short and shallow section of stream- or riverbed shaped by diverse to turbulent flow velocities.
SD	is a standard deviation.
USLE	Universal Soil Loss Equation evaluated by Wischmeier and Smith, (1978). This equation is used to calculate the soil erosion potential by means of erosion models.

1 General Introduction

“This […] dynamic interaction exists between people and other parts of ecosystems, with the changing human condition serving to drive, both directly and indirectly, change in ecosystems. However, changes in ecosystems cause changes in human well-being.” Millennium Ecosystem Assessment, (MA) 2005.

The stream and river landscapes have continually been altered by humans in the past up to our modern times. The growing human population and the increasing strong demand for food have extended agriculture and urbanisation. This modification of land use resulted in habitat fragmentation, a degradation and pollution of freshwaters and consequentially in a loss of biodiversity (MA, 2005). The intensity of agricultural and urban development caused soil compaction along with diffuse nutrient and sediment release into water bodies due to the excessive application of mineral fertilisers, pesticides, excreta from livestock, and domestic detergents. The sediment and nutrient retention were decreased by sealed trapping areas, which transport them faster and more concentrated into water bodies. The unsuitable forestry management accelerates the pollution and soil erosion as a result of excessive planting of non-indigenous conifers or using heavy agricultural machines. In contrast to other anthropogenic pressures such as the eutrophication, acidification and accumulation of toxic components, little is known about the ecological effect of increasing fine sediment amounts in streams and rivers.

The sediment is next to water the most important physical component of aquatic systems, and is determined by processes of terrestrial input, transport dynamics (delivery to and within the streambed) and deposition. Adsorption properties of fine sediment as well as sediment’s terrestrial and hydrodynamic linkage indicate the complexity of interactions and causal mechanisms of sediment. Coarse grain substrate such as stones, pebbles, gravel and fine grain particles are part of streambed substrates and an essential microhabitat for benthic organisms. Fine sediment consists of mineral fractions of less than 2 mm diameter; such as clay (< 2 µm), silt (2 - 63 µm) and sand (0.063 - 2 mm) particles (Zanke, 1982) and adsorbs particulate matter such as organic matter or heavy metals (Chapman, 1990; Estebe et al., 1997; Colas et al., 2011). The fine sediment load also contains organic particles.

The altering of sediment balance is a global phenomenon of river basins caused by the hydraulic engineering measures and the modification of landscape (Owens et al., 2010). High amounts of sediment erode into the headwaters and are transported downstream. Particularly several water engineering measures (e.g., the straightening of the streamline, the construction of embankments, and the removal of streambed substrates) induce the reduction of streambed storage capacity and increase the drainage which results in faster transportation of higher sediment concentration downstream. Ensuring the waterways for ship navigation and flood protection, the high sediment load was dredged from the large rivers and accumulation sections such as river dams or harbours. Hence, this caused an alternation of sediment flux in the estuaries and coastal ecosystems.

The EU Water Framework Directive (WFD; Directive 2000/60/EC) obligates the Water Management to protect and to improve the ecological status of the water bodies. The sediment’s quantity and quality has not directly been implied in the WFD directive, but the impact of fine sediment on biota is rated in the management plans as a great element of uncertainty (EC, 2003; MUNLV, 2008). This is supported by a current study of anthropogenic stressors for the implementation of measurement programmes (Kail and Wolter, 2011).

The problems of sedimentation will become increasingly important in the future as a result of global climate change and human population growth. A high intensity of precipitation has been forecasted for central Europe. This could result in a higher level of soil erosion and flood events (IPCC, 2001; IPCC, 2007; Schuchardt et al., 2008). Additionally, the negative effect of sediment might be stronger on the biota in low flow basins, where hot and dry periods in summer frequently occur.

This research project focuses on the investigation of fine sediment deposition in small headwater streams, which are not monitored for the WFD but strongly determine the quality of larger water bodies. However, the better understanding of the relationship between fine sediment load and the benthic fauna is also transferable to larger streams and rivers. Furthermore, a successful sediment management of river basins requires an integral approach that also takes into account the small headwater streams. Two main aspects of the thesis are which environmental variables influence the input of fine sediment into streams and, secondly, what effect does the enhanced fine sediment have on the biota? Hence, this introduction especially addresses the theoretical knowledge about the pathways and processes of sediment input as well as the physical and biological impact of fine sediment in the running waters.

Sediment arrives in aquatic systems due to soil erosion, which is influenced by climatic (precipitation rate, temperature), geologic (soil type) and topographic conditions (slope gradient and length) as well as by the catchment vegetation cover (Wischmeier and Smith, 1978). The suspended solid underlies a temporal and spatial variability related to a large supply during / after extreme rainfall events, such as storms or snow melt as well as to a hydraulic shift of particles (Milly et al., 2008; Collins et al., 2011). Long-term forecasts of the suspended sediment load are therefore difficult to predict if not impossible.

The sediment travels from the eroded stream banks or hillslopes to a large degree as mass-movement events mobilised by gravitated and hydraulic forces. Management activities, such as the mechanical application of land clearing, tillage, localisation of forestry and agricultural roads, livestock trampling, mining and urbanisation near streams, are responsible for the magnification of erosion and nutrient runoff (Jones et al., 2001; Paul and Meyer, 2001; Quinn and Stroud, 2002; Allan, 2004). Small headwater streams are characterised generally by a high input of sediment and organic matter from terrestrial land, which are stored temporarily in the streambed and also transported downstream in large amounts (from Gomi et al., 2002; Figure 1.1).

An extended riparian zone is hardly present in the landscape of Central Europe today. Hence, the extensive modification of the landscape caused its reduction to a small marginal zone, which decreases efficiency of sediment and nutrient retention. In order to reduce the sediment and nutrient runoff, both the maintenance and expansion of vegetated buffer zones and comprehensive measures for a sustainable agricultural practice in the catchment area are required (e.g., Parkyn, 2004; Yates et al., 2007; Diebel et al., 2009).

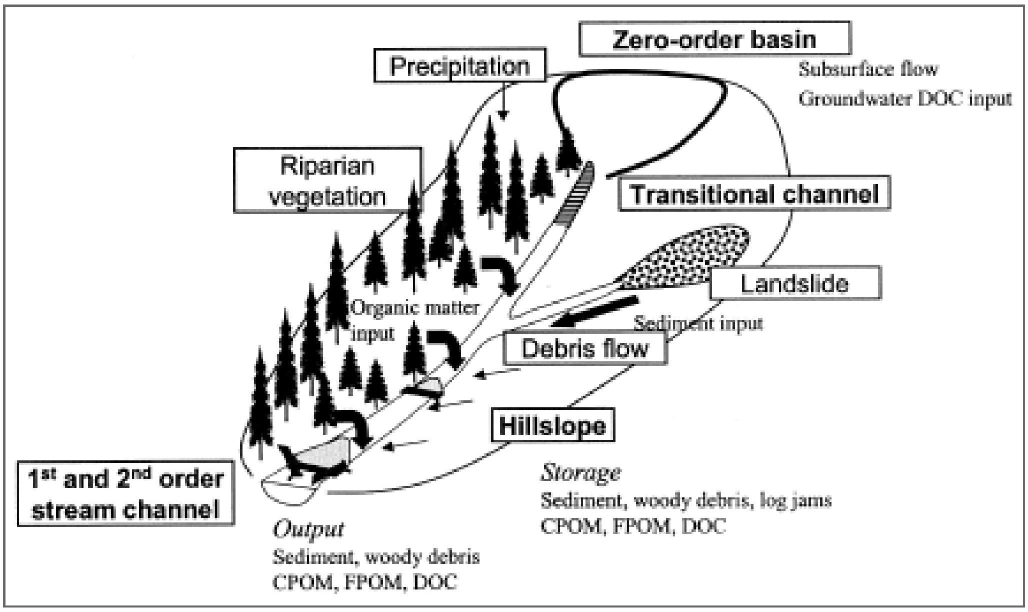

Figure 1.1: Processes and structures in headwater systems. Four topographic units compose headwater system (bold type): hillslopes, transitional channels (temporary or ephemeral channels emerging from zero-order basins), and first- and second-order stream channels. DOC = dissolved organic carbon; CPOM = coarse particulate organic matter; FPOM = fine particulate organic matter (from Gomi et al., 2002).

The modelling of soil and nutrients runoff is an important scientific tool for identifying main entry pathways and for assessing quantities. There are many erosion models related to small catchment areas or large river basins. The models are not described here in detail since this would be beyond the scope of this study. The Universal Soil Loss Equation (USLE) based on Wischmeier and Smith (1978) is widely used today. But this model does not adequately consider the spatial distribution of vegetation and land use or transport mechanisms; therefore, it is inaccurate (Gumiere et al., 2011). In contrast, the process models are restricted to local distribution, very elaborate and costly in their application. Therefore, they are not suitable for a broad range of users.

The shape and size of particles as well as flow patterns have an influence on the transport, storage and accumulation processes on the streambed. The presence of riffle-pool sequences, a high diversity of lateral and longitudinal barriers (large tree trunks or branches, boulders) contributes to the sedimentation of suspended solids. Thus, due to changes in flow direction or velocity, various deposition patches can develop. The increased fine sediment in the running waters is generally present as suspended solids in the water or deposited as a layer on the streambed. But due to the re-suspension process of an instable deposited layer, both level continually interact (Righetti and Lucarelli, 2010). The physicochemical and biological response to enhanced sediment load in running waters is summarised by Figure 1.2.

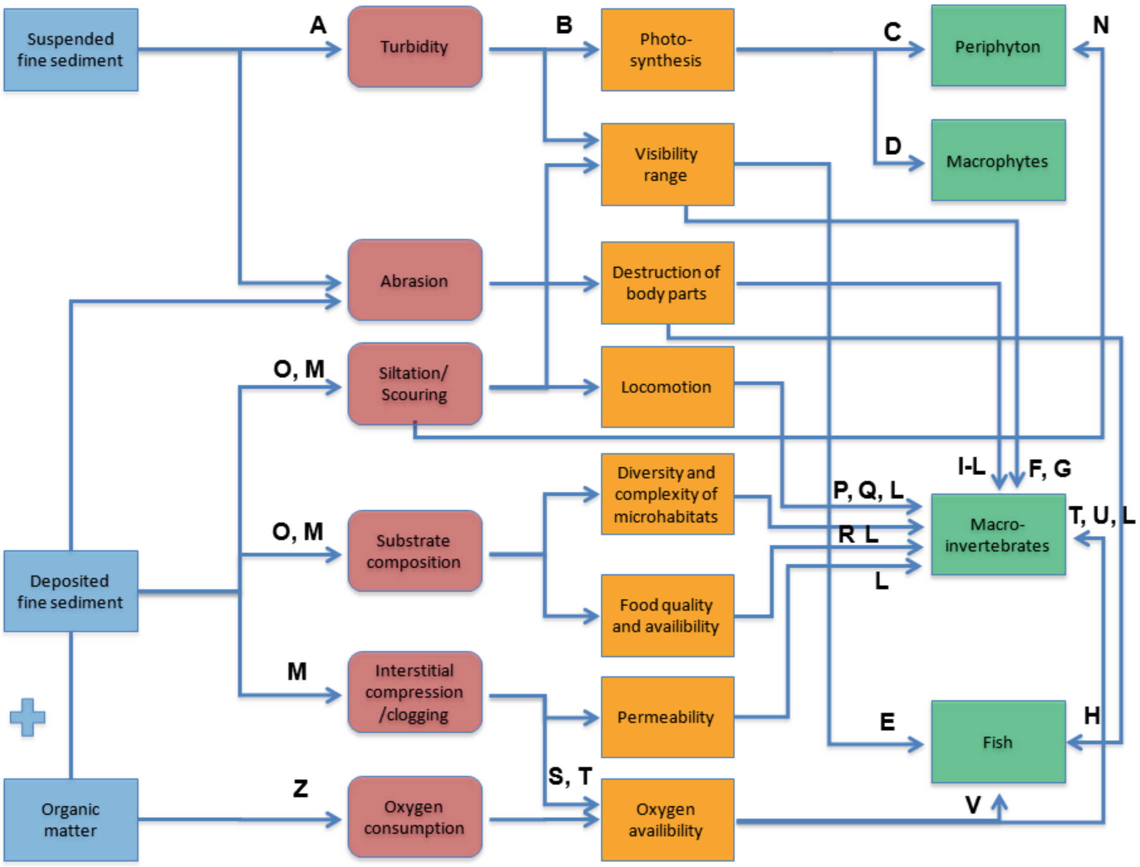

Figure 1.2: The individual effect of suspended and deposited fine sediment load and the contribution of organic matter, respectively (blue box) on stream properties (red box) and different aquatic groups (periphyton = benthic microalgae and bacteria; macrophytes = aquatic plans; fish and benthic macroinvertebrates; green box) in running waters. The yellow box shows physical effect on biota. Some of the references cited in this section are marked with a capital letter.

The high turbidity as a result of the enhanced suspended fine sediment concentration and the particle size and shape (Bilotta and Brazier, 2008; [**A**]) affects the light penetration and its intensity, which influences the photosynthesis of autotroph organisms (Van Nieuwenhuyse and LaPerriere, 1986; Lloyd et al., 1987; Davies-Colley et al., 1992; Bilotta and Brazier, 2008; [**B**]), the quality of periphyton (Quinn et al., 1992; [**C**]) and the growth of macrophytes (Parkhill and Gulliver, 2002; [**D**]). Both the turbidity and the high density of sediment on the streambed reduce the visibility range, which can alter the predator-prey relationship. The visually hunting predators such as fishes (Abrahams and Kattenfeld, 1997; [**E**]) and benthic insect predators (Peckarsky, 1985; Walde, 1986; [**F**]) might be disadvantaged or, on the other hand, benefit due to the susceptibility of the prey resulting from their distracted behaviour (Cover et al., 2008; [**G**]). The shift of large sediment particles such as sand or high amounts of small particles in the suspension or in the bedded load associated with high flow velocity and turbulence induce the abrasion. This can result in mechanic damage or destruction of body parts of fishes (Newcombe and MacDonald, 1991; [**H**]) as well as of the filtering-feeding mechanisms of certain invertebrates. The filtering apparatus of mussels or blackflies might also be clogged by high amounts of fine material, which decreases the efficiency of feeding (Gaugler and Molloy, 1980; MacIsaac and Rocha, 1995; Iglesias et al., 1996, Jones et al., 2011; [**I-L**]).

In contrast to a suspended load, the effects of deposited fine sediment are more widespread and pervasive, causing the altering of community levels and composition (Henley et al., 2000; Suren et al., 2005; Sullivan and Watzin, 2010; Jones et al., 2011).

The increased deposition of surficial sediment or bedded fine sediment, which fill up the spaces between the larger stones such as gravel, pebbles or boulders (interstitial spaces), also has an important level of impact (Schälchli, 1992; [**M**]). The solitary grains of fine particle are accumulated on the surface of hard substrates covered by periphyton and are entrapped within their microalgae matrix. This causes a modification of periphytic biomass (Schofield et al., 2004; Izagirre et al., 2009; [**N**]) and, moreover, of the qualitative change of food sources for benthic grazers (Jones et al., 2011; [**L**]). The compression of the streambed and the aggregation of cohesive sediments cause an alteration of the physical structure of the substrate (Sullivan and Watzin, 2010; [**O**]). Hence, the recirculation of solitary sand grains and absence of compacted structures on the streambed hinder the locomotion of certain aquatic animals such as crawling or burrowing invertebrates (Wood et al., 2005; [**P**]; Jones et al., 2011; [**L**]). Certain insects which occur in the silty and muddy sections with high suspended load are tend to increase drift (e.g., Culp et al., 1986; Suren and Jowett, 2001; Larsen and Ormerod, 2010; [**Q**]). The various experimental and field studies also observed a modification of the community composition (Zweig and Rabeni, 2001; Larsen et al., 2009; [**R**]), a decreased biodiversity (e.g., Matthaei et al., 2006; Larsen et al., 2009; Larsen and Ormerod, 2010), changes in density (e.g., Larsen and Ormerod, 2010), and shifted top-down effects (Schofield et al., 2004). The occurrence of sensitive species such as the larvae of mayflies (Ephemeroptera), stoneflies (Plecoptera) and caddis flies (Trichoptera) were also decreased (EPT taxa; e.g., Kaller and Hartman, 2004; Matthaei et al., 2006).

The progressive fine sediment deposition results in clogging and embedding of interstitial spaces (Schälchli, 1992; [**M**]), which reduce their permeability (Schälchli, 1992) and porosity (Gayraud and Philippe, 2003), hence the water infiltrations and oxygen supply decrease (Schälchli, 2002; Sarriquet et al., 2007; [**S-T**]). This process restricts the important function of the interstitial spaces for benthic animals, as refugial areas from predators or flood events, as a distribution corridor, and as habitat for small larvae of benthic invertebrates (Sarriquet et al., 2007; [**T**], Jones et al., 2011; [**L**]) as well as for reproduction of gravel-spawning fishes and molluscs such as freshwater pearl mussels (Österling et al., 2010; Kemp et al., 2011; [**U-V**]).

The enhanced organic content provides the food sources and hence has primarily a positive effect on the primary producers and on specific trophic guilds of benthic macroinvertebrates such as filtering feeders, grazers, gathers and collectors (e.g., Wipfli et al., 2007). On the other hand, it results in the modification of physical conditions, particularly due to oxygen-reducing bioaccumulation processes in the interstitial such as microbial decomposition (Nguyen, 2000; [**Z**]).

In intensively used catchment areas, multiple environmental stressors simultaneously have an effect on the aquatic biota (Lemly, 1982; Matthaei et al., 2006; Ormerod et al., 2010). Thus, the separate effect of the individual variable such as fine sediment may intensify due to a synergy with certain other variables (Lemly, 1982; Matthaei et al., 2006; Ormerod et al., 2010). The diffuse input of nutrients and solids due to farming and the modification of flow patterns (e.g., water impoundment) alter the flow patterns, which can affect the sediment supply and its behaviour.

The commonly mentioned studies concerning the input of deposited fine sediment on benthic macroinvertebrates are connected to increased fine sediment entry due to anthropogenic management activity in the ambience of streams such as forestry, roads, construction runoffs or mining (e.g., Quinn et al., 1992; Kaller and Hartman, 2004; Weiss and Reice, 2005; Cover et al., 2008). Field studies on fine sediment in upland brooks are rare and related to specific geographical regions such as in the U.S.A. (Hutchens et al., 2009; Bryce et al., 2010; Relyea et al., 2012), in Wales U.K. (Larsen et al., 2009) or in New Zealand (Wagenhoff et al., 2011). Thus, the characteristics of small headwaters are based on existing literature (e.g., Webster et al., 1990; Perrow et al., 1997; Sidle et al., 2000; Peterson et al., 2001; Gomi et al., 2002; Lowe and Likens, 2005; Hassan et al., 2005; MacDonald and Coe, 2007; Wipfli et al., 2007; Clarke et al., 2008). The small headwaters are characterised as follows:

- The streambed is dominated by the coarse-grained substrates (e.g., fine to coarse grained gravel, cobbles and boulders) with a deep and well-developed interstitial spaces and well-connected ground water.
- The baseline of the stream is characterised by low sinuosity with frequent changes of riffle-pool sequences, supported by a high diversity of lateral and longitudinal barriers such as large woods, branches or large stones.
- The water body is characterised by a cool and stable temperature. The terrestrial input of sediments and nutrients determines the physicochemical water conditions.
- The channel flow is low throughout the year with a higher peak flow during or after the snow melting and heavy rain periods derived from surficial and sub-surficial runoff.
- The riparian zone is a narrow corridor between the relatively steep slopes and is dominated by riparian forest in nearly natural conditions.
- The primary production consists of microalgae on the surface of streambed (periphyton); aquatic plants are generally absent because of high shading effects of surrounding vegetation.
- The benthic macroinvertebrate fauna is characterised by a high number of individuals and diverse communities; the fish fauna of Europe are dominated by two species: brook trout (*Salmo trutta*) and bullhead (*Cottus gobio*).

Scope of thesis

There has been no comprehensive case study on the effect of sedimentation on benthic macroinvertebrates in small headwater streams in Central Europe yet. This field study has been performed in the middle catchment area of the river Our in the Ardennes mountain range in northern Luxembourg in cooperation with the LIFE-Nature-Project „Restoration of Freshwater Pearl Mussel populations in the Ardennes" (LIFE 05 NAT /L/000116). The siltation of the stream bottom of the river Our impairs the rare buried mussel populations. The large amount of fine sediment originates in the tributaries and results from the increased soil erosion in the catchment area. The soil types are characterised and dominated by siliceous Cambisols with a large proportion of stones and layers of clay and silt. The agricultural land use on the slopes in the area intensifies the erosive forces. The studied upland streams are of

1st and 2nd order and run into the river Our (nine tributaries, Luxembourg). Two of the streams are located in the Rhineland-Palatinate (Germany; Figure 1.3). In order to assess the main pathways of sediment input in the catchment area, the sampling sites were generally carried out upstream and downstream near junctions of brooks into the Our. We also selected generally ambient forested sites with coniferous (spruce) and deciduous forests (beech, oak, alder) due to the supposed effect of surrounding riparian vegetation on sediment trapping and distribution of adult insects. With the quantitative measurement of surficial deposited fine sediment, environmental data and benthic invertebrates, we addressed the following research questions:

(1) Which environmental variables affect the delivery and deposition of fine sediment?
(2) What impact does the increased fine sediment depositions have on the benthic macroinvertebrates? The second question is the main focus of this thesis.

The objective of this thesis is to quantify and to investigate the terrestrial input sources and the deposition of fine sediment in the 1st and 2nd order upland streams in Central Europe in order to identify explanatory variables and to develop water management measurements for reducing fine sediment input and downstream transports. In order to clarify the linkage between deposited fine sediment and the physical and biological contributions to running waters, the deposited fine sediment in the tributaries of the Our were examined over one year (chapter 2). The linkage of the benthic macroinvertebrates and fine sediment deposition are constituted in chapter 3 and 4. The extended descriptions of the hypotheses follow below.

Figure 1.3: Samples sites; top left: Heimbach (Heim1), October 2008; top right: Janschledeer Bach (J1) site downstream streambed substrates, September 2008; below left: Schleierbaach upstream tributary of Stroumbaach (S5), September 2008; below right: Langbaach (L1) upstream tributary of Janschledeer Bach, September 2008.

This thesis includes the following sections. Each sections exams the hypotheses described below each section headings.

(1) *The impact of environmental variables of different spatial scales on the deposited fine sediment*

The anthropogenic land use, particularly of agricultural land management in the catchment or in the surrounding land, impacts the susceptibility of erosion and retention of soils. This induces the intensive sediment entry and nutrients runoff into streams and rivers. The hydromorphological and dynamic patterns determine the substrate distribution and sedimentation on the streambed. The components of deposited fine sediment (inorganic or organic) are equally strongly dependent on different environmental variables on the spatial scale; for example fine sediment is dependent on the proportion of arable land; organic matter on the vegetation composition; the C/N ratio on the water's chemical properties (chapter 2).

(2) *The impact of deposited fine sediment on the macroinvertebrate community composition*

The high amount of surficial deposited fine sediment influences the physical conditions of running water and their biota. The high mobilisation of deposited layer, the siltation and covering of substrates and the enrichment of organic matter lead to various impairments on physiological and behavioural levels of the biota. The loss of microhabitats, the modification of the availability of food sources and compositions as well as oxygen reduction shaped the compositions and densities of macroinvertebrate communities (chapter 3).

(3) *The impact of deposited fine sediment on eight taxa of mayflies (Ephemeroptera) and caddisflies (Trichoptera)*

The life-history patterns and ecological traits such as trophic gilds, micro- and mesohabitat preferences are species-specific. The response to the deposition of fine sediment is also species-specific (chapter 4).

2 The impact of environmental variables on the deposited fine sediment

2.1 Introduction

Fine sediments eroded from agricultural areas and forest monocultures enter streams and rivers worldwide in increasing amounts (Walling and Fang, 2003). In contrast to other stressors such as eutrophication and organic and toxic pollution, the process of fine sediment entry, deposition and re-mobilisation is still poorly understood, although the phenomenon is very widespread (Lemly, 1982; Collins et al., 2011).

Fine particles (< 2 mm diameter) contain inorganic fractions (clay, silt and, sand particles) and organic matter. Organic matter is primarily derived from eroded plant litter and wood, deposited in coarse (CPOM) and fine particulate forms (FPOM) or transported as dissolved organic matter (DOM) or suspended particles (Gomi et al., 2002; Richardson et al., 2005; MacDonald and Coe, 2007). The transport of suspended fine particles, as well as their retention and accumulation on the streambed, is determined by channel morphology (e.g., substrate type, slope), hydrodynamic parameters (e.g., flow velocity and discharge) and particle size and shape (Wipfli et al., 2007). The major source of fine material in headwater streams is derived from the hillslopes and the surrounding riparian zone (MacDonald and Coe, 2007; Martinez-Carreras et al., 2010). Riparian buffer zones may improve sediment trapping, which is dependent on spatial and vertical characteristics, riparian species and sediment type (Parkyn, 2004; Gumiere et al., 2011). Riparian modifications, such as timber harvesting and road-building, may reduce the retentiveness of fine particles, as is reflected by enhanced suspended sediment and dissolved organic carbon (DOC) in the water (May, 2002; Gomi et al., 2005; Richardson et al., 2005). Moreover, modifications to land use (e.g., intensification of agriculture, urban development, mining) alter overland flow, with enhanced input of fine sediment, organic matter and nutrients into aquatic systems (Jones et al., 2001; Gomi and Sidle, 2003; Kaplan et al., 2006; Wipfli et al., 2007; Molinero and Burke, 2009). Knowledge of sediment sources and nutrient runoff patterns is of great importance to reduce soil erosion and the sediment load entering headwaters, particularly because soil erosion may increase due to the increasing frequency of extreme precipitation events (IPCC, 2007; Schuchardt et al., 2008).

The deposited fine particles provide the aquatic biota with an essential food source (Wipfli et al., 2007). At the same time, the increasing sedimentation of inorganic particles modifies the habitats and changes the community structure and abundance (Wood and Armitage, 1997; Zweig and Rabeni, 2001; Rabeni et al., 2005; Larsen and Ormerod, 2010; Jones et al., 2011). Most of the mentioned studies measured fine sediment deposition at the time of aquatic invertebrate sampling; however, the supply of fine particles in running waters is spatially and temporally variable (Trimble, 1999, Anderson and Lockaby, 2011). Particularly after heavy rainfall and snow melt, there is a major increase in suspended matter (Molinero and Burke, 2009, López-Tarazón et al., 2010). These episodic events may affect the aquatic biota in sensitive phases of their life cycles or may cause strong organismic drift for a short period of time (Jones et al., 2011). The enhanced suspended sediment and significant abrasion of particles cause physical damage to the nets and cases of biota and clog the filtering mechanisms of certain benthic invertebrate (Armitage and Blackburn, 2001; Jones et al., 2011). The siltation of a streambed can affect food and habitat quality and availability due to the loss of habitat complexity, sediment aggregation, and clogging with fine sediment in interstitial of gravels and boulders (Schälchli, 1992; Jones et al., 2011). Furthermore, the fine sediment combined with fine particulate organic matter and nutrients influences the bioavailability of oxygen in the interstitial waters and thus the reproductive success of both salmonids spawning in gravel beds and young freshwater pearl mussels (Soulsby et al., 2001; Österling et al., 2010). The snapshots of sediment input and deposition do not always provide a clear picture of the sedimentary effects on biota.

In the present study, we collected and examined deposited sediments in headwater streams (tributaries of the river Our, Luxembourg) a period of one year. First, we aimed to qualify the influence of different factors acting on different spatial scales on sedimentation as well as the influence of sediment components (fine sediment, organic matter, C/N ratio). To accomplish this goal several environmental variables were measured on three spatial scales, namely the catchment, riparian and in-stream scales, and their explanatory variation was quantified. Furthermore, the single environmental parameters influencing the deposition of fine particles were identified to gain more insight into the drivers of sediment input and deposition in headwaters. As we were also interested in the seasonal variability of the sedimentation rates, sediment deposition and input were analysed separately for spring, summer, autumn and winter. Finally, because the eroded sediment release into the headwater streams acts as a potential stressor disturbing important habitats, food sources and life cycles, management measures to decrease the supply of fine particles into the headwater streams are suggested and discussed.

2.2 Methods

2.2.1 Study area and streams

The study area is located in the Ardennes mountain range in northern Luxembourg (Europe) at altitudes between 286 and 530 m above sea level (Figure 2.1). The dominant soil type is siliceous Cambisols with a large proportion of stones and partially characterised by layers of clay and silt (Colling et al., 1994). The upper parts are mainly used as cropland (rape, maize, corn) and pasture with some smaller villages, whereas the lower parts, including the valleys of the streams, are mainly covered with coniferous (*Picea abies)* and deciduous forests *(Fagus sylvatica, Carpinus betulus, Quercus petraea, Q. robur)*.

29 sampling sites were selected in 1st and 2nd order upland streams within catchment areas ranging from 0.4 to 6.4 km^2. All of the investigated streams are permanent; the bankfull stream width ranges between 0.8 and 7 m, while the wetted zone is 0.5 to 4 m wide for the majority of the year. The stream banks are steep and 0.1 to 3.5 m high; the channels are dominated by riffles (approximately 85%). The nitrate concentration is 10.77 mg l^{-1}, the ammonium concentration is 0.19 mg l^{-1}, the pH ranges from 7.1 to 7.8, and the conductivity ranges from 126 to 253 µS cm^{-1}.

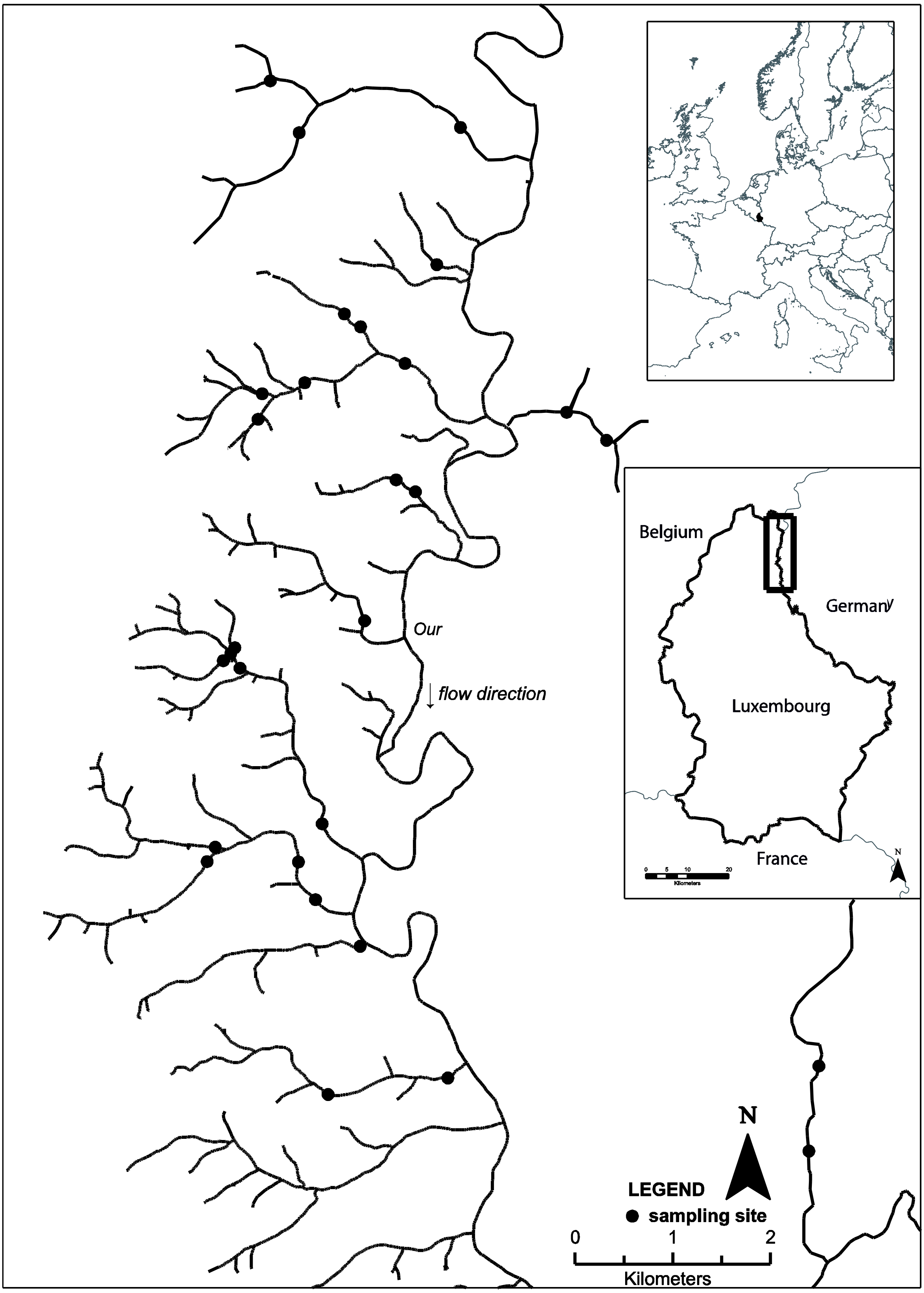

Figure 2.1: Sampling sites and streams in the Our catchment (Luxembourg / Germany).

2.2.2 Sediment sampling

Deposited fine sediment was collected from September 2008 to September 2009 with artificial turf mats (10 x 15 cm) that were anchored with cable ties and iron sticks to the streambed (two samples per site; total per event n = 58). Every three weeks, they were removed from the substrate and carefully transferred into zip-lock plastic bags to avoid any sediment loss and were replaced by new mats placed at the same locations. After transporting the samples to the laboratory, the mats were placed upside down in aluminium dishes containing tap water. After two hours, the mats were transferred into a second dish and rinsed. The coarse inorganic and organic matter (>2 mm) was removed and discarded. After the deposit of the fine sediment, the supernatant water was siphoned off with a tube. The fine sediment was dried in a compartment drier (Memmert, Modell UFE-600) at 100°C for five hours and then weighed; the resulting amounts of sediment deposition per sampling site and per season were measured in kg m^{-2}. The seasons were defined as follows: winter (December to February), spring (March to May), summer (June to August) and autumn (September to November) (Table 2.1).

Table 2.1: Mean ± SD values and range of fine sediment deposition, organic matter content and C/N ratios for 29 headwater streams sampled in 2008-2009 in the Our catchment Luxembourg (Europe). The organic matter and C/N ratios are proportion of the fine sediment content measured.

Variable	Season	Unit	Mean ± SD	Range
Fine sediment	winter	kg m^{-2}	6.1 ± 2.4	2.0 - 10.9
Fine sediment	spring	kg m^{-2}	2.0 ± 1.2	0.3 - 4.8
Fine sediment	summer	kg m^{-2}	1.3 ± 1.6	0.2 - 6.6
Fine sediment	autumn	kg m^{-2}	1.1 ± 1.1	0.2 - 5.4
Organic matter	winter	% $site^{-1}$	6.6 ± 2.4	3.6 - 11.6
Organic matter	spring	% $site^{-1}$	10.2 ± 3.4	4.9 - 16.0
Organic matter	summer	% $site^{-1}$	15.6 ± 3.8	8.8 - 24.8
Organic matter	autumn	% $site^{-1}$	16.1 ± 4.7	7.4 - 26.3
C/N	winter	ratio $site^{-1}$	11.7 ± 1.8	9.6 - 11.2
C/N	spring	ratio $site^{-1}$	13.3 ± 2.2	10.4 - 18.5
C/N	summer	ratio $site^{-1}$	13.8 ± 2.0	9.6 - 18.0
C/N	autumn	ratio $site^{-1}$	13.6 ± 2.1	10.5 - 18.8

The total carbon (TC) and total nitrogen (TN) in the fine sediments were measured with an Elemental Analyser (EuroEA, HEKAtech GmbH). Because the sediment samples contained no $CaCO_3$, the TC corresponded to organic carbon (OC) only.

However, as the soil material contains 58% carbon (Rowell, 1994; Ad-hoc-Arbeitsgruppe Boden, 2005), the organic carbon content was multiplied by 1.724. The C/N ratio was calculated as the organic carbon (OC) divided by the total nitrogen (TN).

2.2.3 Explanatory variables

29 environmental variables potentially influencing the sediment input and describing characteristics of the catchment (C), riparian zone (R) and in-stream (S) habitats were recorded for each site (Table 2.2). On the catchment scale (C), we recorded the area and land-cover variables and calculated the potential soil input using the USLE (Universal Soil Loss Equation) Erosion Model (Table 2.2). The land-cover categories were based on the Corine Land Cover, third level (Commission of the European Communities, (CEC), 1993), where the forest area was divided into deciduous and coniferous forest. The percentage of land cover was partly obtained from the Interreg Projekt NATOUR and Occupation Biophysique du Sol (OBS; 1999) project and completed during the investigation for the sampling sites in ArcGIS version 9.2 (Environmental Systems Research Institute, ESRI). The USLE Erosion Model was developed in Luxembourg (Martinez-Carreras et al., 2007) to estimate the Soil Erosion Potential and is based on the USLE developed by Wischmeier and Smith (1978). It predicts the soil loss in tons per hectare per annum (t ha^{-1} yr^{-1}).

For the riparian zone scale (R), the vegetation types and shading were estimated as the percentage cover for a stretch of 25 m upstream and of 25 m downstream of the sampling sites and for 5-m-wide strips (Table 2.2).

Table 2.2: Mean ± SD values and range of environmental variables on different scales variables recorded for the 29 sampling sites. USLE = Soil Erosion Potential; CPOM = coarse particulate organic matter. Max. = Maximum values

Variable	**Unit**	**Mean ± SD**	**Range**
Catchment (C)			
Area	km^2	2.0 ± 1.6	0.3 - 6.4
Deciduous forest	%	13.5 ± 9.3	0.0 - 30.3
Coniferous forest	%	19.9 ± 9.7	5.2 - 45.3
Cropland	%	26.6 ± 11.8	4.8 - 57.1
Pasture	%	30.8 ± 8.8	14.6 - 47.2
Urban development	%	3.8 ± 3.3	0.0 - 10.8
USLE	t ha^{-1} yr^{-1}	2.4 ± 0.6	1.0 - 3.8
Riparian zone (R)			
Coniferous forest	%	22.6 ± 30.0	0 – 100
Deciduous forest	%	14.4 ± 22.2	0 - 72.5
Grassland	%	9.9 ± 28.9	0 – 100
Herb layer (ferns, mosses)	%	32.9 ± 36.8	0 – 100
Land use (5 m)			
Coniferous forest	%	46.6 ± 40.4	0 – 100
Deciduous forest	%	19.1 ± 32.7	0 – 100
Grassland	%	7.4 ± 17.6	0 – 50
Shading	%	68.4 ± 29.1	0 – 100
In-stream (S)			
Fine gravel (0.2 – 2 cm)	%	6.7 ± 8.7	0 – 30
Microlithal (2 – 6 cm)	%	21.9 ± 12.1	0 – 50
Macrolithal (20 – 40 cm)	%	8.3 ± 12.0	0 – 40
CPOM	%	7.8 ± 5.1	0 – 20
Dead wood	%	6.2 ± 8.7	0 – 40
Mean velocity (riffles)	m s^{-1}	0.3 ± 0.1	0.1 - 0.7
Mean depth (riffles)	m	0.1 ± 0.1	0.1 - 0.3
Mean velocity (pool)	m s^{-1}	0.1 ± 0.1	0.1 - 0.3
Mean depth (pool)	m	0.1 ± 0.1	0.1 - 0.3
Stream width	m	3.0 ± 1.7	0.8 - 7.0
Max. bank height (R/L)	m	1.0 ± 1.1	0.2 - 3.5
Max. conductivity	µS cm^{-1}	239.5 ± 48.7	146.5 - 329.0
NH_4^+	mg l^{-1}	0.2 ± 0.1	0.1 - 0.4

The in-stream variables (S) included the substrate cover and the morphometrical and physiochemical stream characteristics (Table 2.2). The percentage cover of the different substrates and morphometric variables was estimated for a stretch 25 m upstream and 25 m downstream of the sampling site and was measured before and after the sediment sampling period. The stream width, water depth and left and right bank heights (in metres) were measured. Adjacent to the location of the turf mats, the flow velocity (m s^{-1}) was determined with a hydrometric vane (MiniAir2, Schiltknecht), and the water depths (m) of riffles and pools were measured during both the spring and summer. The water samples were taken once per sampling season and analysed for pH, dissolved oxygen, (mg l^{-1}) and available oxygen (%); the NH_4^+ was measured using a photometric method by the 109713 Nitrate Test (DMP 0.10 - 25.0 mg l^{-1}l NO_3^-N 0.4 - 110.7 mg l^{-1} NO_3^- Spectroquant®). The conductivity (µS cm^{-1}) was measured using a Multi350i (WTW) at the time of sediment sampling, and the maximum values were used for further analyses.

2.2.4 Data analysis

A Detrended Correspondence Analysis (DCA) was performed to obtain the gradient length for the three dependent variables separately. For all three variables, the gradient lengths were less than 1.5 and we used the linear method redundancy analysis (RDA) for quantifying the influence of different environmental variables on the seasonal means of the deposited fine sediment, % organic matter and C/N ratio. In a first run of the RDA, the entire set of 28 environmental variables were tested to identify the variables significantly influencing the fine sediment deposition, organic matter and C/N ratio using a Monte Carlo permutation test (499 unrestricted permutations) and Bonferroni correction. Explanatory variables not significantly correlated with the three dependent variables were omitted from further analyses. In a second step, the method of variation partitioning (pRDA) first described by Borcard et al. (1992) and extended by Anderson and Gribble (1998) was used to quantify the variation in the deposited fine sediment, organic matter (%) and C/N ratio explained by the catchment, riparian zone and in-stream factors. The environmental variables were grouped into three components depending on their scale or function: catchment (C), riparian zone (R), and in-stream morphometry (S) (Table 2.2, Figure 2.2). In the first run, a RDA with the remaining environmental variables from the first screening without any co-variables was performed to quantify the total variance (explained and unexplained). Then, several partial RDAs (pRDAs) were performed with two groups of environmental variables and with the third group as co-variables and vice versa. For instance, a run consisted of the C and R variables as environmental variables and the S variables as co-variables. This step was repeated three times with different combinations of all groups, resulting in a total of 13 runs (Table 2.3). This procedure was repeated for each dependent variable (i.e., fine sediment, organic matter and C/N ratio) separately. Thus, the total variation of each dependent variable was decomposed into seven components including co-variable terms (Figure 2.2). To quantify the variance explained, different calculations were applied (Table 2.4). The unexplained variation was obtained through subtraction from the total variation (1.0 for RDA) and the variation explained by the three groups.

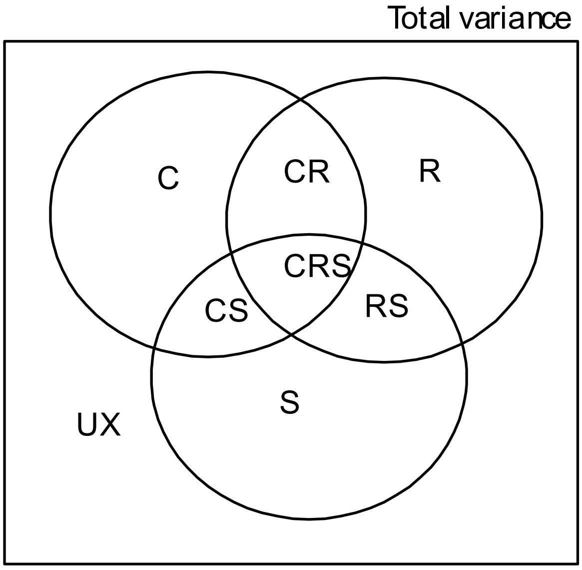

Figure 2.2: Schematic illustration of variation partitioning covering the proportion of catchment (C), riparian zone (R), in-stream site-scale (S) and unexplained (UX) variation. The CR (catchment / riparian zone), CS (catchment / in-stream) and RS (riparian zone / in-stream) show the percentage of variation shared by two spatial scales and CRS (catchment / riparian zone / in-stream) by all spatial scales together.

Prior to the analyses of all dependent variables, the outcome of the USLE Erosion Model, catchment area, morphometric and chemistry data and fine sediment content were log-transformed (x+1). The land-cover use/vegetation cover and substrate variables, as well as the shading and percentage of organic matter, were square root-transformed. The C/N ratio was untransformed. The RDA and pRDA analyses were run using CANOCO Version 4.5 (Ter Braak and Šmilauer, 2002).

Table 2.3: Procedure of variation partitioning of mean deposited fine sediment (n = 4), organic matter (n = 4) and C/N ratio (n = 4) explained by three sets of environmental variables, catchment (C), riparian zone (R), and in-stream site-scale (S) in partial redundancy analysis (pRDA).

Number of runs	Set of environmental variables	Set of co-variables	Eigenvalue Sediment	Eigenvalue Organic matter	Eigenvalue C/N ratio
1	CRS	None	0.997	0.978	0.977
2	Catchment	RS	0.246	0.236	0.334
3	RS	None	0.750	0.741	0.645
4	RS	Catchment	0.585	0.500	0.506
5	Catchment	None	0.412	0.478	0.470
6	Riparian	CS	0.219	0.155	0.100
7	CS	None	0.777	0.822	0.878
8	CS	Riparian	0.704	0.714	0.819
9	Riparian	None	0.293	0.264	0.158
10	In-stream	CR	0.329	0.360	0.390
11	CR	None	0.668	0.618	0.587
12	CR	In-stream	0.471	0.504	0.514
13	In-stream	None	0.525	0.473	0.464

2.3 Results

The amount of deposited fine sediment was greatest during the winter (6.1 kg m^{-2}) and varied between sampling sites (2 to 11 kg m^{-2}) but was very small in all of the other seasons, ranging from 1.1 kg m^{-2} in autumn to 2.0 kg m^{-2} in spring (Table 2.1). In contrast, the proportion of organic matter was smallest in winter (6.6% site^{-1}) but larger in all other seasons, ranging from 10.2 (spring) to 16 (autumn; % site^{-1}). The C/N ratio however, exhibited no seasonal variation, with a value of approximately 11.7 at its lowest in winter, and approximately 13 - 14 in the other seasons.

The environmental variables on the different scales explained nearly 100% of the total variation in the deposited fine sediment (eigenvalue $\lambda = 0.997$), organic matter (eigenvalue $\lambda = 0.978$) and C/N ratio (eigenvalue $\lambda = 0.977$) obtained by the RDA (Table 2.3). The fine deposited sediment was most influenced at the in-stream scale (S; 33%), whereas the catchment scale (C) explained 25%, followed by the riparian zone factors (R) with 22% (Figure 2.3). The combined effect of the catchment and in-stream scales (CS) explained 13% of the deposited fine sediment; the remaining combination of factors on different scales, i.e., the catchment and riparian (CR), catchment and in-stream (CS) and riparian and in-stream (RS) scales, explained less than 4% of the variation (Table 2.4, Figure 2.3).

Table 2.4: Total and unexplained variation for fine sediment, organic matter, and C/N ratio. Column 2 shows the calculation procedure to obtain explanatory power of each component. Λ = eigenvalue; OM = organic matter.

Variation explained	**CALCULATION (number of runs, Table 3)**	**Λ Sedimet**	**Λ OM**	**Λ C/N ratio**
Catchment	2	0.246	0.236	0.334
Riparian	6	0.219	0.155	0.100
In-stream	10	0.329	0.360	0.390
Catchment and riparian	12-6-2	0.006	0.113	0.080
Catchment and in-stream	8-2-10	0.129	0.118	0.095
Riparian and in-stream	4-6-10	0.037	-0.015	0.016
Catchment, riparian and in-stream	7-8-(12-6-2)-(4-6-10)	0.030	0.010	-0.037
Total explained	1	0.997	0.978	0.977
Unexplained	Total Variance-Total explained	0.003	0.022	0.023
Total Variance		1	1	1

Similarly, the organic matter content was best explained by factors on the in-stream scale (S, 37%) followed by the catchment and riparian zone scale factors (C, 24%, and R, 16%, respectively) (Table 2.4, Figure 2.3). Here, the joined effect of the catchment and riparian (CR) scales as well the catchment and in-stream (CS) scales explained 12% of the variation in organic matter content. The remaining combinations of factors on different scales, e.g., the riparian and in-stream (RS), as well as all factors (CRS) explained less than 2% of the variation.

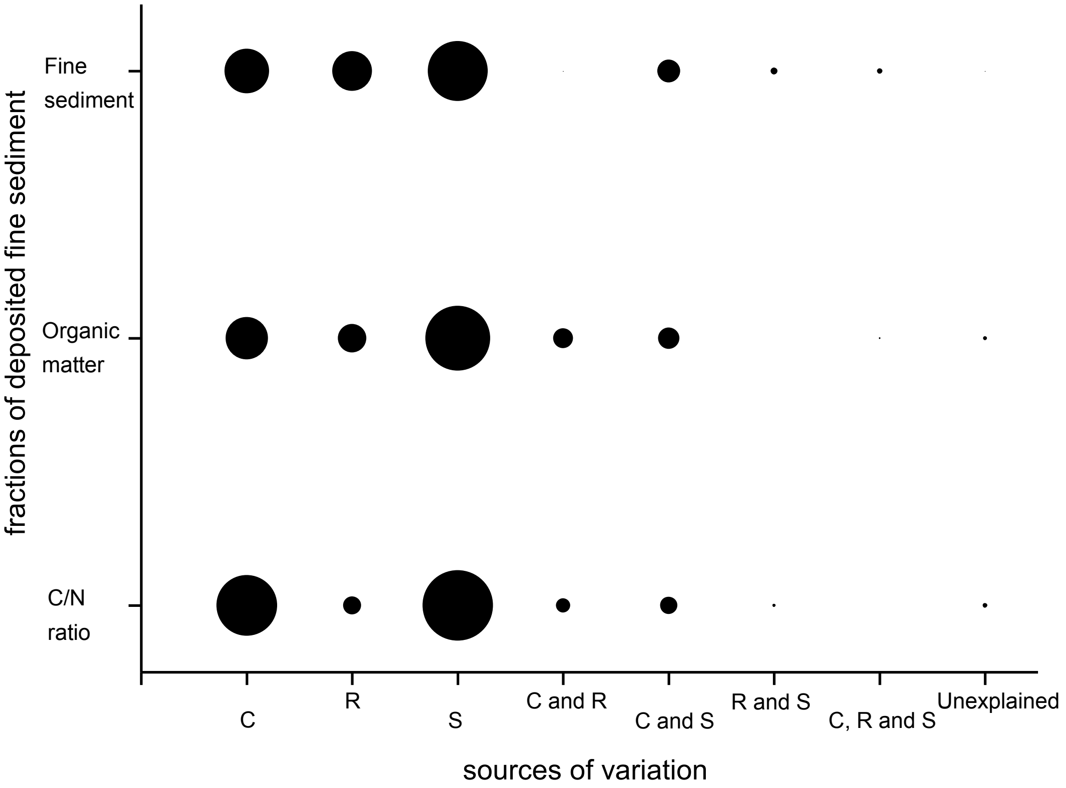

Figure 2.3: Proportion of variation in sediment deposition explained by groups of environmental factors (arranged for spatial scales) obtained by pRDA. C = Catchment; R = Riparian zone; S = In-stream factors. Unexplained shows the unexplained variation in sediment components by groups of spatial scales.

For the sediment C/N ratio of the sediment, in-stream factors alone explained 40% of the variability in the fine sediment deposition, followed by factors on the catchment scale, with 34% (Table 2.4, Figure 2.3). Both the riparian factors (R) and the combination of the catchment scale and in-stream (CS) factors accounted for 10% of the C/N ratio, whereas the combination of catchment and riparian scale factors (CR) accounted for 8%. The combination of riparian and in-stream factors (RS) explained 2% of the variation, whereas the combination of factors on all spatial scales (CRS) yielded a negative value (-0.04, Table 2.4).

In the RDA with fine sediments, the first two axes explained 40.6% (eigenvalue $\lambda = 0.406$) of the total variation (Figure 2.4 A), with two variables explaining significant parts of the variability in deposited fine sediments: coverage of fine gravel (18%, $F = 5.91$, $p = 0.004$) and percentage of cropland in the catchment (12%, $F = 4.47$, $p = 0.008$). The spring and summer sediment deposition correlated positively with the fine gravel coverage; the proportion of cropland in the catchment is related to the high fine sediment content in autumn.

For organic matter, the first two RDA axes explained 56.7% (eigenvalue $\lambda = 0.567$) of the total variation, and three explanatory variables were identified (Figure 2.4 B): the percentage of pasture in the catchment, with 20% ($F = 6.82$, $p = 0.002$); the coverage of fine gravel (11%, $F = 4.61$, $p = 0.016$); and the soil erosion according to the USLE Soil Erosion Model (9%, $F = 4.25$, $p = 0.008$). The enrichment of organic matter in spring, summer and autumn was strongly related to axis 1 and negatively correlated to fine gravel coverage and percentage of pasture.

For the C/N ratio, the first two RDA axes explained 50.3% (eigenvalue $\lambda = 0.503$) of the total variation. The seasonal variance of the C/N ratio was explained by three variables (Figure 2.4 C). The maximum value of the conductivity explained 17% of the C/N ratio variance ($F = 5.56$, $p = 0.006$), followed by the catchment area (16%, $F = 6.42$, $p = 0.010$) and the flow velocity in riffles (12%, $F = 5.15$, $p = 0.006$). During the winter, spring and summer, the C/N ratio was positively related to axis 1 and to the flow velocity in riffles but was negatively correlated with the maximum of conductivity. In autumn, the C/N ratio was negatively correlated with catchment area.

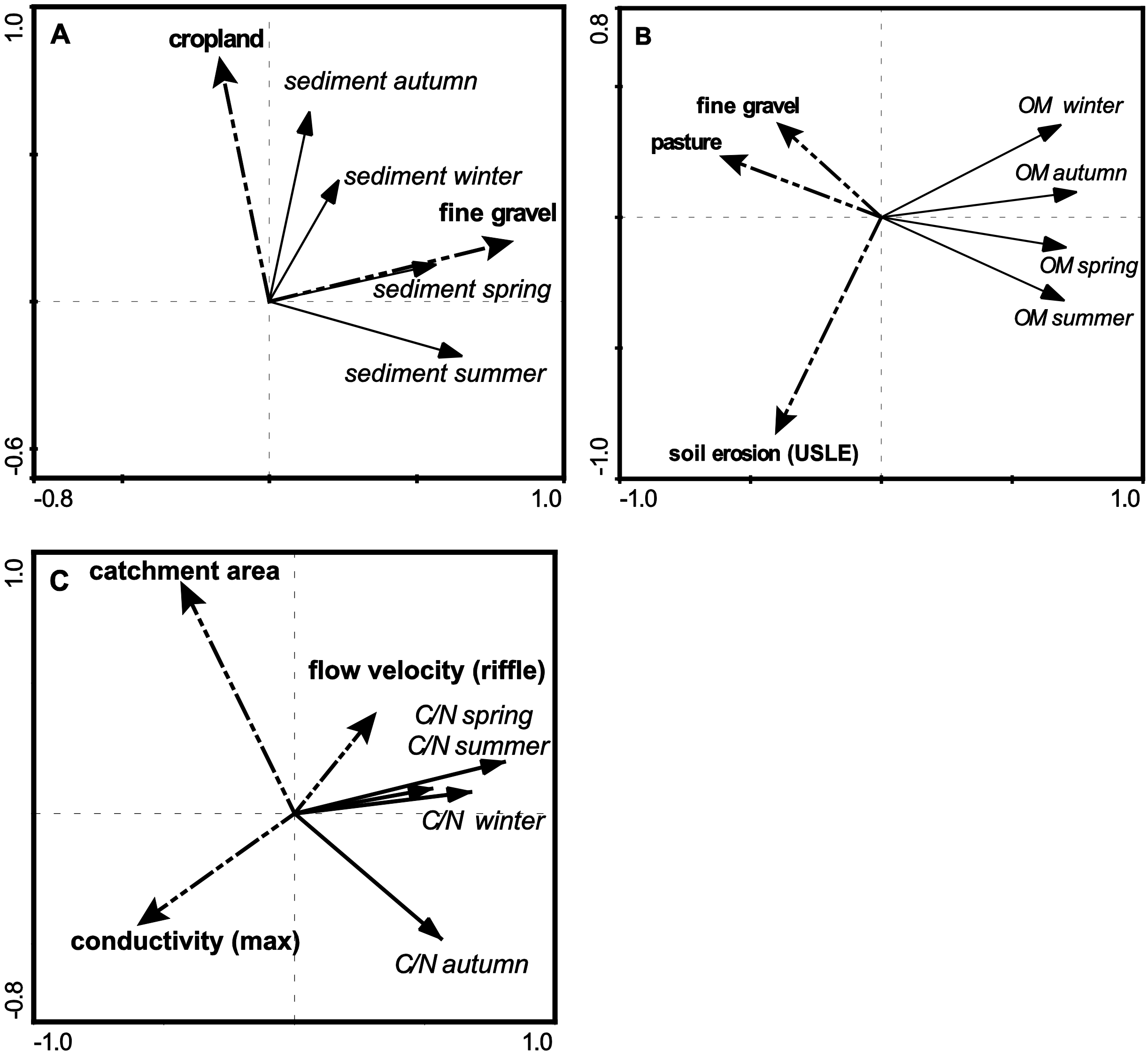

Figure 2.4: RDA biplots of environmental factors and relative share of depended variables for: A mean deposited fine sediment, B mean organic matter (OM), and C mean C/N ratios for different seasons. USLE = Universal Soil Loss Equation (t ha^{-1} yr^{-1}).

2.4 Discussion

2.4.1 The impact of spatial scales on sediment deposition

The results of the partial RDA revealed that the content of deposited fine sediment, nutrients and organic matter are most strongly influenced by in-stream and catchment factors. The in-stream variables reflected the deposition patterns, such as occurrence of substrate and flow velocity, as well as the increase in conductivity for the C/N ratio. The fine sediment and particulate organic matter in headwaters are stored short-term, but the major portion of fine particles is transported downstream (MacDonald and Coe, 2007). In contrast to nutrients, storage, dilution, biological uptake, diminution and chemical transformation occur mostly as a result of the hydrological in-stream processes of headwaters (MacDonald and Coe, 2007). The C/N ratio is more dependent on catchment scale in comparison to the remaining deposited components because of nonpoint supply of fertilisation from agricultural areas (Jones et al., 2001; Molinero and Burke, 2009). The impact of the surrounding riparian vegetation on the transfer and trapping of particulate fine particles is not as important as we assumed (Figure 2.3). This might be because of the narrower width and smaller length of the vegetation strip that was recorded. The effectiveness of fine sediment removal increases with the width; for example, for grasses to buffer, a width up to 10 m is required (Gharabaghi et al., 2002; Parkyn, 2004). Especially in this zone, we investigated the differences in sediment retention between the coniferous trees dominated by the shallow-rooted spruces and deciduous trees. Our results could not find any significant differences. The major importance of catchment scale results from the delivery of the fine sediment, organic matter and nutrients delivered into streams on a broad scale because of nonpoint input, which was observed in several studies (Lenat, 1984; Harding et al., 1998; Allan, 2004).

2.4.2 The impact of environmental factors on sediment deposition

The results of the partial RDA revealed that the deposited fine sediment, nutrient and organic matter contents are most strongly influenced by in-stream and catchment factors. In the following, we discuss the individual environmental variables explaining the sediment deposition patterns, beginning with the large-scale variables.

The catchment area explains the variability in the C/N ratios and organic matter; downstream sites are characterised by a smaller C/N ratio than upstream sites. This is likely a result of the general decomposition of organic matter, which is decomposed as it is transported with the current (Vannote et al., 1980, MacDonald and Coe, 2007). The majority of inorganic nitrogen in headwater channels is typically removed by biological assimilation or is transformed into atmospheric nitrous oxide by nitrification over short time spans corresponding to short distances (Peterson et al., 2001). The largest proportion of ammonium is stored by sorption to sediments (Peterson et al., 2001).

The soil erosion rates derived from the USLE Erosion Model explained only the variability of organic matter (9%), but not, as had been expected, the content of the fine sediment deposition. This might partly be because the USLE Model also addresses coarse and finest sediment fractions (> 2 mm), which were excluded from our study.

Cropland and pasture represented the major land cover categories and significantly influenced the deposited fine sediment and organic matter. This explains the large amount of fine sediment observed in winter. Our results are in line with many other studies (Morgan, 2005; Udawatta et al., 2006); sediments and nutrients may enter rivers as a result of agricultural practices and fertilisation (Jones et al., 2001; McDowell, 2006).

The maximum of the conductivity was negatively related to the C/N value. The linkage between the C/N ratio and conductivity demonstrated that nutrients might enter the streams separately from sediment particles. The C/N ratio is lower at higher decomposition rates. The concentration of dissolved ions in water might increase because nutrient delivery. In addition to the nutrients, the supply of salt resulting from the use of road salt during the winter may have led to an increase in conductivity.

Hydromorphological parameters, such as flow velocity, have a strong impact on the sedimentation rates. We suggest that particularly velocity in the pools might explain the C/N ratio due to the significant enrichment of nutrients. The relatively large C/N ratio correlated in our study to a similar study in riffles, though we supposed that flow into pools influences mostly the nutrients due to the accumulation of organic particles. This finding might reflect the sediment sampling method. Fresh particulate organic material (e.g., fallen leafs, needles or grasses from pasture) can be retained by sticks, and the decomposition has just begun.

The coverage of fine to middle sized gravel (0.2 – 2 cm in particle size) on the stream bottom best explained fine sediment deposition and was negatively correlated to the proportion of organic particles and the C/N ratio. The fine gravel is mainly located upstream of larger obstacles, such as boulders and large branches, thus indicating low current and pools. The gravel may also act as a trap for fine sediments, and this might have a negative impact on biota, such as gravel spawning trouts and freshwater pearl mussels (Soulsby et al., 2001; Österling et al., 2010) because of the interstitial nature of the streambed.

2.4.3 Seasonal differences in the impact of spatial scales on sediment deposition

The fine deposition content is seasonally variable with fast sedimentation rates during the winter compared to the remaining seasons. The seasonal patterns in the organic matter content and C/N ratio are less obvious. While the input of inorganic sediment mainly results from soil erosion by surface runoff, the dissolved organic carbon and nutrients may additionally be supplied through groundwater, which is particularly important during low-flow periods (Tate and Meyer, 1983; Findlay et al., 2001).

Catchment-scale factors are particularly important for sediment deposition patterns during the autumn and winter. In autumn, the percentage of cropland is positively correlated to the content of fine sediment. We supposed that after the mechanical tillage the soil might be loosened and thus enhancing erosion. Beside the vegetation cover, the susceptibly to soil erosion can also depend on the soil roughness and soil clustering, which can also increase during the vegetation-free period (Armand et al., 2009). Unfortunately, we have no data to verify this statement. Snowmelt with a strong surface runoff occurred in December and January, thus increasing soil erosion. Similar observations were made by Hornberger et al. (1994), Creed and Band (1998) and McNamara et al. (2005) concerning the increased concentration of dissolved organic carbon and nutrients and suspended sediment during snowmelts (Langlois et al., 2005). However, according to the hydrometeorological data of this region, long periods of snow recorded in this sampling period were very unusual.

In-stream factors, particularly sections with fine- to middle-sized gravel, are important for fine sediment accumulation mainly in spring and summer. In our studied streams, the mean of precipitation in summer was relatively low, which can decrease flow velocity and cause the depositions processes. This relationship between the deposition of fine sediment and flow patterns has also been observed by Hoffman and Gabet (2007), Petticrew et al. (2007) and Omesová and Helešic (2010).

2.4.4 Implications for Water Management

Sediment deposition has mainly been studied in larger streams and rivers, which collect fine sediments from a large catchment area. The majority of sediment, however, derives from small tributaries related to hillslope soil erosion and surface runoff. Effective sediment risk management should therefore include measurements for headwater streams (Nietch et al., 2005; Owens et al., 2005; Owens et al., 2010).

Land use in our study area is relatively homogeneous. The large proportion of arable fields located on the slopes results in soil erosion during vegetation-free periods, which is further enhanced by the widespread cultivation of maize as an energy crop. Agricultural practices should include soil conservation techniques, such as the “mulch-till” or “no-till” techniques; installing grassland on hillslopes would improve the soil retention capacity (Bundesverband Boden, 2004; Brillen et al., 2005).

In our study, we could not identify relationships between the riparian buffer zone and sediment retention, which have been demonstrated in other studies (Sheridan et al., 1999; Nietch et al., 2005; Udawatta et al., 2006). Obviously, either the riparian buffer zone in our study area is relatively homogeneous, the differences between the types of riparian vegetation are either too small, or the width of the vegetation strip was too narrow.

The significant substrate diversity, channel variability and alternating flow dynamics have positive effects on the transport and deposition of fine sediments. Our study demonstrated that fine sediment is deposited in sections of fine gravel, particularly during low-discharge periods. While the biota of the headwater might be negatively affected by the deposition of the fine particles, the high maintenance of microhabitats, the presence of natural barriers (e.g., wood trunks or debris jams) is of great importance, as they provide natural sedimentation sections (pools) (Hassan et al., 2005) and a high richness of biota and might reduce downstream sediment transport.

Our study emphasises the importance of long-term measurement, at least for one year, of deposited fine sediment to better understand deposition patterns and the terrestrial characterisation of the origin of fine particles.

3 The impact of deposited fine sediment on the macroinvertebrate community composition

3.1 Introduction

High amounts of fine sediment are delivered into aquatic systems, mainly through intensive agriculture (Walling and Fang, 2003; Collins and Anthony, 2008; Collins et al., 2011). Although the problem is widely recognised, little is known about the response of biota to fine sediment deposition (Rowe et al., 2003; Bryce et al., 2008; Collins et al., 2011).

Most of the research on the entry of fine sediment and its effects focused on suspended sediment, which can be determined relatively easily (Rowe et al., 2003; Collins et al., 2011). Several studies have addressed bedded subsurface fine particles, which were recorded as substrate composition during freeze-core analyses (Carling, 1981; Ricking and Schulze, 2003). The measurement of suspended fine sediment from interstitial spaces was conducted by Soulsby et al. (2001) and Larsen et al. (2009); sediment-disturbing methods, such as shower sampling (e.g., Kaller and Hartman, 2004) or the imbedding of sediment traps into the streambed (e.g., Fox, 2011), have also been performed. Few studies investigated surficial sediment deposition, which is mostly estimated visually as the substrata bed-cover percentage (e.g. Zweig and Rabeni, 2001; Rowe et al., 2003; Bryce et al., 2008) or identified by proxies, such as flow patterns (partially by Extence et al., 2011). However, the amount of deposited fine sediment is difficult to quantify as no standard method yet exists. Moreover, sediment loads exhibit high spatial and temporal variability (Acornley and Sear, 1999; Collins et al., 2011) exacerbating the quantification of the sediment deposition.

Elevated fine sediment levels in the suspended solids or the streambed sediments are known to have a wide range of effects on the aquatic biota. Sediment transport and movement of particles affect the feeding and attachment mechanisms of benthic macroinvertebrate such as the clogging of filter-feeding molluscs or blackflies, and the destruction of nets of feeding caddisfly larvae (Kurtak, 1978; Gaugler and Molloy, 1980; Armitage and Blackburn, 2001; Jones et al., 2011). The siltation of streambeds can change the behaviour of organisms by hindering their motility and increasing the drift rate (Culp et al., 1986; Molinos and Donohue, 2009; Larsen and Ormerod, 2010; Jones et al., 2011), and can affect the availability of habitats through a lack of substrate diversity, sediment aggregation and clogging of the interstitial spaces between stones with fine sediment (Burton and Johnston, 2010). This situation can affect the availability of food sources, including the supply of organic matter, and a shift of the periphyton quality (Schofield et al., 2004), thereby influencing the community composition with regard to the richness and abundance of certain invertebrate groups (reviewed by Jones et al., 2011). Indirectly, the entry of fine sediment and organic matter can influence the physical and chemical conditions in streams due to the filling of the interstitial spaces with fine particles, resulting in an increase in decomposition. As a result, the oxygen availability can decline, which is lethal for salmonids spawning in gravels beds and young freshwater pearl mussels (Soulsby et al., 2001; Österling et al., 2010).

Both the sediment load in running waters and aquatic biota are a result of the catchment land use, surrounding vegetation, and in-stream conditions characterised by the geomorphology, hydrology, and topography (Allan, 2004). The non-point input of terrestrial sediments due to soil erosion from tillage or livestock tramping is frequently combined with a runoff of fertilisers, and pesticides and thus is correlated to other stressors (Lenat, 1984; Cooper, 1993; Jones et al., 2001; Allan, 2004). The organic pollution directly or indirectly caused by fertilisers can reduce the abundance of sensitive species (Lenat, 1984; Friberg et al., 2010). Conversely, the surrounding riparian vegetation, such as deep-rooted grasses or trees, stabilises stream banks (Lyons et al., 2000; Allan, 2004; Søvik and Syversen, 2008) and traps sediment and nutrients, thereby reducing the input into aquatic systems (Tomer et al., 2008).

Upland streams are characterised by riffle-pool sequences, a high heterogeneity of substrates, and habitats with different hydrological conditions (Montgomery and MacDonald, 2002). The effect of fine sediment deposition might be expected in riffles due to a high supply of sediment or the accumulation of mud on stones and periphyton, whereas pools may act as natural sinks. The deposited inorganic fine sediment is accompanied to a varying degree by particulate nutrients and organic matter (Parkyn, 2004), and the proportion of mineral particles to organic matter is crucial for decomposition processes and for the quality and availability of food for aquatic macroinvertebrates.

In this study, we measured the fine sediment deposition in 29 riffles and 29 pools of headwater streams one year; all of the sites were also subject to standardised macroinvertebrate sampling and the recording of additional environmental variables. With this data, we addressed the following research questions:

(1) Do benthic macroinvertebrate assemblages on the reach scale respond to the increased amount of fine sediment deposition? If so, which part of the variability in the community composition is explained by fine sediment deposition in comparison to riparian and catchment variables and physicochemical conditions?

(2) Which biotic indices best reflect the biotic response to fine sediment deposition?

(3) Is there a quantifiable relationship between the deposition components (amount of fine sediment, organic matter or C/N ratio)? Which component of deposited fine sediments affects the aquatic macroinvertebrate community the most?

3.2 Methods

3.2.1 Study area and streams

The study area is situated in the Ardennes mountain range in northern Luxembourg (Europe) at elevations ranging from 286 to 530 m above sea level (Figure 2.1). The region is characterised by rock and clay or silt layers, which tend to experience soil erosion due to the dominant agricultural land use of the upper slopes (Colling et al., 1994).

A total of twenty-nine stream reaches, with catchment sizes ranging from 0.4 to 6.4 km^2 and 1st or 2nd stream orders, were selected in a way that the total study sites covered riparian zones dominated by non-native coniferous forests (mainly *Picea abies*) and deciduous forests (*Fagus sylvatica, Carpinus betulus,* and *Quercus petraea/robur*). The stream reaches were 3 to 7 m wide, with a wetted zone of 0.5 to 4 m and substrata dominated by boulders and gravel. The stream waters were well-oxygenated with average nitrate concentrations of 10.77 mg NO_3^- l^{-1}, average pH values of 7.4, and conductivities ranging between 126 and 253 µS cm^{-1}. The macroinvertebrate communities were diverse and characterised by spring brook species dominated by Ephemeroptera, Plecoptera and Trichoptera.

3.2.2 Environmental parameters

We recorded 28 environmental variables characterising the catchment, riparian zone, and in-stream features specifying the deposition parameters, cover of bottom substrates, cover of deposited fine sediment, morphometry, and physicochemical parameters.

Data for the catchment area (km²), land use type and their cover were deduced partly from the project Interreg Projekt NATOUR and Occupation Biophysique du Sol (OBS, 1999) and completed for the sampling sites using ArcGIS version 9.2 (Environmental Systems Research Institute, (ESRI), Table 3.1). The land-use categories were based on Corine Land Cover, third level (Commission of the European Communities, (CEC), 1993). The forest area was subdivided into deciduous, mixed and coniferous forests.

The riparian vegetation type (deciduous forest, coniferous forest, and grassland; mean ± SD and range % of the total area) and amount of shadowing (mean ± SD % of the total area) were recorded as a proportion of the total cover for a stretch of 25 m up- and downstream and a width of 5 m from the banks of the sampling sites (Table 3.1).

Table 3.1: Mean ± SD values and range of environmental variables recorded for the 29 sampling sites. CPOM = coarse particulate organic matter.

Variable	Unit	Mean ± SD	Range
Catchment variables			
Catchment area	km^2	2.0 ± 1.6	0.3 - 6.4
Deciduous forest	%	13.5 ± 9.3	0.0 - 30.3
Coniferous forest	%	19.9 ± 9.7	5.2 - 45.3
Mixed forest		1.1 ± 3.2	0.0 - 15.4
Cropland	%	26.6 ± 11.8	4.8 - 57.1
Pasture	%	30.8 ± 8.8	14.6 - 47.2
Urban development	%	3.8 ± 3.3	0.0 - 10.8
Riparian zone (R) land use (5 m)			
Coniferous forest	%	46.6 ± 40.4	0 - 100
Deciduous forest	%	19.1 ± 32.7	0 – 100
Grassland	%	7.4 ± 17.6	0 – 50
Shading	%	68.4 ± 29.1	0 – 100
Sediment variables			
Fine sediment (deposited)	$kg\ m^{-2}$	2.8 ± 1.2	0.9 - 6.1
Organic matter	%	11.8 ± 3.0	7.7 - 18.3
C/N ratio		13.1 ± 1.7	10.8 - 17.3
In-stream variables			
Fine gravel (0.2 - 2 cm)	%	6.7 ± 8.7	0 – 30
Microlithal (2 - 6 cm)	%	21.9 ± 12.1	0 – 50
Macrolithal (20 - 40 cm)	%	8.3 ± 12.0	0 – 40
CPOM	%	7.8 ± 5.1	0 – 20
Dead wood	%	6.2 ± 8.7	0 – 40
Cover of deposited fine sediment (< 2 mm) (visual estimated)	%	54 ± 24.6	10 – 95
Pool	%	12.4 ± 10.3	2 – 35
Max. bank height (R / L)	m	1.1 ± 0.1	0.2 - 3.5
Oxygen (dissolved)	$mg\ l^{-1}$	10.2 ± 0.5	9.4 - 11.6
Oxygen (saturation)	%	93.4 ± 4.6	85.5 - 101.2
Conductivity	$\mu S\ cm^{-1}$	239.5 ± 48.7	146.5 - 329.0
NH_4^+	$mg\ l^{-1}$	0.2 ± 0.1	0.1 - 0.4
NO_3^-	$mg\ l^{-1}$	9.1 ± 1.7	4.8 - 12.6
NO_2^-	$mg\ l^{-1}$	0.1 ± 0.0	0.1 - 0.1

The deposited fine sediment (< 2 mm in diameter) was collected upstream of the macroinvertebrate sampling sites to avoid the entry of additional sediment through macroinvertebrate sampling from September 2008 to September 2009 at two sections (one riffle and one pool) at each tested reach. Artificial turf mats (10 x 15 cm) were used for the sampling. The mats were anchored with cable ties and iron sticks to the streambed; at three-week intervals, the mats were carefully removed and placed into zip-lock plastic bags to avoid the loss of sediment and transferred to the laboratory. After the collection, new mats were placed at the same locations to enable consecutive sediment sampling. In the laboratory, the upside-down mats and associated water were transferred to aluminium dishes. The residue in the zip-lock bags was suspended with as little tap water as possible and washed into the corresponding aluminium dish. Following these preparations, the mats were left to suspend of sediment for a couple of hours. The mats were subsequently washed with additional tap water, and the remaining water from the aluminium dish was rinsed through a sieve (mesh width = 2 mm) to remove coarse inorganic and organic matter. As a result of this procedure, all of the collected sediment from one site was concentrated in one aluminium dish. Next, the dishes were left undisturbed for at least two hours to allow the sediment to settle. When the overlaying water was clear, it was removed by suction, leaving only the moist sediment in the dish. The moist sediment was dried in a compartment drier (Memmert, Modell UFE-600) at 100°C for approximately five hours. With this procedure, we ensured that the inorganic fraction < 2 mm was obtained. All of the samples were weighed using a balance (FAUST FA 1500-2, maximum weight 1.500 g and an accuracy of 0.01 g). The following fine sediment components were obtained. The total carbon (TC) and total nitrogen (TN) were recorded using an Elemental Analyser (EuroEA, HEKAtech GmbH). The presence of $CaCO_3$ was evaluated using HCl and was not found in the sediment; hence, the TC equals the organic carbon (OC). The percentage of organic matter was calculated as a multiplication of the OC by 1.724, assuming the soil material contains 58% carbon (Ad-hoc-Arbeitsgruppe Boden, 2005; Rowell, 1994). The C/N ratio was calculated by dividing the organic carbon (OC = OT) by the total nitrogen (TN). The sediment variables were calculated as the arithmetic means for each sampled reach per year. For linking the sediment deposition patterns to the biota, we calculated all of the sediment variables per season and site (Table 2.1). The seasons were defined as follows: winter (December to February), spring (March to May), summer (June to August), and autumn (September to November).

The in-stream parameters of substrate cover, percentage of fine sediments (< 2 mm), and morphometry were collected prior to and after each sediment sampling period, the estimates based on a length of 25 m up- and downstream of the sampling site. The percentages of the substrates were estimated prior to the macroinvertebrate sampling; the percentage of fine sediment and the proportion of pool habitats were visually estimated. The maximum value of the bank height was obtained from the right and left bank. The following physicochemical parameters were collected: the pH value; the dissolved oxygen (mg l^{-1}), available oxygen (% of saturation), and conductivity (µS cm^{-1}) were measured using the Multi350i (WTW); and the nitrogen components (NO_3^-, NO_2^-, and NH_4^+) were obtained using a photometric analysis using the 109713 Nitrate Test (Merc Spectroquant® Tests). The conductivity was measured at all of the sediment samplings, and the maximum value per site was used for further analyses. The remaining parameters were measured once per macroinvertebrate sampling season, except for the nitrogen fractions, which were measured in spring of 2009 only.

3.2.3 Macroinvertebrate sampling

Macroinvertebrate samples were collected using a 25 x 25 cm frame shovel sampler (500 µm mesh width) in two seasons: 29 samples in the early autumn of 2008 (September/October) and 29 in the spring of 2009 (March/April). The substrate composition was estimated prior to the multi-habitat sampling procedure (Barbour et al., 1999; Hering et al., 2004). Ten samples reflecting the substrate composition were collected in the riffles and pools within a 25 m stretch, preserved (96% ethanol), and transferred to the laboratory for sorting, identification, and counting. When possible, the organisms were identified to the species level with the exception of Oligochaeta (family level) and Diptera (mostly family or tribus level). For further analysis, taxalists resulting from both of the sampling seasons were tallied and used for the calculation of the taxa composition and density for each reach. With the resulting composite taxalists, we calculated the biotic indices and species traits that potentially reflected the influence of fine sediment deposition, such as the diversity and functional metrics (Table 3.2).

Table 3.2: Mean ± 1SD of biological metrics calculated for the 29 sampling sites.

Biotic Indices	Unit	Mean ± SD	Range
Shannon-Wiener-Index		3.02 ± 0.36	1.86 - 3.48
Evenness		0.74 ± 0.08	0.47 - 0.85
Pelal	%	9.54 ± 6.44	2.59 - 37.1
Agryllal	%	0.35 ± 0.51	0.00 - 1.92
Gatherer/Collector	%	33.2 ± 7.33	17.44 - 52.62
Grazer	%	25.71 ± 6.39	10.40 - 36.04
Active Filter	%	3.87 ± 2.77	0.88 - 12.49
Passive Filter	%	5.87 ± 6.50	0.76 - 33.87
Predators	%	8.00 ± 2.87	2.03 - 13.75
Burrowing/boring	%	18.00 ± 8.02	5.72 - 39.44
EPT richness	%	57.22 ± 15.38	24.54 - 79.55
LIFE (Lotic- invertebrate Index for Flow Evaluation)		7.85 ± 0.22	7.31 - 8.21

3.2.4 Biological indices

Twelve biotic indices and species traits were assumed to reflect the impact of sediment on the benthic macroinvertebrates and were calculated using Asterics 3.3. (ASTERICS, 2008) (Table 3.2). We utilised a metric of the invertebrate richness/diversity using Shannon-Wiener-Index (Shannon and Weaver, 1949) and Evenness. The composition/abundance was addressed by the proportion of Ephemeroptera, Plecoptera, and Trichoptera (EPT). The functional measures, such as the microhabitat preference, feeding types, and locomotion types (Schmidt-Kloiber and Hering, 2012), potentially provide additional information on the response to sediment deposition. We selected a proportion of the species preferring habitats of pelal (mud) and agryllal (clay) because the occurrence of these groups may be increased by a high accumulation of mud and clay. The enhanced load of inorganic and organic particles affects both the food source quality and availability; the effect is assumed to be positive for gatherer/collector and passive filter feeders (excess of food) and negative for grazers (reduction of periphyton composition; Schofield et al., 2004), active filter feeders (clogging of filters), and predators (high turbidity decreasing the visual range). Furthermore, metrics indicating the locomotion type of the invertebrates were chosen, such as the proportion of burrowing/boring organisms, to test whether a disturbance in the streambed due to clogging and the embeddedness of interstitial spaces may affect the biota. Lastly, we selected the

Lotic-Invertebrate Index for Flow Evaluation (LIFE; Extence et al., 1999), which provides information on flow preferences of different invertebrate species and is highly correlated to the Index of Proportion of Sediment-Sensitive Invertebrates (PSI; Extence et al., 2011).

3.2.5 Statistical analysis

Different ordination methods were used to assess and quantify the impact of the 28 environmental variables and deposited sediment components on the macroinvertebrate community composition and biotic indices. First, a detrended correspondence analysis (DCA) was used to determine the gradient lengths of the response variable data sets (i.e., the community composition and diversity and functional indices). As the gradient length of the community composition data was >1.5 SD units, a canonical corresponded analysis (CCA) as a unimodal method was used to analyse the response of the community composition to environmental variables. Forward selection with Bonferroni correction was used (499 Monte Carlo unrestricted permutations) to identity the single environmental variables explaining the variation in the community composition and metrics. Because the catchment area proved to be dominant within the data set, this parameter was run as a co-variable in the CCA to partial out its influence on the explanatory power of the remaining variables. Furthermore, a partial CCA (pCCA; Borcard et al., 1992) was used to separate and quantify the effect of the sediment components (fine sediment, organic matter and C/N ratio) on the community composition.

In pCCA, the variation in the macroinvertebrate community composition was partitioned and the effect of the sediment components was quantified. In the first run, a CCA with all three sediment components was performed to quantify the total variance (explained and unexplained). Then, several partial CCAs (pCCAs) were performed with two sediment components as main explanators and the third component as co-variables and vice versa. For instance, a run consisted of fine sediment and organic matter as two main explanators and the C/N ratio as co-variable. This step was repeated several times with different combinations of all sediment components, resulting in a total of 13 runs. With three sediment components, the total variation of the macroinvertebrate community composition was then partitioned into seven components including covariance terms. The variation explained by these components is then subtracted from the total variation to obtain the unexplained variation. This procedure was repeated for each season (autumn 2008 and spring 2009) separately.

The DCA with the metric data revealed a gradient length < 1.5 SD units; thus, the metrics were analysed using redundancy analysis (RDA; Ter Braak and Šmilauer, 2002). Forward selection with Bonferroni correction was also used (499 Monte Carlo unrestricted permutations) to determine the significant variables explaining the variation within the biological metrics.

Linear regression was used to evaluate the relationship between the amount of fine sediment (kg m^{-2}) and percentage of organic matter and C/N ratio and between the percentage of organic matter and the C/N ratio of the sediments (arithmetic means per annum and site).

Prior to the statistical analyses, all of the environmental variables, catchment area, morphometric data, chemistry data, and content of fine sediment were log-transformed (x+1). The land-use/vegetation cover and substrate variables and shading and percentage of organic matter were square-root-transformed. The community composition data, biological metrics, and C/N ratio were processed untransformed. All of the ordination methods (CCA, RDA and pCCA) were performed using CANOCO Version 4.5 (Ter Braak and Šmilauer, 2002), and the linear regressions were performed using Statistica 10.0 (Statsoft Inc., 2009).

3.3 Results

3.3.1 Relationship between environmental variables and community composition

All of the environmental variables explained 20.8% (cumulative percentage of species data of the first two CCA axes) of the variance in the benthic invertebrate assemblages. The variance in the community composition was best explained by the oxygen saturation, 15% (F = 2.56; p = 0.002), followed by the percentage of fine gravel on the streambed (13%; F=2.38; p = 0.002) and C/N ratio (11%; F = 2.04; p = 0.002). The catchment variables, such as land-use cover and the amount of deposited fine sediment in the sampling sites are not significant for explaining the community composition (Figure 3.1).

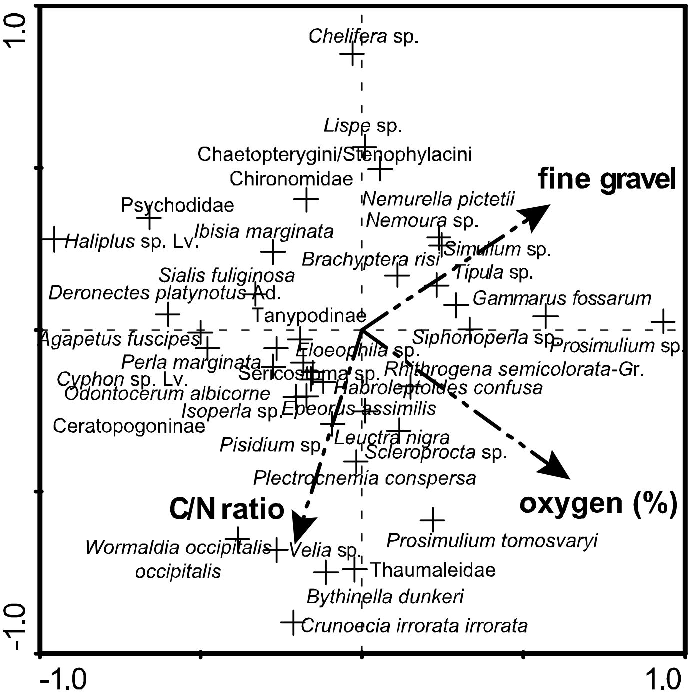

Figure 3.1: CCA biplot of significant environmental variables explaining the community composition variation. Taxa with a fit range >10% are also shown. The fit range affords a measure for the variance explained by an individual species (Ter Braak and Šmilauer, 2002). Fine gravel = percentage of fine gravel in the substrate cover; oxygen (%) = oxygen saturation.

Many taxa were correlated with the presence of fine gravel on the streambed, such as *Brachyptera risi* (Morton, 1896), *Nemurella pictetii* Klapalek, 1900, *Nemoura* sp., *Siphonoperla* sp. (Plecoptera), *Simulium* sp., *Tipula* sp. Linnaeus, 1758, (Diptera), and *Gammarus fossarum* Koch in Panzer, 1836 (Crustacea) (Figure 3.2). The oxygen saturation is positively related to *Rhithrogena semicolorata*-Gr. (Ephemeroptera) but negatively to *Sialis fuliginosa* Pictet, 1836 (Megaloptera), *Ibisia marginata* (Fabricius, 1781), Psychodidae Gen. sp. (Diptera) and larvae of *Haliplus* sp. A high C/N ratio correlated with *Crunoecia irrorata irrorata* (Curtis, 1834), *Plectrocnemia conspersa* (Curtis, 1834), *Sericostoma personatum* (Kirby and Spencer, 1826), *Wormaldia occipitalis occipitalis* (Pictet, 1834) (Trichoptera) *Bythinella dunkeri* (von Frauenfeld, 1857), *Pisidium* sp. Pfeiffer, 1821 (Bivalvia), *Scleroprocta* sp. Edwards, 1938, Thaumaleidae Gen. sp. (Diptera), *Velia* sp. (Heteroptera), *Leuctra nigra* (Olivier, 1811), *Isoperla* sp. (Plecoptera), *Epeorus sylvicola* (Pictet, 1865), and *Habroleptoides confusa* Sartori and Jacob, 1986 (Ephemeroptera).

3.3.2 Relationship between environmental variables and biological metrics

Two environmental variables explained 33.6% of the variance in the biotic metrics (cumulative percentage of the metric data of the first two RDA axes): the C/N ratio in the deposited fine sediment explained 18% (F = 6.83; p = 0.004) and dissolved oxygen 16% (F = 5.42; p = 0.016) of the variance in the biotic metrics. The content of dissolved oxygen was linked to the abundance of passive filter feeders, such as caddisfly larvae (e.g., *Philopotamus ludificatus* and *Hydropsyche instabilis*), but it was negatively correlated to the gatherers and sediment collectors (e.g., worms and certain Ephemeroptera, respectively (Figure 3.2). The C/N ratio was connected with taxa richness, such as the evenness, Shannon-Wiener-Index and EPT richness, burrowing/boring biota and LIFE metric, and correlated negatively to the number of active filter feeders (e.g., molluscs) and taxa preferring the pelal. The remaining metrics showed no obvious relationships.

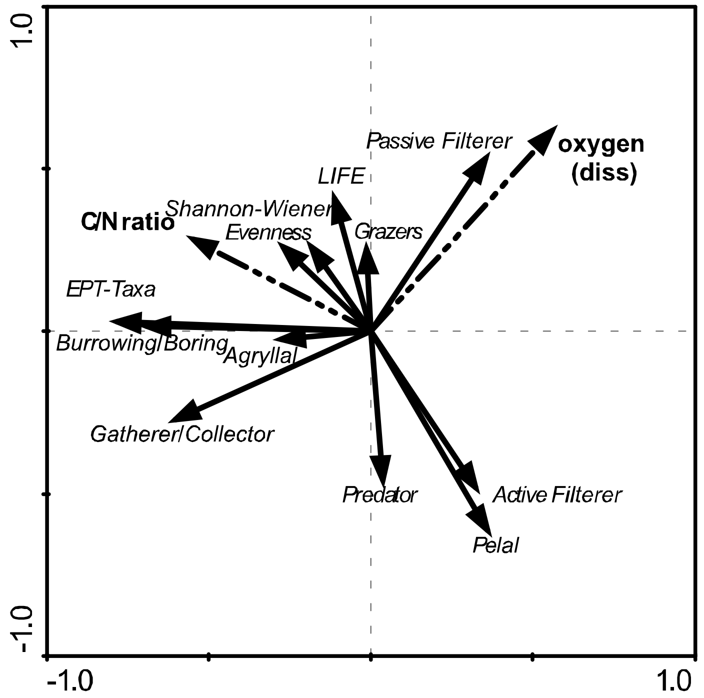

Figure 3.2: RDA biplot of the environmental variables in relation to the selected biotic metrics. Only significant variables are shown. LIFE = Lotic-Invertebrate Index for Flow Evaluation; EPT-Taxa = proportion of Ephemeroptera, Plecoptera, and Trichoptera; oxygen (diss) = dissolved oxygen.

3.3.3 Relationship between components of the deposited fine sediment to each other and to the taxa composition with regard to the season

The amount of deposited fine sediment was negatively correlated to the organic matter content with high significance ($R^2 = 0.51$, $p < 0.0001$) and the C/N ratio ($R^2 = 0.46$), $p < 0.0001$; Figure 3.3 A and B). In contrast, the correlation between the organic matter and the C/N ratio is positive but weak ($R^2 = 0.32$, $p < 0.05$; Figure 3.3 C).

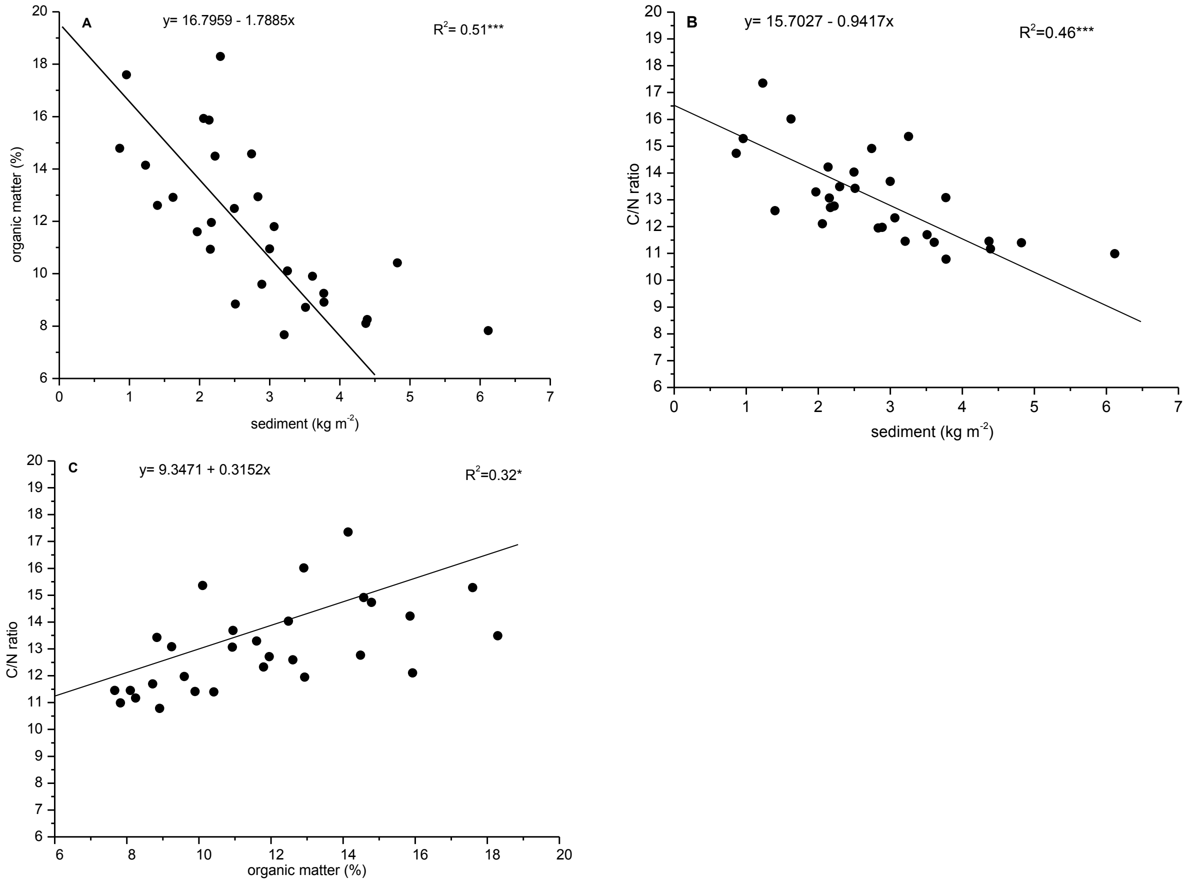

Figure 3.3: Linear regression between the components of fine sediment (mean yr^{-1} at 29 sites showing [A] the amount of fine sediment ($kg\ m^{-2}$) and organic matter (%), [B] the amount of fine sediment ($kg\ m^{-2}$) and C/N ratio, and [C] the organic matter (%) and C/N ratio. Statistical significance: *$p < 0.05$; **$p < 0.001$; ***$p < 0.0001$.

The amount of deposited fine sediment, proportion of organic matter, and C/N ratio explained 57.1% of the total variance in the taxa for the autumn samples and 52.9% for the spring samples (Figure 3.4 A and B). For both seasons, the unique effect of the tested variable on the taxa is explained best by the C/N ratio (20.1% autumn; 18.1% spring) and second-best by the organic matter (14.9% autumn; 15.2% spring) followed by the content of fine sediment (14.5% autumn; 15% spring; Figure 3.4 A and B).

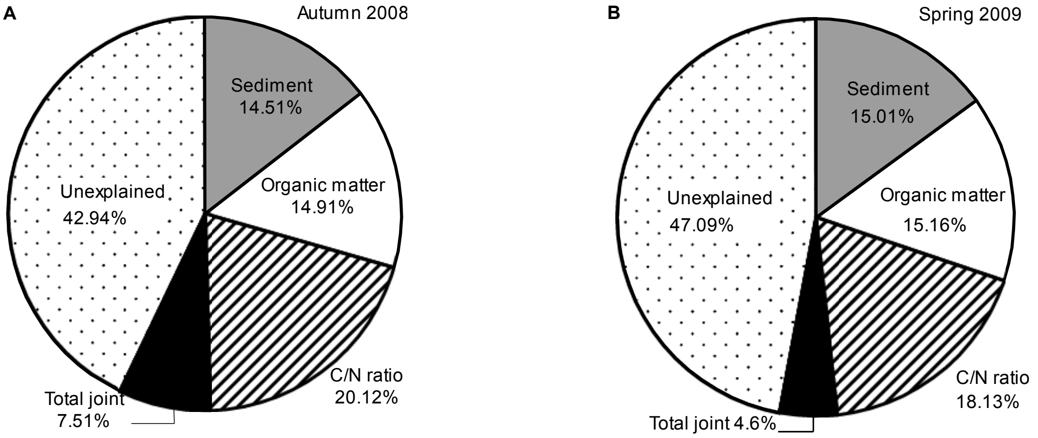

Figure 3.4: The sources of variation in the invertebrate composition explained by three components of the fine sediment for autumn 2008 (A) and spring 2009 (B). The percentages of the unique variation for the deposited fine sediment (kg m^{-2}) in grey, percentages of organic matter in white, the C/N ratio (banded), the combined variance of all of the components (in black) and unexplained variance (dotted) of the macroinvertebrate composition are shown.

In comparison, the high cumulative effect of the C/N ratio, which was recorded as a total of the combined and unique effect, was higher in the autumn and lower in the spring (Figure 3.5 A and B). The cumulative effect of the fine sediment on the biota was strong in comparison to the unique value for both seasons (Figure 3.4 and Figure 3.5). The cumulative explanation power was higher for the autumn assemblages that the spring assemblages (Figure 3.5 A and B).

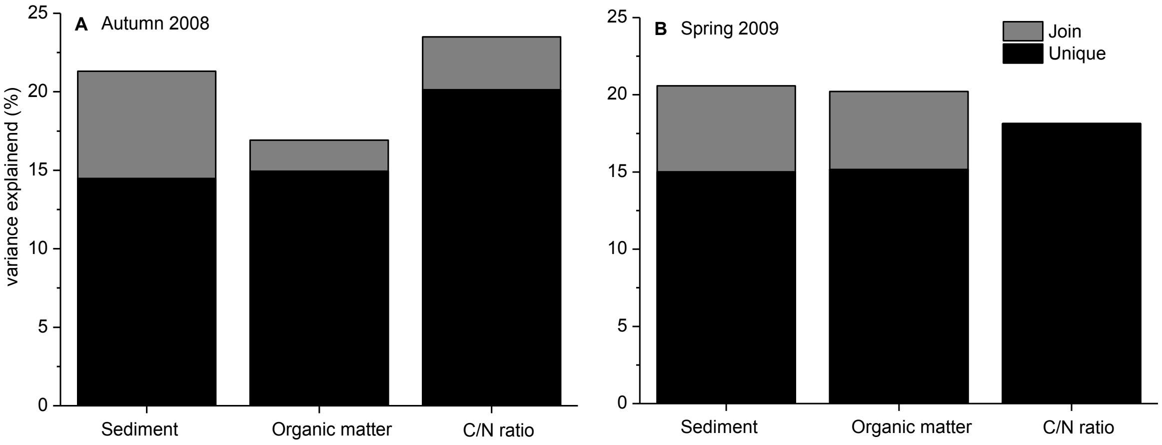

Figure 3.5: The cumulative effect of the fine sediment components on the taxa composition in autumn 2008 (A) and spring 2009 (B).

3.4 Discussion

3.4.1 Relationship between environmental variables and taxa composition

As a criterion of microbial decomposition, the in-stream variability, characterised by the oxygen saturation, substrate composition and C/N ratio, explained approximately 20.8% of the variance of the macroinvertebrate composition. Certain taxa, mainly occurring in the lentic sections, e.g., larvae of Psychodidae (Diptera) and larvae of alderflies (*Sialis fuliginosa*), are tolerant to oxygen limitation. Several taxa preferred the sections of fine gravel, including the larvae of Plecoptera (e.g., *Nemurella picteti* and *Nemoura* sp.), which are associated with gravel (Graf et al., 2007), whereas the larvae of the crane fly *Tipula* sp. prefer the wet zone along the shoreline. The strong relationship with the substrate can partly be explained by the preference for certain food sources (Lammert and Allan, 1999; Rempel et al., 2000; Usseglio-Polatera et al., 2000; Piscart et al., 2009). Another impairment reflected by the substrate composition is the clogging of the interstitial spaces between the gravel particles by fine sediments, which may particularly affect the early larval instars of several taxa living in the hyporheic zone (Minshall, 1984). Several Trichoptera (e.g., *Crunoecia irrorata irrorata, Plectrocnemia conspersa,* and *Wormaldia occipitalis occipitalis*), molluscs (*Bythinella dunkeri* and *Pisidium* sp.), and Plecoptera (*Leuctra nigra* and *Isoperla* sp.) predominantly occurred in the sites with a high C/N ratio. The abundance of these taxa ranged from sporadic (*W. occipitalis occipitalis* and *C. irrorata irrorata*) to highly dense (*Isoperla* sp. and *Leuctra nigra*). Most of these taxa prefer spring brooks and are sensitive to organic pollution; therefore, they prefer unimpaired sites with high C/N ratios. The C/N ratio has a greater effect on the biota than the remaining physicochemical parameters (except for the oxygen saturation). The long-term effect of nutrients in deposited fine sediment might therefore be a key factor for shaping the macroinvertebrate community by impacting the bioavailability of oxygen and dissolved nutrients at the microhabitat level. However, these results could be not validated by other physicochemical variables, such as the biological oxygen demand consumed in five days by bacteria (BOD_5) or hardness, because these variables were not recorded. In contrast to the C/N ratio, the amount of fine sediment and the proportion of organic matter have no significant effect on the composition of taxa. The C/N ratio affects the physiological conditions directly, whereas the ecological impact of increased amounts of fine particles on the biota is wide-ranging and more complex. The critical effect of fine particle release might be dependent on the physicochemical and hydrological streams conditions. The response of aquatic insects to the sediment load might also be influenced by their actual life stage, i.e., emergence or juvenile. For instance, Hanquet et al., (2004) found that the larvae of *Ephemera danica* prefer different sections of the substrate, depending on larval stage. The young larvae occur in the sections with a higher frequency of coarse substrates and in medium depth, whereas larger nymphs prefer shallow and sandy sections. Many studies suggested that the land-use cover in the catchment and riparian land can predict the biota diversity (e.g., Lenat, 1984; Fritzpatrick et al., 2001), and this linkage is based on the terrestrial provision of nutrients and the alternation of structures in the surrounding area (Lammert and Allan, 1999; Vondracek et al., 2005; Yates et al., 2007). The relationship between the catchment land cover and riparian vegetation to the biota could not be demonstrated directly by our results. Allan (2004) suggested that the impact of land-use variables on the biota is the highest when the land-use status in the catchment area ranges from nearly natural to degraded. This co-variation of the anthropogenic and natural gradient in our study is marginal because of the typical topography of low mountain ranges. This rural region is sparsely populated and dominated by agricultural use in the upper hills and wooded downstream areas. However, the impact of the land-use cover was indirectly connected through the physicochemistry in our study.

In conclusion, our results lend support to the conjecture that chemical composition of the deposited substrates plays a major role and small-scale in-stream factors are crucial for the macroinvertebrate community composition of small streams, which is in contrast to what has been described for streams of a higher stream order (Vondracek et al., 2005; Feld and Hering, 2007; Walsh et al., 2007; Wasson et al., 2010). Hence the land use cover such as in particular the proportion of urbanisation or riparian zone is also a strong significant for the taxonomic composition.

3.4.2 Relationship between environmental variables and biological metrics

Only two in-stream variables, the C/N ratio and oxygen solubility, were related to the metrics; the remaining variables, including the amount of fine sediment in the deposition, were not significantly linked. In several studies regarding the increase of the fine sediment load, a decline of taxa richness (e.g., Cline et al., 1982, Quinn et al., 1992; Jones et al., 2011) and proportion of EPT taxa (Kaller et al., 2001; Matthaei et al., 2006; Pollard and Yuan, 2009) was observed. Those changes in the biota were caused by the modification of the substrate and food sources and by behavioural changes. The C/N ratio is associated with the processes of decomposition and nitrification, which impact the food quality and particularly affect the oxygen concentration. The patches of deposited fine sediment are probably characterised by a reduced oxygen uptake, which alters the diversity of certain sensitive species.

The linkage of the taxa preferring muddy habitats to the physicochemical conditions was obvious, as these taxa tolerate the limitation of oxygen to a greater extent. However, the occurrence of active filterers was negatively correlated to the C/N ratio, and these taxa were generally rare in the spring brooks. In our study, this group was dominated by the mayfly *Ephemera danica* and the mollusc *Pisidium* sp., which occupy muddy substrates that are characterised by a high level of oxygen consumption due to the deposition of fine particles. Passive filterers (for example larvae of the black fly Simuliidae) occurred mainly at the sites with high oxygen saturation, being feeding groups that usually benefit from the supply of particles and an enhanced oxygen availability. This is also shown by the correlation of the LIFE metric for the flow response of the invertebrates and increase of the C/N ratio and amount of oxygen.

3.4.3 Relationship between components of the deposited fine sediment to each other and to the taxon composition with regard to the season

The amount of deposited material per annum is variable, and the ratio between the inorganic sediment and organic matter within this deposited fine material is also variable: the more total material is deposited, the more the proportion of organic material decreases. Although the entry of sediment is a consequence to episodic runoff events, which translates into a short-term increase of the inorganic content, the terrestrial supply of organic matter is more consistent and strongly linked to the surrounding vegetation, such as the dropping of leaves or branches (e.g., Webster et al., 1990; Nietch et al., 2005). The shift between the proportion of a low and high total deposition is caused by the runoff from the surrounding land and hydrological events throughout the hydrological year, such as discharge peaks (e.g., Delmas et al., 2011).

The weak relationship between the organic matter and C/N ratio suggests that the nutrient content is not solely derived from the organic matter and decomposition processes but is also enhanced through the runoff of fertiliser or animal faeces (e.g., Jarvie et al., 2010). These fractions ultimately accumulate in streambeds.

The results of the pCCA emphasise the high importance of the C/N ratio in comparison to the organic matter and the amount of fine sediment for the benthic macroinvertebrate community and confirm the results of the CCA and RDA with various environmental variables. Aquatic insects represent a wide variety of life history patterns, such as emergence, which has a temporal pattern (Corbet, 1964). Due to this variety, we expected a seasonal difference in the impact of the chemical composition on the taxa composition. The impairment of fine sediment on the biota is equal for both assemblages. In contrast to the organic matter, the cumulative effect of the C/N ratio was stronger in the autumn compared to the spring. These differences might be due to the increase of the algal biomass and the beginning of decomposition processes in the spring, thereby supplying fresh organic matter during this period.

3.5 Conclusions

The impact of fine sediment on the macroinvertebrate community in running waters has been discussed intensively. In this study, we mainly addressed the question of whether the fine sediment load has a separate effect on the biota or whether the impairment by sediment entry might be intensified as a result of the synergy with variables, such as the flow pattern, solids or nutrient supply (Lemly, 1982; Matthaei et al., 2010; Ormerod et al., 2010). Furthermore, we were interested in the spatial scale to which communities respond, such as the reach scale or patch/microhabitat scale (Larsen et al. 2009). Our results suggest that the chemical composition of fine sediment is mainly responsible for the alternation of the macroinvertebrate community composition in small headwater streams; whereas the overall amount of fine sediment offered no significant explanation for community composition. Both the C/N ratio of the deposited fine sediment and variables representing the oxygen availability were significantly explanatory for the taxa composition. The oxygen demand probably becomes stronger in patches with deposited fine sediment due to silty fractions with lower proportions of fine sand, which is characteristic of fine sediment grains in this region. These cohesive sediments have an affinity for the absorption of organic or toxic components (e.g., Droppo et al., 1997). Agricultural and forested areas dominated in our study; thus, portions of the sediment contain high amounts of nutrients, which can advance the decomposition processes. The significance of fine gravel stretches for the biota reveals the importance of the local stream conditions, which may have a greater effect on the relative abundance of the benthic communities compared to the catchment land-use variables. According to our results, the proportion of EPT Taxa, diversity (Shannon-Wiener-Index and Evenness) and functional metrics such as the LIFE metric are suitable parameters for assessing responses to fine sediment. Although the chemical composition of the sediment load is more important than the actual amount entering the stream, certain mitigation measurements such as having a natural riparian zone, the maintaining of the patchy structure of the stream bed as well the river course help reducing the sediment load into the stream as well as provide more qualitative food such as leaves, and thus reduce the decomposition and the lack of oxygen. However, further experimental studies are needed to measure the impact of sediment load, nutrient supply and oxygen demand of the different fine sediment fractions as well as the impact on aquatic biota.

4 The impact of deposited fine sediment on eight taxa of mayflies (Ephemeroptera) and caddisflies (Trichoptera)

4.1 Introduction

The high amount of fine sediment release into streams and rivers is often associated with anthropogenic land use changes, especially due to deforestation, intensive agriculture and urbanisation (e.g., Allan, 2004; Owens et al., 2010).

The suspended and deposited sediment on the streambed causes a wide range of alterations in the physicochemical and morphological stream conditions of running waters. The suspension and accumulation of particles is frequently accompanied by turbidity (Bilotta and Brazier, 2008) and abrasion of grains (Newcombe and MacDonald, 1991). The siltation and compression of fine sediment induces the modification of microhabitats and decline of their diversity (Sullivan and Watzin, 2010). Progressive clogging of interstitial spaces also leads to a reduction of permeability and porosity in interstitial spaces and, as a consequence, decreases the supply of nutrients and oxygen (Schälchli, 1992).

The impact of fine sediment entry on benthic macroinvertebrates were examined mostly in relation to the changes in the community composition, such as an alternation of their diversity, abundances as well as functional groups (e.g., feeding, microhabitats preferences, locomotion; Zweig and Rabeni, 2001; Rabeni et al., 2005; Wood et al., 2005; Larsen et al., 2009; Bryce et al., 2010; Jones et al., 2011). The extent of changes is thus species-specific; hence depending on ecological traits including the preference of substrates or feeding habits, locomotion types, hydraulic preferences, and life stages (e.g., Usseglio-Polatera et al., 2000; Lamouroux et al., 2004).

Only a few field studies focused on the response of individual species to deposited fine sediment, which often reflected the shift of density related to its proportion in the small patches or in the streambed substrates (reviewed by Jones et al., 2011). The freshwater pearl mussel (*Margaritifera margaritifera*) is an example for the detailed study on the modification of habitat requirements caused by fine sediment load. This sessile mussel is a highly endangered species in Central Europe, primarily due to the progressive degradation of its streambed habitat (Geist and Auerswald, 2007; Österling et al., 2008; Österling et al., 2010; Cooksley et al., 2012). The response to siltation depends on the age of the mussel. While the adults are more tolerant to muddy and silty sections of gravel streambeds, the young post-parasitic mussels avoid these stream areas (Hastie et al., 2000). The decrease in oxygen and pH as well as the high turbidity, resulting from clogging and compaction of streambed interstitial spaces, may determine this behaviour (Geist and Auerswald, 2007; Österling et al., 2010). Moreover, the high amount of fine sediment might also have a negative effect on spawning habitats of salmonid-species (Kemp et al., 2011), which can affect the development of the parasitic stage of freshwater pearl mussel and hence their reproduction success.

Beside the habitat heterogeneity, which can be impaired due to entry of fine sediment, the various and abundant benthic communities in headwater streams are caused by varied local environmental conditions (e.g., Clarke et al., 2008). The flow pattern can directly alter benthic community compositions due to the adaptation to different flow velocities or the catastrophic drift (Bond and Downes, 2003). This also shapes the riffle and pool sections as well as the accumulation of organic particles (e.g., Smock et al., 1989; Hoover et al., 2006). These great leaf and debris dam patches originating from the surrounding riparian zone and hillslopes are an important food source for aquatic invertebrates and also a key factor of channel processes (Wallace et al., 1999; Kobayashi and Kagaya, 2002; Gomi and Sidle, 2003). In addition, the shadowing and groundwater runoffs influence the water temperature as well as the amount and composition of periphyton, which provide oxygen, which is essential for growth and survival or organisms and respiration and decomposition processes in streams and rivers (e.g., Quinn et al., 1996; Daufresne et al., 2004; Haidekker and Hering, 2007; Clapcott and Barmuta, 2010; Klove et al., 2011; Studinski et al., 2012).

In our investigation we focused on the larval stages of eight benthic macroinvertebrates. In order to evaluate the impact of deposited fine sediment and additional environmental variables on the species densities, we analysed abundances of selected benthic insects in 29 riffles and 29 pools in 1st and 2nd order upland streams. We supposed that the response to the local exposition of deposited sediment can be dependent on the species' habitat preferences. This also means that the densities of selected species might change as a result of an altered food availability and quality due to high entry and deposition of fine sediment as well as small-scale deposition of fine sediment.

We focused on the following research questions: (1) Is there an interaction between the locally morphometric variables of patches and is the deposition of fine sediment influenced by these variables? (2) Do the locally morphometric variables and surficially deposited fine sediment on the patches affect the taxa densities? (3) Does the amount of fine sediment deposited on the streambed in the sites and the additional, local catchments and riparian environmental variables have an impact on the taxa densities?

4.2 Methods

4.2.1 Study area and streams

The study area is situated in the Ardennes mountain range in northern Luxembourg. 29 sites were sampled in spring 2010 in the small headwater streams. A detailed description of the streams can be found in chapter 2.2.1. The sampling sites were located adjacent to the sections of fine sediment sampling but the collected surface was larger (50 x 50 cm). The samples were taken both in a riffle and pool zone, resulting in a total number of 58 samples. For each spot we recorded local morphometric variables and the cover of mineral substrates and deposited fine sediment (including fine particulate organic matter) was assessed.

4.2.2 Macroinvertebrate sampling

Macroinvertebrates were collected using a simple sieve (500 µm mesh size; 50 x 50 cm sampling area) and picked up by tweezers in spring 2010. All species were counted and identified in the field. In order to examine preferred patches of occurrence of selected taxa, the sampled areas were scanned in detail. First of all, we collected the organisms on the surface of the mineral and organic substrates. The patches of coarse organic matter were very heterogeneous, consisting of a mixture of leafs, branches or needles and deposited mud. Subsequently, remaining organisms were picked up from the front as well as from the sides and from the back of cobbles, stones and larger parts of organic material. Finally, we lifted the stones and removed the deposited particulate matter in the spaces between the stones. Then, all species attached to the bottom side of the stones were counted.

The following taxa were investigated: *Ephemera danica*, MÜLLER, *Habroleptoides confusa*, SARTORI and JACOB and *Rhithrogena semicolorata* group belonging to Ephemeroptera order and *Agapetus fuscipes* CURTIS, *Synagapetus iridipennis/moselyi, Sericostoma personatum* (KIRBY and SPENCE), *Odontocerum albicorne*, SCOPOLI and *Philopotamus ludificatus*, McLACHLAN belonging to the Trichoptera order. All taxa inhabit hypocrenal up to epirhithral headwaters (Schmidt-Kloiber and Hering, 2012). While *A. fuscipes* and *S. iridipennis/moselyi* mostly occur in spring brooks, the occurrence of *E. danica* ranges from hypocrenal to potamal stream parts. It also occurs in lentic sections such as lakes or ponds (Buffagni et al., 2009; Schmidt-Kloiber and Hering, 2012). The ecological traits of these taxa were assessed with respect to their feeding groups and substrate preferences according to Schmidt-Kloiber and Hering (2012). All taxa have different food preferences ranging from plant consumers of detritus (*E. danica*, *H. confusa*), grazers and scrapers of microalgae of stones (*A. fuscipes*, *S. iridipennis/moselyi*, *R. semicolorata* group), passive filterers (*P. ludificatus*), shredders of coarse particulate organic matter (*S. personatum*) to predators of benthic invertebrates (*O. albicorne*; Figure 4.1). The taxa inhabit mainly stony substrates such as coarse-grained gravels, cobbles or boulders and generally avoid muddy habitats, except for *E. danica* (Figure 4.2). *O. albicorne, S. personatum* and *H. confusa* are more tolerant to fine sediment and occur in both mineral and organic microhabitats such as woody debris, macrophytes or organic matter. The preferred substrates for the *Rhithrogena semicolorata* group are stones and the group represents the six species belonging to this group (*R. carpatoalpina, R. iridina, R. picteti, R. puytoraci, R. rolandi and R. semicolorata*).

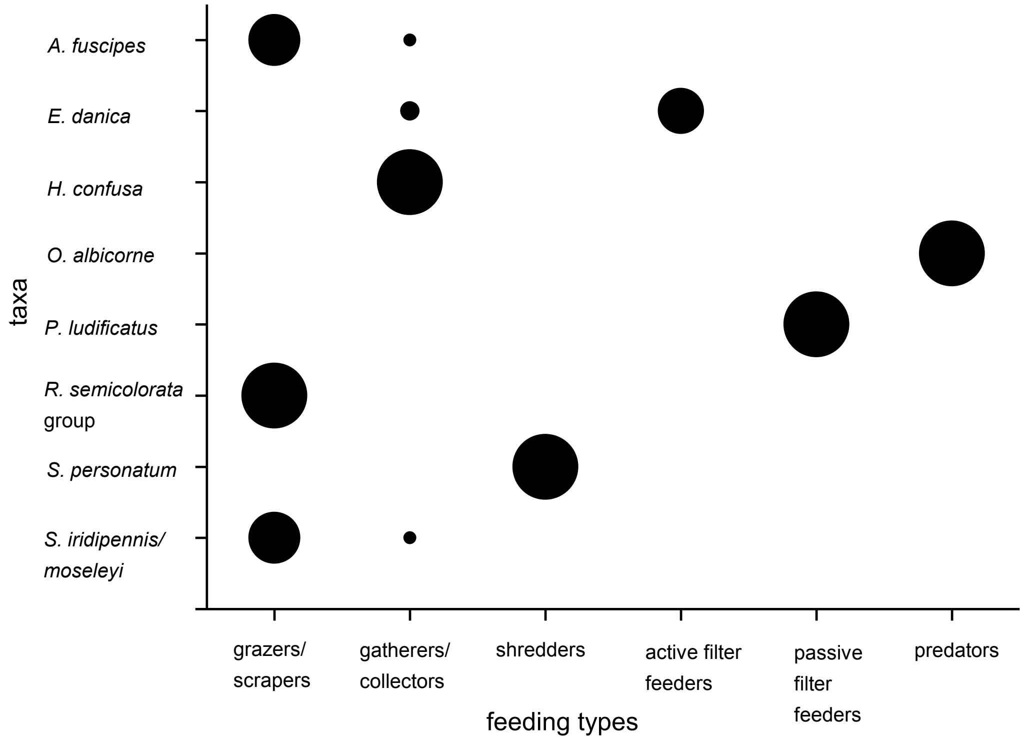

Figure 4.1: Strength of the association of selected taxa to specific feeding types. Data coded using ten-point-system per taxon from Schmidt-Kloiber and Hering (2012).

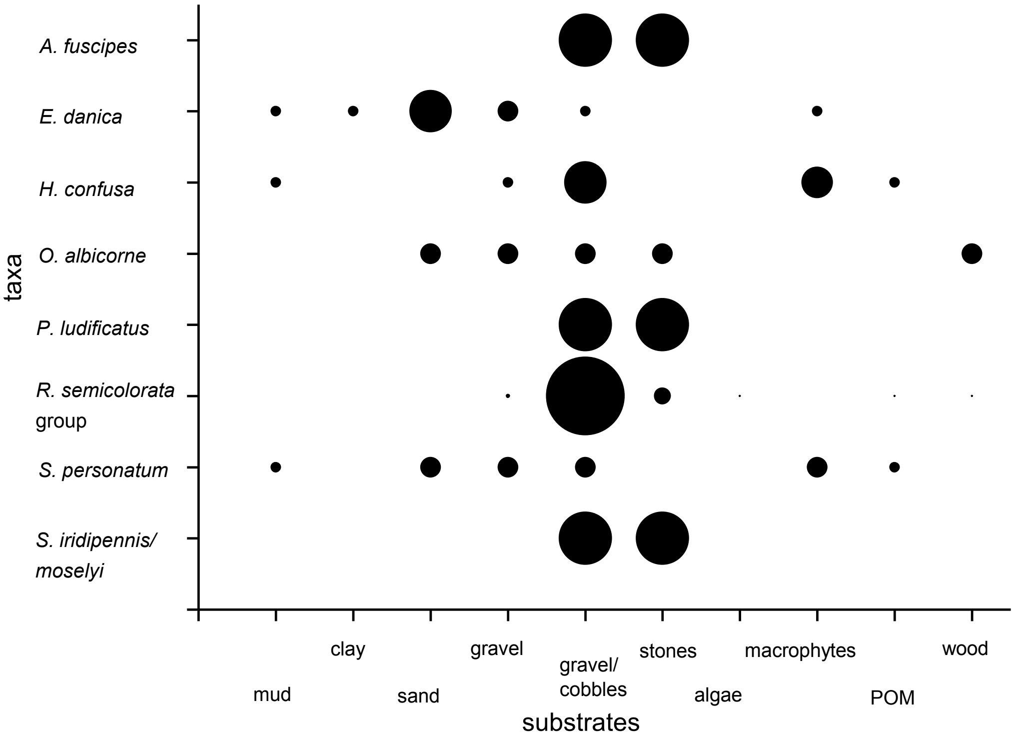

Figure 4.2: The proportion of preferred substrates for selected taxa. gravel / cobbles = coarse gravel to hand-sized cobbles; grain size 2 – 20 cm (microlithal and mesolithal); stones = stones, boulders, bedrock; grain size > 20 cm (macrolithal and megalithal); POM = particulate organic matter; wood = woody trunks. Data coded using ten-point-system per taxon from Schmidt-Kloiber and Hering (2012).

4.2.3 Environmental variables

For the analysis a set of environmental variables was used, which were sampled in current and previous studies (Table 4.1).

The location of samples in relation to the stream bank (m), water depth (m), flow velocity (m s^{-1}), substrate and fine deposited sediment were recorded a priori for each patch area in spring 2010. The distance to the bank (m) was measured on the parallel sides of the investigated square area (sampling area 0.25 m^2) and obtained as an arithmetic mean. The arithmetic mean of flow velocity and water depth was calculated for eight (flow velocity) to 12 (water depth) values due to the high variability of flow and depth patterns. The flow velocity was measured with a hydrometric vane (MiniAir2, Schiltknecht). First, the proportion of fine sediments (< 2 mm diameter) were visually estimated as a percentage of mud and fine organic matter surface and also classified in classes (0 - 30% low; > 30 - 70% medium; > 70% high). Subsequently, the distribution of mineral components was assessed.

Table 4.1: Environmental variables used for the statistical analyses. The sampling period, statistical analysis and data source reference are shown.

Variable	Sampling events / Time period	Statistical Analysis	Appendix
Patch variables			
Morphometric variables	spring 2010	Spearman Rank order Correlation; T – test; Multiple Linear Regression / Binary Logistic Regression	IV-B
Flow velocity and deposited fine sediment in classes	spring 2009	T - test;	III-B
Sampling sites variables			
Catchment land cover (%)	2008 - 2010	Spearman Rank order Correlation Linear Regression / Multiple Linear Regression / Binary Logistic Regression	I-A
Riparian land cover (%)	autumn 2008 - 2009		I-A
Amount of deposited fine sediment (kg m^{-2}), percentage of organic matter and C/N ratio of fine sediment	autumn 2008 - 2009 sediment sampling		II
Substrate cover (%)	autumn 2008 - 2009		I-A
Morphometric parameters	autumn 2008 - 2009		I-A
Physicochemical parameters	spring 2010		V

Flow variables and fine sediment variables measured during the macroinvertebrate sampling in spring 2009 were used in order to examine the effect of the flow patterns on the deposited fine sediment. A total of 290 samples were obtained. Ten samples per site were collected using the standardised multi-habitat sampling (0.0625 m² sampling area). The flow velocity and deposited fine sediment (in classes) were measured.

The sampling sites were also characterised by land use cover in the catchment area (%), streambed substrates (%), fine sediment variables (kg m^{-2}), proportion of riffles and maximal stream bank height (m) and physiochemical stream properties.

Data on the catchment area (km²), the percentage of land use type in the catchment area based on Corine Land Cover (CEC, 1993) and riparian land cover were estimated for 5-m-wide strips, which were described in chapter 2.2.3 in detail.

The deposited surficial fine sediment (< 2 mm diameter) was collected during one year (September 2008 to September 2009) by means of artificial turfs (sampling area 0.015 m^2; per sample). Two sections were collected (one riffle, one pool) at each tested reach. The fine sediment fraction (kg m^{-2}) was recorded as annual arithmetic mean for site, and for riffles and pools separately. The proportion of organic matter and C/N ratio in fine sediment were determined. The fine sediment sampling and measurement procedures were described in detail in chapter 2.2.2.

The percentages streambed substrates were visually estimated before and after the sediment sampling period; the bank heights (in metres) and the proportion of riffles were also measured (chapter 2.2.3).

Finally, physicochemical parameters were measured in spring 2010. The pH-values; dissolved oxygen (mg l^{-1} and %), and conductivity (µS cm^{-1}) were recorded using the Multi350i (WTW, Appendix V).

4.2.4 Statistical Analysis

After verifying the normal distribution by the Shapiro-Wilk test, the T test was used to test the morphological variables in the riffles and pools. Spearman rank order correlation was used to check the relationship between the morphological patch variables and the taxa as well as the different environmental variables (untransformed data).

In order to achieve the normality for all regression, the environmental and species data were log-transformed (x+1). Several environmental variables (the percentage data such as a land cover use/vegetation cover and substrate variables, the shading and percentage of organic matter), were square root-transformed.

Simple and multiple linear regressions were applied to examine the strength of the relationship between species and simple as well as combined environmental variables, respectively. The analyses were carried out in order to find the best single model related to species abundances. The taxa densities were related to the specific places where the species occurred in the sampling spots, the riffles and pools (separately) as well as the sites (recorded as a mean of both samples). Only species with higher frequencies (more than five sites) were tested.

Since some species were not normally distributed, the relationship between the variables and the occurrence of species was verified using binary logistic regression, but the models were not significant.

For examining the response of the taxa in the patches, the patch environmental variables combined with sediment and physicochemical variables were used. For the remaining analysis a selected data set was applied using the factor analysis with a principal components extraction. After checking the eigenvalue of most explained components, multi-correlated variables were removed and as a result, 25 environmental variables were generated for the analysis (including the correlated variables after spearman rank order). Both, the simple variable and combined variables related to the taxa occurrence were identified. The significant variables were verified after removing the cases with a large Cooks distance and high leverage value.

The correlations, normality and t-test were conducted using Statistica 10.0 (Statsoft Inc., 2009). All regressions were performed in SPSS Statistics 20 (IBM Corporation, 2011).

4.3 Results

4.3.1 Descriptive analyses of morphometric patch variables

Both riffles and pools were located near the stream bank (mean ± SD of riffle and pool was equal 0.6 ± 0.4; Figure 4.3 A). In contrast, the deposited fine sediment covers ranged for riffles from 0 to 25% and for pools from 50 to 100%. Differences between riffles and pools were tested for significance (mean ± SD of riffle 7.4 ± 8.7; pool 79.6 ± 15.7; t test; $p < 0.0001$; Figure 4.3 B). Samples taken in riffles were generally characterised by greater depths (0.07 ± 0.03) in contrast to the pools (0.06 ± 0.02; t test; $p < 0.001$; Figure 4.3 C). Flow velocity was also higher for riffle patches (0.30 ± 0.13; pool 0.10 ± 0.06; t test; $p < 0.0001$; Figure 4.3 D).

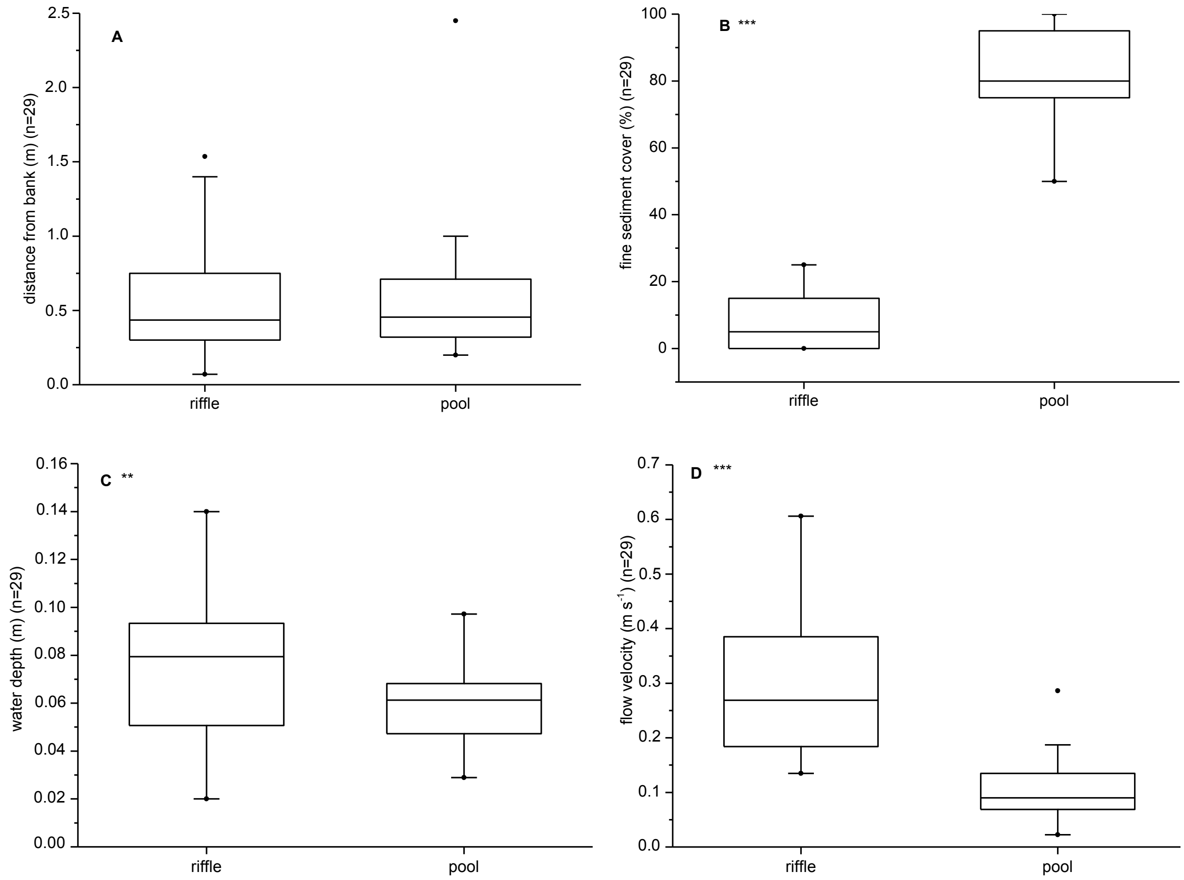

Figure 4.3: Distribution of morphometric variables in riffles and pools (n = 29). A: mean of distance from bank (m); B: percentage of fine sediment cover; C: mean of water depth (m); D: mean of flow velocities ($m\ s^{-1}$). A dash in the box is a median; box: 25% – 75%; whisker: 75% – 95%; ●extreme value. Significance level T test: $*p < 0.05$; $**p < 0.001$; $***p < 0.0001$.

Significant correlations between the morphometric patch variables were only obtained for riffles (Figure 4.4 A-C). In contrast, pools samples showed no significant correlations (Figure 4.4 A-C). The fine sediment cover on the patches was not related to morphometric variables for both riffles and pools.

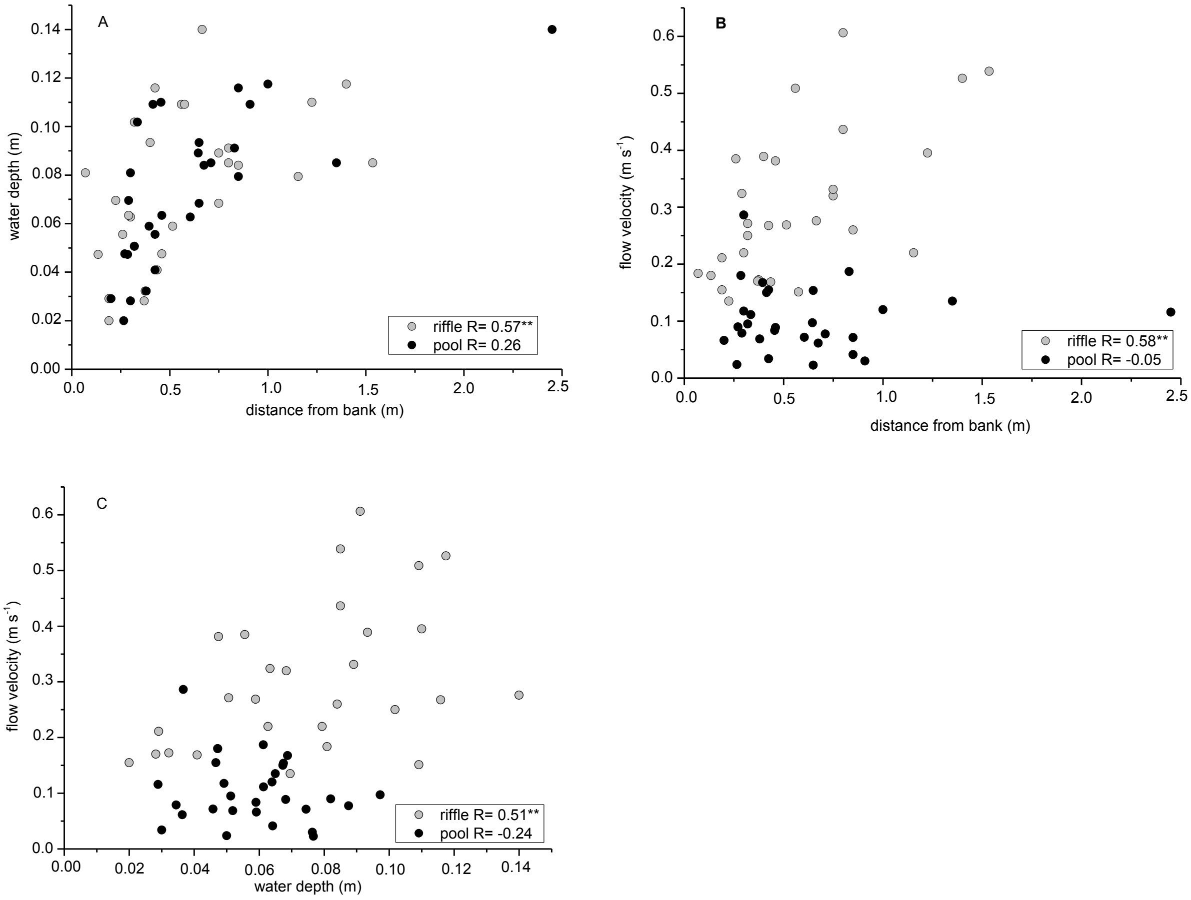

Figure 4.4: Relationship between morphometric stream parameters for riffle (grey dots) and pool (black dots) samples between A: distance from stream bank (m) and water depth (m); B: distance from stream bank (m) and flow velocity (m s^{-1}); C: water depth (m) and flow velocity (m s^{-1}). Spearman rank order correlations with a significance level: *$p < 0.05$; **$p < 0.001$.

The flow patterns recorded for fine sediment covers in classes of patches in sampling events in spring 2009 and 2010 were significantly different (Figure 4.5 A-B). The fine sediment cover increased generally with a lower flow velocity. The recorded flow velocity was higher in 2009 compared to 2010, particularly for lower fine sediment covers. The flow velocity recorded for the lower fine sediment class in spring 2010 was equal to the medium fine sediment class in spring 2009.

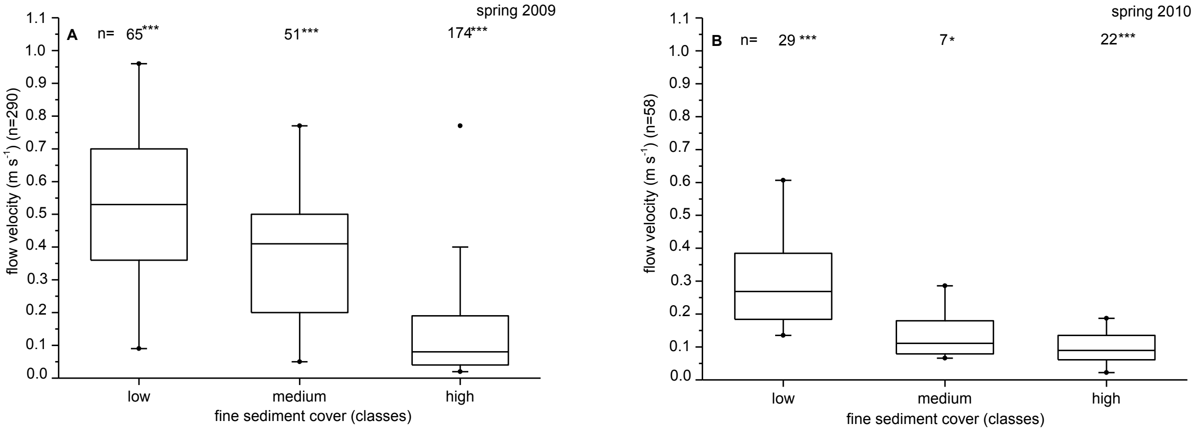

Figure 4.5: Impact of flow velocity (m s^{-1}) on fine sediment deposition (in classes) for patch sampling events in: (A) spring 2009 and (B) spring 2010. Fine sediment deposition cover in classes: low (0 - 30%), medium (> 30 - 70%), high (> 70%). A dash in the box is a median; box: 25% – 75%; whisker: 75% – 95%; ●extreme value. Significance level T test: *$p < 0.05$; **$p < 0.001$; ***$p < 0.0001$.

4.3.2 Distribution of taxa in riffles and pools

All taxa were recorded in both riffles and pools (Figure 4.6). The most common species was the larvae of the mayfly *H. confusa* occurring more frequently in pools (25 sites), followed by *S. personatum*. This species occurred in riffles and pools. *A. fuscipes* and the *R. semicolorata* group were also prevalent, in particular in riffles. In contrast, *E. danica* was predominantly recorded in pools (15 sites). *P. ludificatus* was rare and occurred in 14 sites (8 in riffles and 6 in pools).

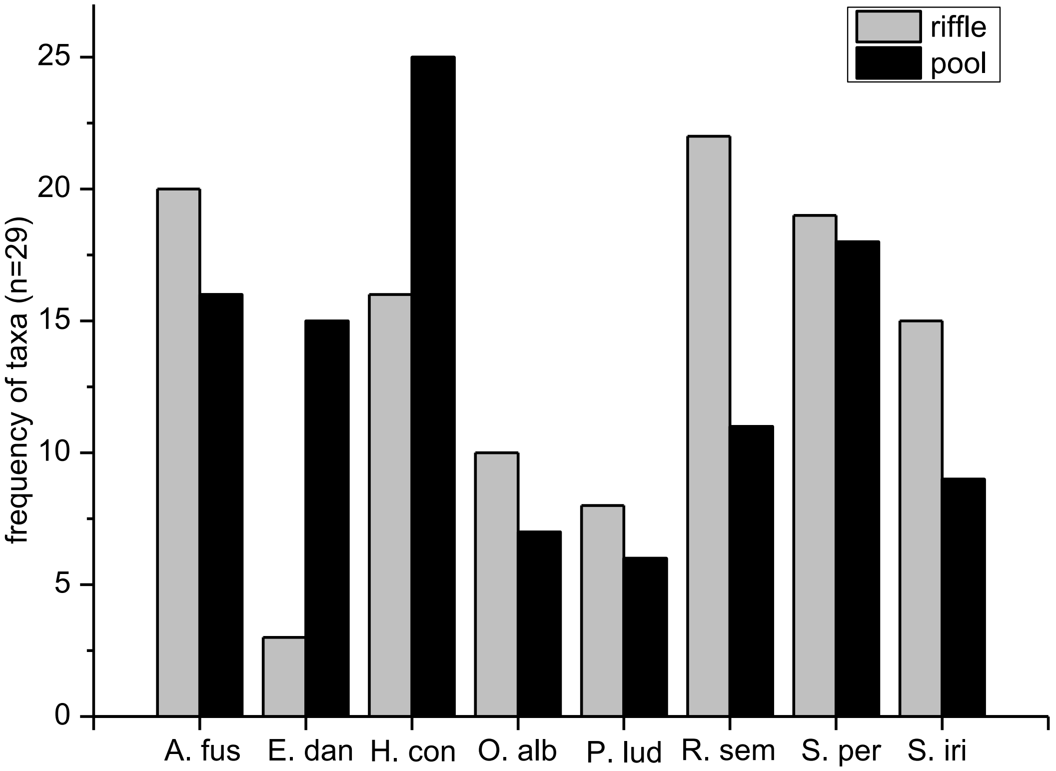

Figure 4.6: Frequency of taxa in riffle and pools. A. fus = *A. fuscipes*, E. dan = *E. danica*, H. con = *H. confusa*, O. alb = *O. albicorne*, P. lud = *P. ludificatus*, R. sem = *R. semicolorata* group, S. per = *S. personatum*, S. iri = *S. iridipennis/moselyi*.

A. fuscipes showed high abundances in both sections (909 individuals in riffles, 302 in pools), followed by *S. iridipennis/moselyi,* which was mainly recorded in riffles (704 in riffles, 28 in pools; Figure 4.7). *R. semicolorata* was found most frequently in riffles (144 individuals) as opposed to *E. danica* (98 individuals in pools). *P. ludificatus* and *O. albicor*ne showed a lower density.

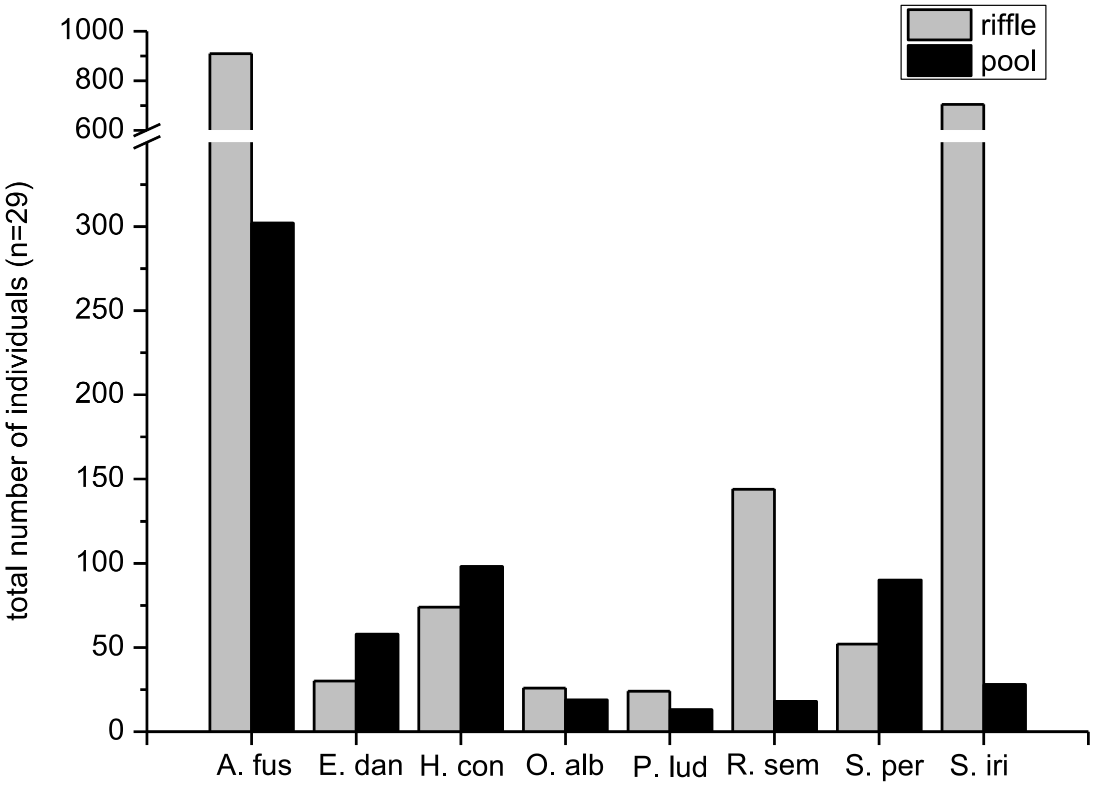

Figure 4.7: Total number of individuals in riffles and pools. A. fus = *A fuscipes*, E. dan = *E. danica*, H. con = *H. confusa*, O. alb = *O. albicorne*, P. lud = *P. ludificatus*, R. sem = *R. semicolorata* group, S. per = *S. personatum*, S. iri = *S. iridipennis/moselyi.*

The back of the stones followed by the surface and the section below the stones were the most frequently colonized patches (Figure 4.8). Hence, *A. fuscipes* and *S. iridipennis/moselyi* predominantly occurred on the surface, front and lateral sides (Figure 4.9). In contrast, the back of the stones was abundantly colonized by different taxa, in particular *O. albicorne*, *S. personatum* and the *R. semicolorata* group were found there. *E. danica* and *P. ludificatus* were most frequently recorded in the highest density below the stones. *H. confusa* predominantly occurred in interstitial spaces but most often inhabited the CPOM. The CPOM was the least densely colonized microhabitat, particularly by *E. danica* and *H. confusa.*

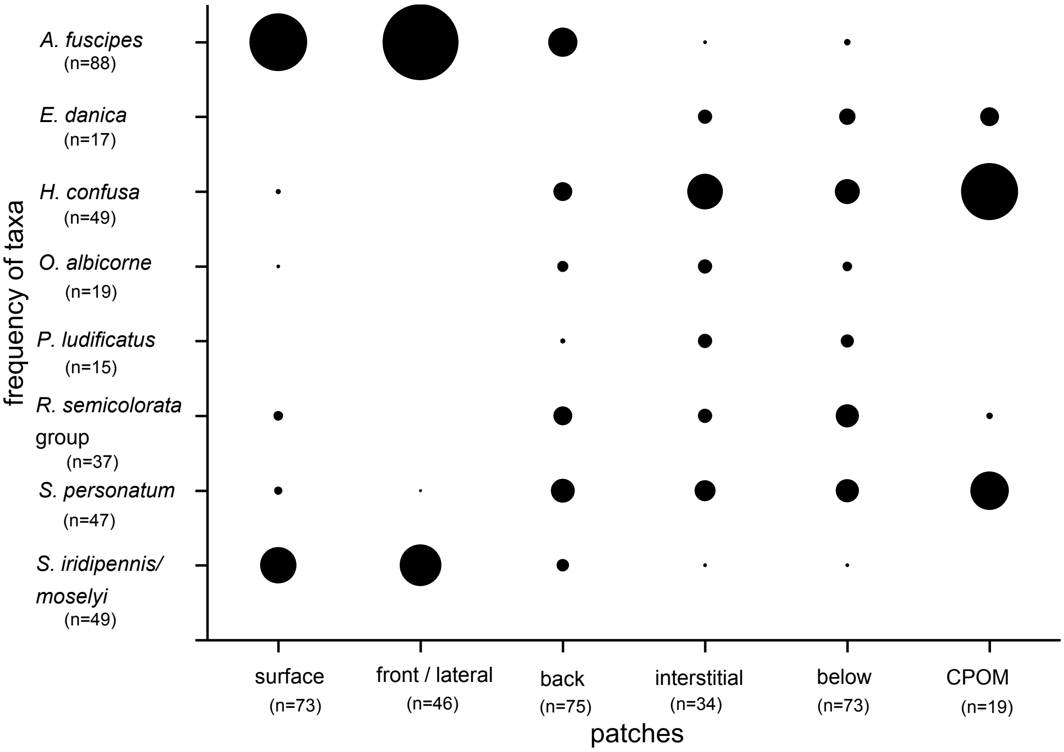

Figure 4.8: The proportion of number of specific places inhabited by taxa. CPOM = coarse particulate organic matter.

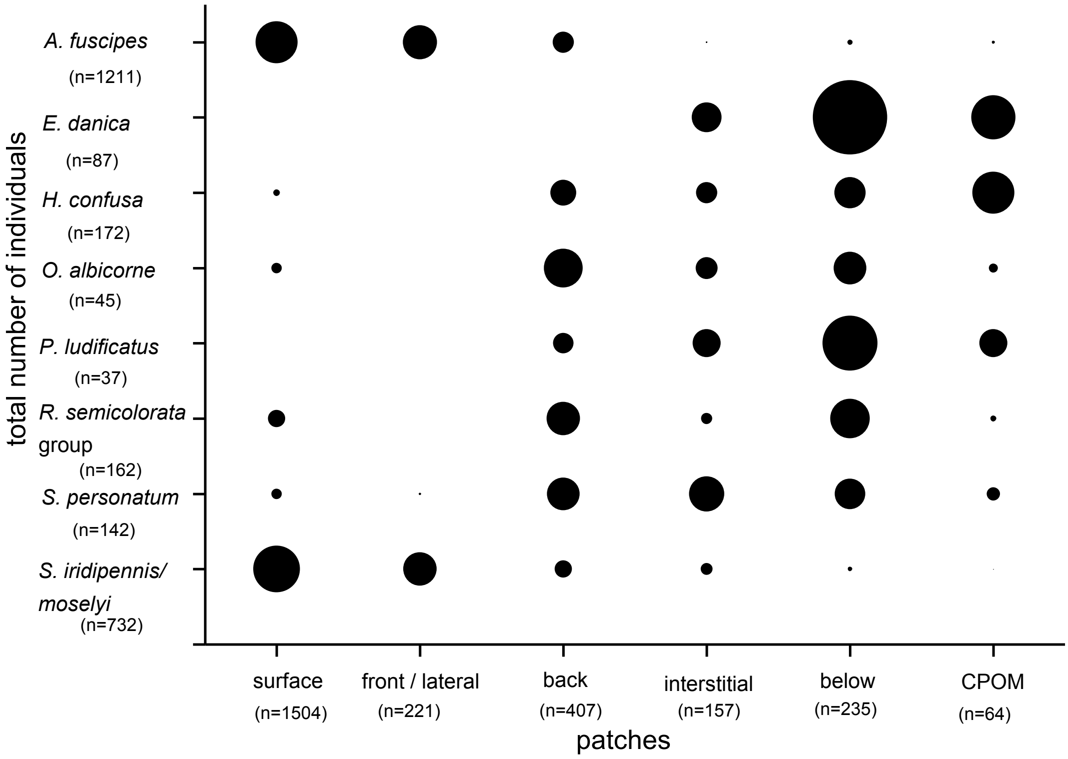

Figure 4.9: The proportion of number of individuals of taxa occurred on the patches. CPOM = coarse particulate organic matter.

4.3.3 The relationship between the taxa density on various patches and micro-scale environmental variables

Micro-scale variables revealed weak correlations to the number of taxa within different patches of riffles and pools (Table 4.2). Several taxa showed negative correlations to the distance from the stream bank (m), the percentage of fine sediment cover, and the flow velocity ($m\ s^{-1}$). The abundance of *A. fuscipes* and *S. iridipennis/moselyi,* attached to the surface of stones in pools as well the abundance of *S. personatum*, which was located on the back of stones, were negatively correlated to the fine sediment cover. The predator *O. albicorne* found below the stones showed a negative association to fine sediment in riffles. *S. iridipennis/moselyi* occurred on the surface and on the lateral side of stones in the riffles and was negatively correlated to flow velocity. In contrast, *E. danica,* which was found below the stones in pools, was positively related to flow velocity.

The mineral substrates, such as mesolithal (hand-sized cobbles) and macrolithal (stones), were significant for *P. ludificatus.* Similarly, the proportion of fine gravel was related to the occurrence of *A. fuscipes* on the surface of stones in riffles.

The occurrence of *A. fuscipes* and *S. iridipennis/moselyi* on the surface and partly on the lateral side of stones was positively related to the C/N ratio in riffles. This variable was recorded as a mean for sampling sites in the deposited fine sediment collected during the previous sampling. In contrast, the amount of fine sediment recorded for the sites was not significant for the taxa. The analysis was also repeated only for the sampling sites where taxa were present, but the Spearman rank coefficient showed no significant results, except for *S. iridipennis/moselyi* on the surface in riffles. This taxon was negatively correlated to the distance of the bank (Spearman coefficient $R = -0.69$, $p < 0.05$) and to the proportion of gravel in pools (Spearman coefficient $R = 0.81$, $p < 0.05$). The frequency of *A. fuscipes* occurred on the surface in riffles was related to the proportion of mesolithal (linear regression, $R^2 = 0.25$, $F = 6.96$, $p < 0.05$). The fine sediment cover was only significant for *E. danica* in pools ($R^2 = 0.74$, $F = 33.82$, $p < 0.001$).

Table 4.2: Spearman rank order correlation of micro-scale environmental variables on taxa abundances for different patches in rifles and pools (n = 29). The C/N ratio of the deposited fine sediment was recorded for riffles and pools separately. Only significant variables are shown. Significance level: *$p < 0.05$; **$p < 0.001$. Meso. = Mesolithal; Macro. = Macrolithal. A. fus = *A. fuscipes*, E. dan = *E. danica*, H. con = *H. confusa*, O. alb = *O. albicorne*, P. lud = *P. ludificatus*, S. per = *S. personatum*, S. iri = *S. iridipennis/moselyi*, *R. semicolorata* group was not significant.

TAXON	SIDE RELATED TO THE STONES	SAMPLE	DISTANCE (m)	FINE SEDIMENT (%)	FLOW VELOCITY (m s^{-1})	DEPTH (m)	GRAVEL (%)	MESO. (%)	MACRO. (%)	C/N RATIO (FOR DEPOSITED FINE SEDIMENT)
A. fus	Surface	riffle					-0.44*			0.41*
A. fus	Surface	pool		-0.42*						
S. iri	Surface	riffle			-0.57**	-0.40*				0.47*
S. iri	Surface	pool	-0.41*	-0.41*		-0.54**				
S. iri	Lateral	riffle	-0.38*		-0.38*					0.50*
H. con	Back	pool	-0.46*							
O. alb	Back	pool	-0.41*							
S. per	Back	pool	-0.41*	-0.41*						
E. dan	Below	pool			0.42*					
O. alb	Below	riffle		-0.38*						
P. lud	Below	riffle						-0.39*	0.49**	

4.3.4 The relationship between taxa density and environmental variables at different spatial scales

Several environmental variables on different spatial scales such as land use in the catchment and riparian zone as well as substrate cover impacted taxa occurrence and abundance significantly. The *S. iridipennis/moselyi* was negatively correlated to catchment area ($R = -0.56$; $p < 0.05$). *A. fuscipes* was also negatively related to the percentage of urbanisation in the catchment ($R = -0.55$; $p < 0.05$) and the *R. semicolorata* group to the percentage of coniferous forest in the riparian zone on the stream bank ($R = -0.56$; $p < 0.05$). The abundance of *O. albicorne* per the sampling site was significant to the proportion of wood trunks cover in the stream substrate ($R = -0.55$; $p < 0.05$). The occurrence of *H. confusa* was negatively related to the percentage of coniferous forest on the stream bank ($R = -0.41$; $p < 0.05$). *P. ludificatus* was correlated to three variables such as a percentage of gravel ($R = 0.62$; $p < 0.05$), amount of fine sediment ($R = 0.68$; $p < 0.05$) and proportion of organic matter ($R = -0.69$; $p < 0.05$).

The linear regression between the deposited fine sediment and taxa densities were not significant except for *P. ludificatus* ($R^2 = 0.72$; $p < 0.001$; Figure 4.10 A-H).

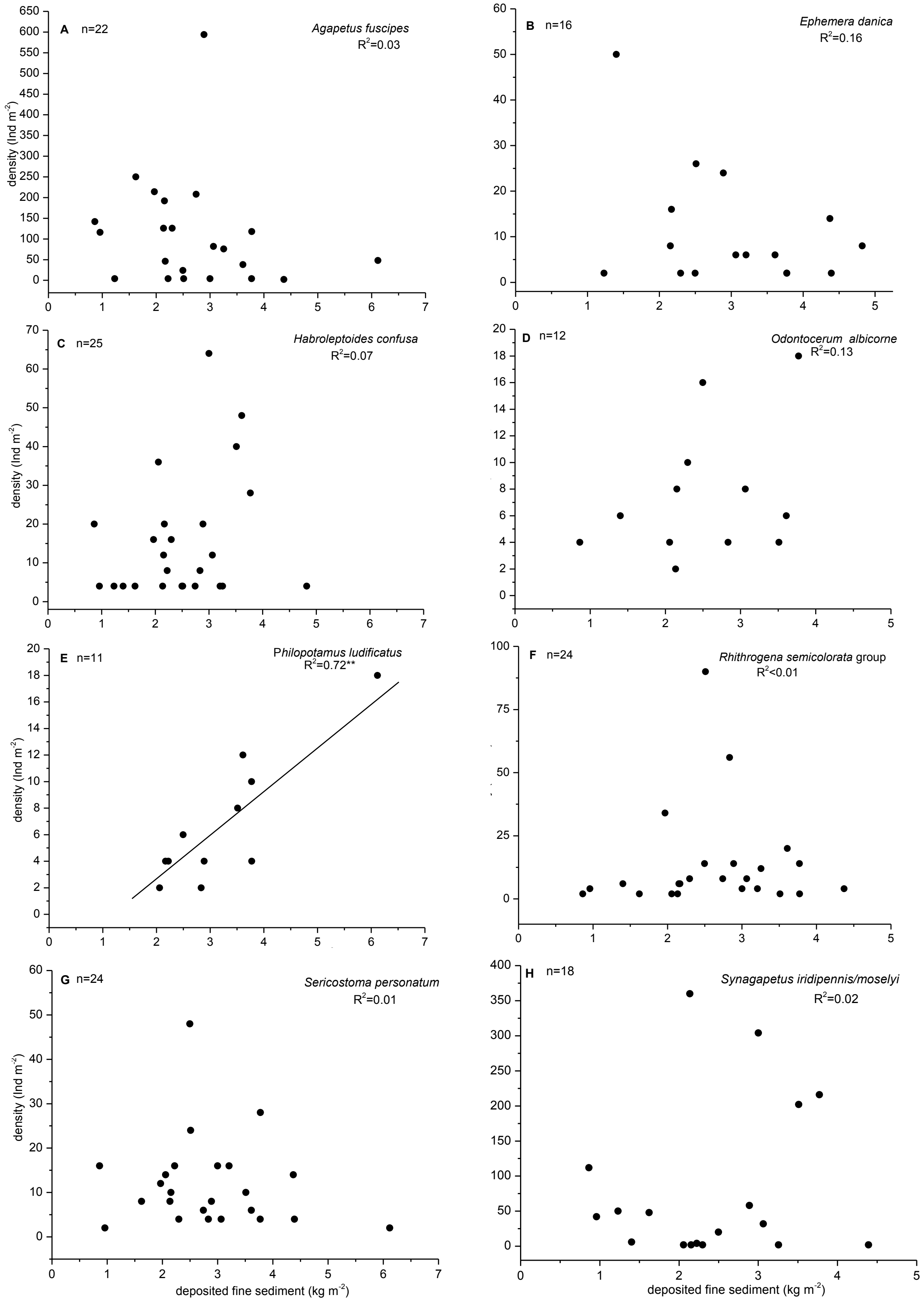

Figure 4.10: Regression analysis of taxa density (Ind m^{-2}) and the amount deposited fine sediment for the sampling sites (kg m^{-2}) A: *A. fuscipes*; B. *E. danica*; C: *H. confusa*; D: *O. albicorne*; E: *P. ludificatus*; F: *R. semicolorata* group; G: *S. personatum*; H: *S. iridipennis/moselyi*. Significance $^{**}p < 0.001$.

4.4 Discussion

4.4.1 Relationship between the morphometric patch variables

The investigated sites were very shallow with a maximum depth of 14 cm, and the riffles were generally deeper than the pools, which was in contrast to larger streams characterised by shallower riffles (Kershner et al., 2004). The deeper the water in the riffles, the faster the flow velocities increases, in particular, if the riffles were located in the middle of the channel. The pools were more heterogenic than the riffles, which resulted, for instance, in fine sediment cover of up to 50 per cent for a few samples. We mainly found that shallow pools (the deeper pools developed behind large obstacles) were rarely present and with a smaller size than the investigated area (0.25 m^2). We had only expected the linear relationship between water depth and flow patterns within riffles and not within pools, because the pools are generally deeper behind obstacles or very shallow in the small streams such as in our brooks (e.g., Kappesser, 2003; Kershner et al., 2004).

We observed a change of flow velocity between the years. The recorded flow velocities in spring of the previous year were considerably higher than for 2010. The greater variability of discharge was derived from surface and subsurface runoff and is characteristic for headwaters (e.g., Gomi et al., 2002; Klove et al., 2011). The variance of the flow pattern might be also due to the mathematical calculations of the flow velocity for 2010. This arithmetic mean was based on eight single measurements of flow velocity, which varied within the investigated area. The relatively large sampling spots (0.25 m^2), representing a very heterogenic structure, caused a wide range of flow velocity in 2010. It would have been better to use a smaller area in order to evaluate the small-patch variability of the small brooks. The fine sediment cover was not linked to the distance from the stream bank and morphological variables for riffles and pools. However, the percentage of the deposited fine sediment increased with a decrease of flow velocities, which generally reflected the accumulation processes of sediment.

4.4.2 The impact of environmental parameters on eight benthic species

All species showed specific responses to the differing environmental variables, which will be discussed in more detail in the following paragraphs.

A. fuscipes and *S. iridipennis/moselyi* occurred in high densities on the surface of stones, which revealed their large dependence on microlithal and macrolithal components (Fischer, 2003). Despite this microhabitat preference, both taxa prefer slightly different local conditions, particularly in terms of stream width, depth and flow velocity as well as their sensitivity to nutrient input and to dry periods (Fischer, 2003). The high fine sediment cover on the surface in pools impaired densities of both taxa, which was particularly true for *A. fuscipes*. This species was more common in pools in contrast to *S. iridipennis/moselyi*. The patches with a high silted layer can accumulate the casings of larvae or alter the quality of microalgae growth (Izagirre et al., 2009). However, the species can intentionally avoid the deposited patches. Hence, Wood and Armitage (1999) observed that after the reduction of sediment caused by a dry period, *A. fuscpies* inhabited only the areas of clean stones. The proportion of fine gravel on the patches was also negatively correlated to the abundance of this species, reflecting its relation to larger-sized substrates such as pebbles or cobbles (Graf et al., 2008).

The densities of these species within the site were also negatively related to the percentage of urban area in the catchments. This variable can generally indicate the susceptibility to organic pollution combined with the runoff of sewage water. The higher discharge variability can also result from the reduction of infiltration due to sealed surfaces. This finding corresponded with Nijboer (2004), who stated a high sensitivity for this species towards organic pollution and varying discharges. However this contradicts to Fischer (2003), who described this species as very tolerant against flow variability and emphasized its low demand for oxygen in contrast to *S. iridipennis/moselyi*. The positive relation between the C/N ratio in the deposited sediment and density of both, *A. fuscipes* and *S. iridipennis/moselyi* in the riffles, confirmed the sensitivity of these taxa to organic pollution. Organic pollution can be associated directly to suspended solids (e.g., adsorption of orthophosphate) as well as to nutrient runoff. In addition, the anthropogenic pollution might be slightly due to a minor gradient of urbanisation in our study area, in contrast to the nutrient release from agricultural (organic manure, fertiliser). However, the percentage of agricultural area was not related to the abundance of these species.

The flow patterns were not a key factor for the occurrence of taxa in pools but in riffles; hence, this variable was negatively correlated to densities of *S. iridipennis/moselyi* on the surface and lateral sides of stones. The faster flow velocity can cause the increase of the suspended load, which can damage parts of casings. The resulting stress due to repair work can lead to a decrease of abundance in these places. This taxon was also less frequently found on patches with deeper water located near the stream bank, which indicates hydraulic stress rather than the response to sedimentations. The negative correlation to the catchment's area size of this taxon also revealed its distribution in small headwaters.

E. danica was abundant in pools, located within mud and organic matter. This is in accordance to its burrowing habits and a preference of lentic sections (Buffagni et al., 2009). The species gathers there and shredders detritus or swirls fine particles using the respiratory movement of gills (López-Rodríguez, 2009). *E. danica* was more frequently found below the stones of pools characterised by increased flow velocities. The microhabitat preferences of this species can vary between different developmental stages (Hanquet et al., 2004). The young larvae inhabit boulders with medium depth and current velocity. In contrast, later instars occur in shallow and sandy sections with weak flow velocity (Hanquet et al., 2004). However, Armitage and Davies (1989) noted an increase of burrowing activity by nymphs of *E. danica* (> 15 mm long) with an increase of flow velocities. The ability of burrowing was also higher in the presence of grains greater than 2 mm diameter but stopped with a dominance of sandy substrate. The fine sediment cover in pools was also related to *E. danica* inhabiting these sections. We did not determine the live cycle stages of the larvae, but in agreement with Armitage and Davies (1989), higher flow velocity and lower deposition of fine sediment might be an important factor for its ingestion and movement. Thus, the ingestion and movement can be limited in the compacted streambed associated with the clogging of fine sediment, which can consequently result in the decline of *E. danica* density.

H. confusa was found mostly in pools, where it can gather and collect detritus and diatoms in the deposited sediment between the leaves and stony substrates (González et al., 2003; Buffagni et al., 2009). However, the abundance of this species declined in the pools section if this section was located within a certain distance from the bank. The response to the stream bank suggests that the species *H. confusa* can tolerate the supply of the eroded sediment originating from bank. The direct response to fine sediment could not be determined. We can also assume that this species prefers small streams, which is not in accordance to findings of Dittmar (1955), who observed a high density of this species in primarily in larger headwaters. The author found it sporadically in the spring brooks and only in the sections with a permanent flow, which was able to clean off the stones of the deposited sediment layer. The percentage of coniferous forest on the bank also negatively influenced the abundance of *H. confusa.* We could not prove the link between sediment and coniferous forest, although this might be a consequence of a lack of available nutrients normally derived from leaf decomposition. Therefore, plants' remains such as needles of coniferous trees are not a highly qualitative food source in contrast to the leaves of deciduous trees (e.g., Gessner et al., 1999; Albers et al., 2004).

O. albicorne occurred below the stones in the riffle patches and was negatively correlated to a fine sediment cover. This species forages on benthic insects and is most active at night (Elliott, 1970); hence it requires hiding-places and the like because of its night-activity in a lesser degree a good visibility range. Some aquatic predators such as the larvae of the dragonfly *Cordulegaster boltoni* are burrowed in mud in order to be invisible for the pray (Bo et al., 2011). This camouflage technique is unknown among *O. albicorne*. The sections of riffles below the stones might be less common and also difficult for hunting. We could not explain the negative correlation to the woody substrates recorded at the sampling sites. Overall, this species occurred at nearly all patches in our brooks and microhabitats (Schmidt-Kloiber and Hering, 2012). *O. albicorne* can move but is also described as partly semi-sessile species (Schmidt-Kloiber and Hering, 2012). Possibly the morphological conditions developed by large wooden trunks constantly varied, which can hinder its hunting method or territorial behaviour.

P. ludificatus was more abundant in riffles and occurred on the patches below as well as in the interstitial spaces of stones. This reflected its microhabitats preference. It builds nets in order to collect detritus (Schmidt-Kloiber and Hering, 2012). The abundance of this species below the stones was positively correlated to the percentage of macrolithal and negatively to mesolithal. *P. ludificatus* requires coarse grain substrates, which range from larger gravel to boulders and bedrock with a grain size of up to 20 cm. Perhaps larger substrates are more stable for its constructions. However, this finding contradicts the positive correlation between its densities and the percentage of fine gravel recorded at the site. The other factor related to the densities of those taxa in brooks was the deposition of fine sediment. Between the amount of fine sediments and the abundance of *P. ludificatus,* a high linear relationship could be observed. The suspended load contains both the detritus and fine sediment, which can be transported upstream in large amounts, benefiting the filter feeders (Hering et al., 1993). However, such a strong connection between this species and the percentage of gravel could not be confirmed. Thus, we assumed this apparent correlation was due to autocorrelation between these environmental factors. In contrast to fine sediment, the percentage of fine gravel is not an important factor for this species.

According to Graf et al. (2008), *S. personatum* occupies most microhabitats. In our study, it was less frequently found in the patches on the back of stones in the pools with a high fine sediment cover located near the channel. Similar to our findings, Larsen et al. (2009) observed the decline of densities for this species with the small-scale increase of fine sediment cover. We supposed that *S. personatum* is able to migrate to patches, which provide a better availability of food and which are not exposed to fine sediment.

The *R. semicolorata* group inhabited mostly riffles and was found in high densities on the back of stones and less frequently below the stones. This taxon is generally adapted to faster current; however, it prefers sides not directly exposed to faster flow velocities. We could not demonstrate the direct link to fine sediment and other environmental factors (expect a percentage of coniferous forest on the stream bank), possibly due to its excellent locomotion. In order to find an optimal place for foraging or to protect itself against the predators, it is able to swim for a short distance and to cling to stones. Thus, it can relatively quickly move and migrate to the stony substrates characterised by the growth of filamentous algae and the presence of fine plant detritus, which are essential food sources for this taxon (Buffagni et al., 2009). The roughness of substratum can also be a factor, responsible for its occurrence. Crosa and Buffagni (2002) observed that *R. semicolorata* inhabited primarily smoother substrates, but we could not investigate this variable. The high percentage of coniferous forest on the stream bank, comparable to *H. confusa,* negatively affected its abundance. As with *H. confusa*, this might also be a result of a limitation in the food supply.

4.5 Conclusions

Our study demonstrated that the deposition of fine sediment had a minor influence on species density. Although certain species occupied specific places, they were connected to the cover of patch-sediment and to the C/N ratio of deposited fine sediment; however, this relationship could not be strongly correlated. Only two species, *E. danica* and *P. ludificatus*, responded to the fine sediment load, which reflected a direct linkage to sediment. The response of *E. danica* to the patch-cover exposure indicates habitat preference of this species. This was in contrast to *P. ludificatus,* which occurred below or between larger stones, and was best protected against exposure to surficial deposition. This species responded to fine sediment amount in the site-scale due its feeding type; hence it benefits from the supply of fine sediment accompanied by detritus.

However, the densities of the remaining species were neither connected to the fine sediment cover nor to the amount of fine sediment for the sampling sites. We assumed that the small headwater streams provide highly diverse patterns of microhabitats and food sources; hence the animals can avoid the deposition of fine sediment and locally migrate to patterns characterised by optimal food sources and habit conditions. On the other hand, the input of fine sediment might be homogeneous over a wide area due to the geographical proximity of the studied sites and the dominance of agriculture. This might be a reason why the effects of sedimentation on the biota were quite low, which was also suggested by Benoy et al. (2012). As a result of high sediment load, certain species can be absent due to the mortality of eggs or young larval stages.

In addition, the strong response of the benthic community composition, which was observed by the previous study described in chapter 3, to the C/N ratio in the deposited fine sediment could not be determined. The impact of the chemical composition of sediments and not of the amount of deposition suggests the presence and interaction of multiple stressors on the benthic fauna. The biological limitation can be due to short-term changes, accompanied by the altering of water chemistry parameters. A similar response to sediment between both studies might be attributed to different periods of sampling as well as to the differences between the response on an individual and on a community level. While the eight species reflected only a minor range of the biological response, the community composition revealed a comprehensive pattern, including additional benthic groups such as mussels, worms and other insect orders. The shift in the benthic community can be caused by the alternation of the related groups, which require habitats responding directly to the fine sediment such as a mud section.

We could not identify the best interactive factors required for the abundance of species. However, the density of the species low correlated with several environmental factors: characteristically stream size (catchment area, water depth), hydromorphological stream conditions (substrate cover, flow velocity), and, to some degree, land use (particularly in the riparian zone) as well as the impact of urbanisation. A missing link between physicochemical conditions, the cover of land use in the catchment (with the exception of urbanisation), and the species was unexpected. In small, headwater streams, hydraulic parameters are possibly key factors influencing the bioavailability and substrate distribution as well as connecting the catchment area and providing the sediment and nutrients (e.g., Gomi et al., 2002). Thus, the lack of response of species may reflect the current stream hydraulics, which was less related to catchment during the species sampling.

5 General conclusions and summary

5.1 Summary

We investigated current questions regarding the deposition of fine sediment in small headwater streams:

1) Which environmental factors have an impact on the deposition of fine sediment?

2) Does the deposited fine sediment or other environmental factors impair the benthic macroinvertebrate community?

3) Does the deposited fine sediment or other environmental factors impair selected insect larvae of the order Ephemeroptera and Trichoptera?

A total of 29 sampling sites in 1st and 2nd order upland streams in the Ardennes mountain range in northern Luxembourg were studied in detail. The most important methods, results and interpretations were as follows:

Chapter 2:

The impact of environmental variables on the deposited fine sediment

We collected the deposited fine sediment (< 2 mm diameter) from the streambed in riffle and pool sections for one year and developed a new method for the sampling of fine sediment using artificial turfs. After that, we determined the fine inorganic content, the proportion of organic matter, the total carbon and the total nitrogen ratio (C/N ratio). Additionally, we recorded the explanatory variables such as land use and cover in the catchment and the riparian zone, the soil erosion potential, hydromorphological stream variables, and physicochemical parameters.

We applied a partial redundancy analysis (pRDA) to determine and quantify the impact of environmental variables acting on different spatial scales of fine sediment deposition, organic matter and C/N ratios. The variables acting on the in-stream (S) and catchment scale (C) were the most important predictors for the deposition of fine sediment associated with the organic matter and C/N ratio (Fine sediment content S; 33%;
C, 25%; organic matter S, 37%; C, 24%; C/N ratio S, 40%; C, 34%). The explained variance for all components of sediments was nearly 100%.

The results of the redundancy analysis (RDA) revealed two significant parameters for fine sediment such as the coverage of fine gravel on streambeds, which explained 18% of total variance and the percentage of cropland in the catchment (12%). The eigenvalue of the first two axes was $\lambda = 0.406$. The percentage of pasture was with 20% the most significant variable for the proportion of organic matter (eigenvalue of the first two axes together was $\lambda = 0.567$). In contrast, the C/N ratio was mainly explained by the maximum value of the conductivity (17%) and the catchment area (16%). The eigenvalue of the first two axes together was $\lambda = 0.503$. The input of fine sediment and nutrients was mainly dependent on land use in the catchment; hence a significant proportion of cropland leads to increased soil erosion and amount of fine sediment in streams. In contrast, the in-stream factors had a major impact on the accumulation of fine sediment.

Chapter 3:

The impact of deposited fine sediment on the macroinvertebrate community composition

We collected macroinvertebrate assemblages in the streams in autumn 2008 and spring 2009. We adapted the method according to multi-habitat samplings, e.g. we took ten samples instead of 20. For the analysis we used a set of environmental variables, which contains land use in the catchment and riparian zone, sediment, hydromorphological and physicochemical variables.

The relationship between the amount of fine sediment and its components was calculated. We found a strong negative relationship between the fine sediment content and the C/N ratio ($R^2 = 0.46$, $p < 0.0001$) as well as between the fine sediment content and organic matter ($R^2 = 0.51$, $p < 0.0001$). Canonical Correspondence Analysis (CCA) revealed three important variables explaining the variance in the macroinvertebrate community composition oxygen saturation with 15%, followed by the proportion of fine gravel on the streambed (13%) and the C/N ratio (11%). The variance in the macroinvertebrate community composition was explained by 20.8% of all environmental variables (cumulative percentage of species data of the first two CCA axes). Twelve biotic indices (Shannon-Wiener-Index; Evenness; the proportion of Ephemeroptera, Plecoptera, and Trichoptera; and the functional indices) reflecting the impact of fine sediment on the macroinvertebrates were calculated using Asterics 3.3. Redundancy Analysis (RDA) showed two environmental variables: the C/N ratio (18%) and dissolved oxygen (16%) explained most of the variance in the biotic metrics (33.6% cumulative percentage of the metric data of the first two RDA axes):

The chemical composition of the deposited sediment was more important than the amount of sediment, as the C/N ratio alone explained a substantial amount of variance in species composition. The biological response to oxygen deficits and the C/N ratio of the deposited fine sediment indicate the potential effects of fine sediment deposition through oxygen consumption.

Chapter 4:

The impact of deposited fine sediment on eight taxa of mayflies (Ephemeroptera) and caddisflies (Trichoptera)

We selected the following taxa: *Ephemera danica, Habroleptoides confusa,* and *Rhithrogena semicolorata* group belonging to Ephemeroptera as well as *Agapetus fuscipes, Synagapetus iridipennis/moselyi, Sericostoma personatum, Odontocerum albicorne*, and *Philopotamus ludificatus* belonging to the Trichoptera order.

The animals were counted at each site and at defined spots (50 x 50 cm^2) in riffles and pools in spring 2010. We counted the insects on various patches such as on the opposite sides of stony substrates, on interstitial places between stones, and on the organic matter as well. At each spot, we assessed local morphometric variables (water depth, distance to stream bank, flow velocity), the cover of mineral substrates, and the deposited fine sediment (< 2 mm; including fine organic matter). The environmental variables for the site and land use were recorded in previous studies (chapter 2 and 3). We used the environmental variables to examine the impact of these variables on taxa occurring in patches as well as in sites.

The water depth of these headwater streams was low (mean depth for riffles and pools was 6.5 cm). In particular, the riffles were more diversely characterised by a higher range of flow velocity and water depth, which stood in contrast to pools. The flow velocities were significant to classes of deposited fine sediment and slower in spring 2010 than in spring 2009, while revealing its variability within the same season. However, the deposited fine sediment cover in both riffles and pools was not significant to local morphometrical variables.

Fine sediment was strongly related only to two species as an estimated surficial cover of the sampling area in pools for the density of *E. danica* ($R^2 = 0.74$, $p < 0.001$) and as an amount of deposited fine sediment recorded for the site density of *P. ludificatus* ($R^2 = 0.72$; pc < 0.001). Unfortunately, we could not identify the best model of interacting variables ideally responding to taxa. However, several local variables were significantly correlated to the number of taxa on the patches (water depth, flow velocity, substrate cover), but the relationship was only strong for *A. fuscipes* occurring on the surface in riffles to a percentage of mesolithal (pebble) in spots ($R^2 = 0.25$, $p < 0.05$). The additional significant variables related to species on the site-scale were catchment areas, the percentage of urbanisation in the catchment area, percentage of coniferous forest on the stream bank, and the proportion of substrate such as gravel and trunks.

5.2 General conclusions

The catchment area and land use in the catchment as well as the hydromorphological and physicochemical in-stream variables have a significant influence on the deposited fine sediment in small headwater streams, which has been proved by a strong explanation power of RDA and pRDA analyses.

Intensive agriculture induces a non-point release of fine sediment, which is reflected by the strong relationship between the amount of deposited fine sediment and the proportion of cropland in the catchment (chapter 2). In addition, the provision of the nutrients' origin from fertilisers and organic manure from cropland and pasture as well as sewage water can influence the chemical composition of deposited fine sediment, which was shown by the linkage between the C/N ratio of fine sediment and the water chemistry, in particular by the increased level of conductivity (recorded simultaneously to sediment sampling). We could not accurately identify the origin of nutrients in deposited fine sediment, but the agriculture might strongly contribute to the release of nutrients.

Despite the fact that the mineral nitrogen fertiliser use has decreased within the last years in Luxemburg (Dairyman, 2010), the levels of nitrate and ammonia concentration in the streams and the river Our are still too high (Hall et al., 2010).This can be attributed to the use of organic manure such as liquid manure. The release of both mineral and organic fertilisers can certainly influence the chemical composition of deposited fine sediment.

Additionally, a high demand for energy and forage crops results in the transformation of grassland into cropland. The present study generally supports the maintenance of pasture, because the proportion of pasture was not directly connected to the amount of sediment or nutrients in this study. The pasture was only related to the proportion of organic matter in deposited fine sediment, which can be explained for example by the remaining plants after grass cutting. Various sources prove that the grass vegetation buffer can effectively retain nutrients and sediments (e.g., Parkyn, 2004; Udawatta et al., 2006; Yates et al., 2007). Thus, with a loss of pasture, the soil and nutrient retention of agricultural areas will decrease and the release of fine sediment and nutrients will increase due to the soil management practices and the use of fertilisers.

Generally, the in-stream variables such as hydromorphological (e.g., substrate distribution, flow patterns) and physicochemical variables play an essential role for the chemical properties and the behaviour of deposited fine sediment as well as species abundances and community compositions, which revealed our results of ordination, correlation and regression analyses (chapters 2, 3 and 4). In particular, flow patterns influence the bioavailability, the transport and accumulation processes of sediment as well as the shaping of the streambed structure. This was partially shown by the relationship between flow patterns and the proportion of C/N ratio of deposited fine sediment as well as the linking between the deposition and the proportion of fine gravel in the substrate cover (chapter 2 and 4). The presence of large fine gravel sections impaired the benthic community, which was reflected by the RDA results (chapter 3), but small-scale patches behind large obstacles such as woody debris or stones can contribute to the diversity of substrate, and hence provide varied local environmental and hydromorphological conditions, which are generally significant for the fauna in small headwater streams (e.g., Clarke et al., 2008). The diversity of substrates and flow patterns and the channel structure contribute to the transformation processes of sediments and nutrients (Peterson et al., 2001; Gomi et al., 2002).

Our main results showed that the chemical composition of deposited fine sediment and not its amount impaired the benthic macroinvertebrate community. The C/N ratio of deposited fine sediment and oxygen concentration in the water were significant related to benthic community composition (chapter 3). Those variables are associated with nutrient enrichment and as a consequence high biological activity and oxygen consumption. However, on the basis of these results we could not distinguish if either the individual impact of eutrophication on biota was stronger than sedimentation or if both stressors affected the community composition simultaneously. Generally, the effect of sedimentation on the abundances of selected species was low and based on the habitat requirements and food preferences directly connected to fine sediment (chapter 4). For example this includes the muddy areas of streambeds inhabited by *Ephemera danica* or the suspended particles captured by *Philopotamus ludificatus*. In contrast, the locally deposited patterns or the amount of deposited fine sediment in the stream site could not influence the frequency of the other studied species. We can presume that the indirect effect based on the causal assumption was not strong. For instance the loss of quality food sources or the top-down shift (e.g., periphyton composition, prey) resulting from siltation was not comprehensive in small headwater streams, hence the biota can locally migrate to patterns characterised by optimal conditions, which are highly diverse. On the other hand, the high deposition of fine sediment can be due to short-term precipitation events. Thus, the average fine sediment content measured for winter was higher compared to other seasons (chapter 2). However, the effect of fine sediment compositions on the community within two different sampling seasons was similar (chapter 3). The larvae can possibly escape to refugial areas in interstitial spaces, which are not clogged by fine sediment. Moreover in late spring or summer certain insects have hatched and do not inhabit the streams anymore. To measure episodical effects of sedimentation more precisely, sampling should be in accordance with water levels and extreme precipitation events.

On the basis of our results on the impact of sedimentation on macroinvertebrates, we can draw these general conclusions with regard to small headwater streams and to our specific studied area:

Firstly, the sedimentation in the studied area is present, but we could not measure it in detail. This case study focused on a specific study area, which is dominated by a homogeneous land use. Thus, the non-point sediment entry can be widely and consistently distributed in the studied area. As a consequence, the fine sediment load in these sections can cause the extinction of numerous sensitive species. The lack of these species could influence our results; hence the effect on the species was not very strong and did not reflect physical thresholds, which was suggested by Benoy et al. (2012).

Secondly, eutrophication can generally increase the effect of sedimentation in small headwater streams. The effect of sedimentation is particularly related to species with habitat requirements that are directly connected to fine sediment. The individual and combined impact of both stressors as a result of agricultural pressure is recently investigated more frequently (e.g., Matthaei et al., 2006; Ormerod et al., 2010; Wagenhoff et al., 2011). The recent studies suggested that the single effect of individual sedimentation on the biota is stronger than the eutrophication (Townsend et al., 2008; Wagenhoff et al., 2011; Wagenhoff et al., 2012). However, in our study, we could not separate the effects of stressors, eutrophication and sedimentation, because a larger range of physicochemical parameters and long-term measurements accompanied by frequent sediment sampling is required.

Finally, regarding our study area, the eutrophication as a consequence of nutrient provision from agriculture seems to be a more pervasive stressor on biota. We can generally exclude the supply of sewage water, which was minor and only slightly present at four sites. Our statement based on the results in chapter 2 and 3, which showed the relationship between the chemical composition of deposited fine sediment to both water chemistry and benthic community composition is supported by the above-mentioned water chemistry report of the studied stream (Hall et al., 2010).

5.3 Future prospects

The ecological effect of increasing fine sediment deposition in streams and rivers is mostly unknown. The reason might be that the commonly used methods for measuring fine sediment load are often unsuitable or inaccurate for quantifying the surficial deposition. We therefore successfully established a new sampling technique using artificial turfs, which can be used for sampling surficial deposited fine sediment from water columns in small headwater streams. The application of this method for the larger streams should be tested, thus the long-time exposition and the sampling of mats could be difficult due to higher water levels.

With the large sampling sites, we have accurately identified the “hot spots” of fine sediment in our study area. Since the fine sediment input was generally high in winter and partially in spring (due to episodic precipitation events), we recommended the application of soil conservation techniques and the installation of grassland buffers on hillslopes in the agricultural practices, which would protect against soil erosion. In order to develop additional measurements for controlling sediment and nutrient release in the catchment with a high input of fine sediment, the local hillslope and soil cultivation as well as a large length and width of riparian zones should be taken into account in future studies.

Our results revealed that the shift in the species composition is mainly dependent on the chemical composition of fine sediment. Thus, future field studies particularly in agricultural areas should separate the effect of sedimentation and eutrophication, for instance by concurrent water monitoring of nitrogen and oxygen parameters. Additionally, it would be interesting to measure phosphate or heavy metals respectively in the fine fractions such as silt (2 - 63 µm) or clay (< 2 µm) due to their high binding affinity to particulate matter or nutrients.

Since the stream hydraulic (e.g., flow patterns) is the a important factor for the transport and deposition of sediment and for the biota in running waters, and a higher variability of water levels due to the forecast of precipitation events is expected, it would be interesting to examine the effects of siltation on biota during extreme situations such as after floods or low level periods. Thus, the time-limiting effect, which is connected to flow patterns, can be detected more easily. In this context, changes of the amount of sediment can be expected, which can influence the clogging and deposition patterns as well as the changes of species composition due to drift or long-time exposition to sedimentation.

For the assessment of sedimentations by means of indicator species or biological metrics, the widest possible range of functional measurements should be taken into account. Thus, these ecological traits can influence the effect of sedimentation, for example the corresponding response of species belonging to passive filterer feeders such as the larvae of black flies (Simuliidae) can be different in contrast to *Philopotamus ludificatus*; hence Simuliidae are exposed to high suspended load. In addition, the habitat requirements of certain buried species such as mussels should be studied in more detail, preferably in-situ with field studies for a better evaluation of the interaction between the environmental parameters in the streambed and the water zone.

6 Zusammenfassung

6.1 Hintergrund

Seit frühester Zeit waren Fließgewässer und Fließgewässerlandschaften aufgrund der ertragreichen Böden und dem Nahrungsreichtum bevorzugte Siedlungsareale für Menschen. Demzufolge wurde die Gewässeraue gerodet, ackerbaulich erschlossen und dem Gewässer sein Raum für eine eigendynamische Laufentwicklung genommen (Küster, 1999). Mit den wachsenden Nahrungs- und Platzansprüchen wurden die landwirtschaftliche Nutzung erweitert und intensiviert sowie neue Bebauungsgebiete geschaffen. Dies führt einerseits zur Habitatzerstückelung und zum Verlust der ökologischen Biodiversität, anderseits tragen diverse organische und stoffliche Einträge, zur Verschmutzung und Degradierung der Gewässer bei (MA, 2005).

Die übermäßige Anwendung von mineralischen, synthetischen und organischen Düngermitteln führt bei Niederschlägen zur Freisetzung von hohen Mengen an Nitraten und Phosphaten, welche in die Gewässer eingeleitet werden. Eine starke Verdichtung der Böden durch den maschinellen Einsatz und die großräumige Flächenversiegelung vermindert die Versickerung, die Zwischenspeicherung und den biologischen Abbau der Einleiter. Dies verstärkt den Oberflächenabfluss und die Bodenerosion und führt dazu, dass die Sediment- und Nährstoffeinträge schneller und in hoher Konzentration in die Gewässer gelangen (z.B. Jones et al., 2001; Allan, 2004).

Während die ökologischen Folgen der anthropogenen Einleitungen in die Fließgewässer seit längerem untersucht werden, ist das ökologische Wirkungsgefüge des Sedimentüberschusses im Fließgewässer noch wenig erforscht.

Das Sediment ist neben dem Wasser ein wichtiger stofflicher Bestandteil der aquatischen Ökosysteme und wird zum Teil vom Land eingetragen. Sein Verhalten wird durch die Hydrodynamik beeinflusst, wobei es als Geschiebe oder Schwebstoff in der Wassersäule mobilisiert und flussabwärts transportiert oder direkt vor Ort akkumuliert wird. Die grobkörnigen mineralischen Substrate wie Steine, Geröll oder Kies und die auf der Gewässersohle abgelagerten feinkörnigen Substrate bilden einen wichtigen Lebensraum für benthische Organismen. Das Feinsediment setzt sich zusammen aus mineralischen Fraktionen mit einem Durchmesser geringer als

2 mm, wie Ton (< 2 µm), Schluff (2 - 63 µm) und Sand (0.063 - 2 mm; Zanke, 1982), und es kann stoffliche Verbindungen wie beispielsweise organische Substanzen oder Schwermetalle binden (Chapman, 1990; Estebe et al., 1997; Colas et al., 2011).

Mit dem Inkrafttreten der Europäischen Wasserrahmenrichtlinie (EG-WRRL; Directive 2000/60/EC) verpflichtet sich das Gewässermanagement zum Schutz und zur Verbesserung des ökologischen Zustands der aquatischen Ökosysteme. Das Sediment ist als Belastungsquelle in der Richtlinie nicht unmittelbar implementiert. Im Bewirtschaftungsplan wird jedoch seine Wirkungsweise als ein hoher Unsicherheitsfaktor eingestuft (EC, 2003; MUNLV, 2008). Eine aktuelle Studie über wichtige Belastungen und Maßnahmenschwerpunkte zur Umsetzung der Maßnahmenprogramme unterstützt nun diese Annahme (Kail und Wolter, 2011).

Neben den gewässergestalterischen und ökologischen Aspekten ist die Überwachung der Sedimentmenge wegen ihrer hohen mechanischen Energie und zerstörerischen Kraft für den Hochwasserschutz von Bedeutung. Aufgrund des Klimawandels und der für Mitteleuropa prognostizierten höheren Niederschlagsintensität kann sich das Auftreten von Hochwasser und Bodenerosion steigern (IPCC, 2001; IPCC, 2007; Schuchardt et al., 2008). Ferner ist nach heißen und trockenen Sommerperioden wegen der damit verbundenen niedrigen Pegelstände mit einer Ausweitung der Folgen der Sedimentation auf die aquatischen Organismen zu rechnen.

Im Rahmen dieser Forschungsarbeit steht die Erforschung der Feinsedimentablagerung in kleinen Mittelgebirgsquellbächen im Vordergrund, da bisher keine umfassenden Freilandstudien über die Wirkung der Sedimentation auf die benthische Fauna in Mitteleuropa existieren. Wenn auch die untersuchten Fließgewässerabschnitte wegen ihrer kleinen Größe nicht direkt unter die EU-WRRL Regelung fallen, ist für das erfolgreiche Sedimentmanagement im Gewässersystem die ganzheitliche Betrachtung der Gewässersysteme einschließlich kleiner Zuflüsse notwendig, da sie größere Sedimentmengen liefern. Diese Arbeit untersucht zwei Hauptaspekte: Die Faktoren des Feinsedimenteintrags und die biologischen Folgen der erhöhten Feinsedimentmengen auf der Gewässersohle. Letzteres steht hierbei im Vordergrund.

6.2 Kurzfassung

Durchführung der Arbeit

Die vorliegende Forschungsarbeit wurde als Freilandstudie im nördlichen Einzugsgebiet des Flusses Our (Luxemburg) in Zusammenarbeit mit dem LIFE-Natur-Projekt „Schutz und Erhalt der Flussperlmuschel in den Ardennen (LIFE 05 NAT /L/000116)“ durchgeführt. Der verstärkte Eintrag von Feinsediment aus den Zuflüssen der Our gilt als mögliche Ursache für den fehlenden Nachwuchs der vereinzelten Flussperlmuschel Populationen. Das Untersuchungsgebiet liegt auf dem Hochplateau der nordluxemburgischen Ardennen, wobei sich die landwirtschaftliche Nutzung und spärliche Besiedlung auf die Hänge konzentriert. Die Bachtäler dagegen sind überwiegend mit Nadel- und Laubforst bewachsen. Die Erosion und der hohe Sedimenteintrag sind durch die typische Topographie, wie relativ steile Hänge und charakteristisch skelettreiche Böden mit stellenweise auftretenden Auenlehmlagen, erhöht. Die untersuchten Mittelgebirgsquellbäche fließen rechtsseitig in die Our (neun Zuflüsse, Luxemburg). Zwei weitere Zuflüsse liegen in Rheinland-Pfalz und münden linksseitig in die Our. Um die Haupteintragsquellen vom Feinsediment besser abschätzen zu können, wurden daher die Probestellen möglichst vor dem Zusammenfluss der Nebenarme im Oberlauf und unterhalb vor der Einmündung der Zuflüsse in der Our ausgewählt. Weitere Kriterien für die Auswahl der Probestellen waren die visuelle Feinsedimentablagerung auf der Gewässersohle und die Vegetationstypen (Nadel- bzw. Laubforst) in unmittelbarer Gewässernähe: Die Beschaffenheit der Bäume spielt eine wichtige Rolle für das Retentionsvermögen der Böden und die Verbreitung der adulten Insekten. Insgesamt wurden 29 Probestellen im Zeitraum Herbst 2008 bis Frühjahr 2010 ausführlich untersucht. Das abgelagerte Feinsediment (Durchmesser < 2 mm) wurde ein Jahr (September 2008 bis September 2009) mit Hilfe von Kunstrasenstücken gesammelt. In jedem Gewässerabschnitt wurden zwei Bereiche, strömungsberuhigte und schnelle Bereiche (Pools / Riffles), beprobt. Der Gehalt an Feinsediment, der relative Anteil an organischer Substanz und das Verhältnis von Kohlenstoff zu Stickstoff (C/N Verhältnis) wurden bestimmt. Des Weiteren wurden die Landnutzung im Einzugsgebiet und der Gewässeraue, das Bodenerosionspotential, hydromorphologische und physikochemische Gewässerparameter miterfasst. Die Makrozoobenthos Besammlungen wurden im Herbst 2008 und Frühling 2009 mit Hilfe der substratspezifischen Multi-Habitat Methode beprobt. Im Frühjahr 2010 wurde je Gewässerabschnitt an zwei quadratischen Stellen (50 x 50 cm^2) in Riffles und Pools folgende Taxa gezählt: *Ephemera danica*, *Habroleptoides confusa*, und *Rhithrogena semicolorata* Gruppe, die zur Ordnung der Ephemeroptera und *Agapetus fuscipes*, *Synagapetus iridipennis/moselyi, Sericostoma personatum*, *Odontocerum albicorne,* sowie *Philopotamus ludificatus,* die zur Ordnung der *Trichoptera* gehören. Die Insekten wurden auf Steinen (Ober-, Unterseite und an den Seiten), in Zwischenräumen (Interstitial) sowie im Grobdetritus gezählt. An jeder Stelle wurden die lokalen morphometrischen Variablen (Wassertiefe, Entfernung zum Bachufer, Fließgeschwindigkeit), die Verteilung der mineralischen Substrate und das abgelagerte Feinsediment (< 2 mm, mit Feindetritus) optisch abgeschätzt.

Bei der quantitativen und qualitativen Erfassung der oberflächlichen Ablagerung von Feinsediment standen zwei Fragen im Vordergrund.

(1) Welche Umweltfaktoren beeinflussen den Eintrag und die Ablagerung von Feinsediment?

(2) Wie wirkt sich der erhöhte Feinsedimentgehalt auf die Makrozoobenthos Gemeinschaft bzw. ausgewählte benthische Insektenlarven aus?

Ziel der vorliegenden Forschungsarbeit war, kleine Mittelgebirgsquellbäche in Mitteleuropa auf ihren terrestrischen Feinsedimenteintrag und dessen aquatischen Ablagerungsmuster zu quantifizieren und zu erforschen. Diese Arbeit hat eine praktische Relevanz für das Gewässermanagement, da so erst eine Planung von zielgerichteten Maßnahmen zur Reduzierung des Feinsedimenteintrags und zur Verminderung der flussabwärts transportierten Schwebstoffmengen möglich wird. Gleichzeitig trägt die Arbeit zum Verständnis der fließgewässerökologischen Zusammenhänge zwischen dem erhöhten Feinsedimentgehalt und der benthischen Biozönose in Fließgewässern bei. Um Einflussgrößen auf den Eintrag und die Sedimentation in den Fließgewässern besser identifizieren zu können, wurde die Feinsedimentablagerung ein Jahr lang beobachtet (Kapitel 2). Die Auswirkungen des Feinsediments auf das Makrozoobenthos werden im Kapitel 3 und 4 dargestellt.

Diese Forschungsarbeit beinhaltet folgende Abschnitte (die Arbeitshypothesen werden in jedem Abschnitt erläutert):

(1) *Die Auswirkung von Umweltfaktoren auf das abgelagerte Feinsediment*

Die land- und forstwirtschaftliche Bewirtschaftung im Einzugsgebiet bzw. im direkten Gewässerumfeld beeinflussen die Vegetationsdecke und somit die Erosionsanfälligkeit und das Retentionsvermögen der Böden sowie den Oberflächenabfluss. Aus ackerbaulichen Flächen werden die stofflichen und organischen Einträge verstärkt in die Gewässer eingeleitet. Die hydromorphologischen Gewässerparameter beeinflussen die Substratverteilung und Ablagerung. Die Bestandteile des Feinsediments in der Ablagerung (mineralischer Anteil, organische Substanz, Verhältnis von Kohlenstoff zu Stickstoff) sind unterschiedlich stark von bestimmten Umweltfaktoren geprägt. Beispielsweise kann der Feinsedimentgehalt im Gewässer durch den prozentualen Anteil an Ackerbau im Einzugsgebiet, der organischen Substanz (Vegetationsdecke) und dem C/N Verhältnis (Wasserchemie) beeinflusst werden (Kapitel 2).

(2) *Die Wirkung des abgelagerten Feinsediments auf die Zusammensetzung der Makrozoobenthos Gemeinschaft*

Der erhöhte Feinsedimentgehalt auf der Gewässersohle bringt eine Veränderung der physikalischen Bedingungen im Fließgewässer und dessen Biozönose mit sich. Die Verschlammung bzw. die Versandung führt zu einer starken Verlagerung und Mobilisation der Ablagerungsschicht sowie der Überdeckung der Sohlsubstrate bzw. der Anreicherung an organischer Substanz. Diese wiederrum rufen verschiedenartige physiologische und verhaltensspezifische Veränderungen der Biozönose hervor. Der Verlust an Mikrohabitaten, die Verschiebung der Nahrungszusammensetzung und -verfügbarkeit bzw. das Sauerstoffdefizit wirken auf die Artenzusammensetzung und die Besiedlungsdichte der benthischen Gemeinschaften (Kapitel 3).

(3) *Die Wirkung des abgelagerten Feinsediments auf acht Insektenlarven der Ordnung der Eintagsfliegen (Ephemeroptera) und Köcherfliegen (Trichoptera)*

Die ausgewählten Arten zeichnen sich durch ein variables Verteilungsmuster und mikroskalige und artspezifische autökologische Ansprüche aus, wie z.B. die Zugehörigkeit zu trophischen Gilden, Mikrohabitat- oder Strömungspräferenzen. Die

Auswirkung des Feinsediments basiert daher auf artspezifische Ansprüche (Kapitel 4).

Kurzfassung der wichtigsten Methoden und Ergebnisse sowie der Interpretation der Ergebnisse

Kapitel 2:

Die Auswirkung von Umweltfaktoren auf das abgelagerte Feinsediment

- Eine partielle Redundanzanalyse (pRDA) wurde angewandt, um die Auswirkung der Umweltfaktoren auf die verschiedenen Bestandteile von Feinsediment zu untersuchen. Dabei wurde der Einfluss von unterschiedlichen räumlichen Maßstäben wie Gewässer, Gewässeraue und Einzugsgebiet quantifiziert.
- Die Gewässerparameter (S) und Einzugsgebietsparameter (C) beeinflussen am stärksten alle Bestandteile des Feinsediments (Feinsedimentgehalt: S; 33%; C, 25%; organische Substanz S, 37%; C, 24%; C/N Verhältnis S, 40%; C, 34%). Die Umweltvariablen erklärten nahezu zu 100% die Varianz in allen Sedimentbestandteilen.
- Die Ergebnisse der Redundanzanalyse (RDA) zeigen zwei bedeutende Parameter für Feinsediment. Zum einen erklärt der prozentuale Anteil an feinkörnigem Kies auf der Gewässersohle 18% der Varianz im Feinsedimentgehalt und zum anderen den prozentualen Anteil an Ackerbau im Einzugsgebiet (12%). Der Eigenwert der ersten zwei Achsen beträgt $\lambda = 0{,}406$. Hingegen hat der Anteil an Weideland mit 20% am stärksten die organische Substanz erklärt ($\lambda = 0{,}567$). Im Gegensatz hierzu, wird das C/N Verhältnis hauptsächlich durch den Maximalwert der Leitfähigkeit (17%) und die Einzugsgebietsgröße (16%) erklärt. Der Eigenwert der Varianz der ersten zwei Achsen beträgt $\lambda = 0{,}503$.
- Der Sedimenteintrag und die Nährstoffanreicherung werden hauptsächlich von der Landnutzung im Einzugsgebiet beeinflusst. Der intensive Ackerbau führt zu erhöhter Bodenerosion und erhöhten Feinsedimentgehalten im Gewässer. Gleichzeitig spielen die Gewässerparameter bei der Feinsedimentablagerung eine große Rolle.

Kapitel 3:

Die Wirkung des abgelagerten Feinsediments auf die Zusammensetzung der Makrozoobenthos Gemeinschaft

- Es wurde eine stark negative Beziehung zwischen dem Feinsedimentgehalt und dem C/N Verhältnis ($R^2 = 0,46$, $p < 0,0001$) wie auch zwischen dem Feinsedimentgehalt und der organischen Substanz ($R^2 = 0,51$, $p < 0,0001$) festgestellt.
- Mittels der Kanonischen Korrespondenzanalyse (CCA) wurden drei wichtige Variablen für die Makrozoobenthos Gemeinschaft ermittelt: Die Sauerstoffsättigung mit 15%, gefolgt vom Anteil an feinkörnigem Kies auf der Gewässersohle (13%) und dem C/N Verhältnis (11%). Die Umweltfaktoren erklären 20,8% der Variabilität in der Makrozoobenthos Gemeinschaft (Gesamtanteil an der Artenzusammensetzung der ersten zwei CCA Achsen).
- Zwölf biotische Indizes (Shannon-Wiener-Index; Evenness; Prozentualer Anteil an Ephemeroptera, Plecoptera, und Trichoptera; und die funktionalen Indizes) wurden ausgewählt und mit Hilfe von Asterics 3.3 berechnet, um die Wirkung des Sediments auf das Makrozoobenthos zu überprüfen. RDA zeigte zwei Umweltfaktoren; das C/N Verhältnis (18%) und der gelöste Sauerstoff (16%) erklären größtenteils die Varianz der biotischen Indizes (33,6% Gesamtanteil an der Artenzusammensetzung der ersten zwei RDA Achsen).
- Die chemische Zusammensetzung des abgelagerten Sediments ist von größerer Bedeutung als die Sedimentmenge für die Artenzusammensetzung. Allein das C/N Verhältnis erklärt einen erheblichen Anteil der Varianz in der Makrozoobenthos Gemeinschaft. Die biologische Reaktion auf Sauerstoff und das C/N Verhältnis des abgelagerten Feinsediments könnte auf einen potenziellen Effekt der Feinsedimentablagerung durch Sauerstoffverbrauch hinweisen.

Kapitel 4:

Die Wirkung des abgelagerten Feinsediments auf acht Insektenlarven der Ordnung der Eintagsfliegen (Ephemeroptera) und Köcherfliegen (Trichoptera)

- Die Wassertiefe der kleinen Quellbäche war gering (Mittelwert für Riffles und Pools betrug 6,5 cm). Im Gegensatz zu Pools werden Riffles durch eine hohe Variabilität an Fließgeschwindigkeit und Wassertiefe charakterisiert. Die Fließgeschwindigkeit hatte generell einen signifikanten Einfluss auf die

Feinsedimentablagerung, wobei sie im Frühjahr 2010 niedriger als im Frühjahr 2009 war. Der Anteil an Feinsedimentablagerung in Riffles und Pools war aber nicht signifikant von den morphometrischen Variablen abhängig.

- Eine stark lineare Beziehung konnte lediglich zwischen Feinsediment und zwei Arten festgestellt werden. Die Besiedlungsdichte von *E. danica* wurde in Pools durch den geschätzten Feinsedimentanteil in diesen Bereichen beeinflusst ($R^2 = 0{,}74$, $p < 0{,}001$). Dagegen zeigte *P. ludificatus* einen linearen Zusammenhang zum Feinsedimentgehalt, ermittelt im jeweiligen Gewässerabschnitt *(*$R^2 = 0{,}72$; $p < 0{,}001$).
- Mehrere einzelne Variablen korrelieren mit den Arten. Dazu zählen lokale hydromorphologische Variablen (Wassertiefe, Fließgeschwindigkeit, Substratverteilung), die die Besiedlungsmuster dieser Arten beeinflussen. Nur *A. fuscpies*, welches die Oberfläche in Riffles besiedelte, zeigte eine lineare Beziehung zum Anteil an Geröll (Mesolithal) auf der Gewässersohle ($R^2 = 0{,}25$, $p < 0{,}05$). Weitere signifikante Variablen, die mit der Besiedelungsdichte im Gewässerabschnitt reagieren sind die Einzugsgebietsgröße, Anteil an Urbanisation, Anteil an Nadelforst direkt am Gewässerufer und die Substratverteilung im Gewässer wie der prozentuale Anteil an Kies oder an Totholz.

6.3 Schlussfolgerungen

Die Einzugsgebietsgröße und dessen Landnutzung sowie die hydromorphologischen und physikochemischen Gewässerparameter beeinflussen die Feinsedimentablagerung in Mittelgebirgsquellbächen am stärksten, worauf der hohe Erklärungsanteil in den RDA und pRDA Analysen hinweist.

Die intensive ackerbauliche Bewirtschaftung verursacht einen erhöhten Feinsedimenteintrag. Dies zeigt der hohe Zusammenhang zwischen der Feinsedimentmenge in der Ablagerung und dem relativen Anteil an Ackerflächen im Einzugsgebiet (Kapitel 2). Ferner erklären die Wasserchemieparameter, wie z.B. der Maximalwert in der Leitfähigkeitsreihe, das C/N Verhältnis in der Feinsedimentablagerung. Dies deutet darauf hin, dass die chemische Zusammensetzung des abgelagerten Feinsediments durch die Nährstoffanreicherung aus mineralischem und organischem Dünger oder dem

Abwasser beeinflusst werden kann. Die Herkunft der Nährstoffanreicherung konnte nicht eindeutig bestimmet werden, aber sicherlich hat die Landwirtschaft einen großen Anteil daran. Obwohl die übermäßige Verwendung von mineralischem Stickstoffdünger in Luxemburg in den letzten Jahren zurückgegangen ist (Dairyman, 2010), konnten nach wie vor erhöhte Nitrat- und Ammoniumkonzentrationen in den untersuchten Bächen und der Our nachgewiesen werden (Hall et al., 2010). Dies ist sicherlich auf die Verwendung von organischem Dünger wie Gülle oder Jauche zurückzuführen. Die Auswaschung beider Düngerquellen ist für die chemische Veränderung in der Ablagerung des Feinsediments verantwortlich.

Die steigende Nachfrage an erneuerbaren Energiequellen und der erhöhte Bedarf an Futterpflanzen in der Tiermast führten dazu, dass Grünland zu Ackerland umgewandelt wird. Diverse Literaturquellen sehen vor, dass die Pufferzone aus krautiger Vegetation effektiv die Nährstoffe und die Sedimente zurückhalten kann (z.B. Parkyn, 2004; Udawatta et al., 2006; Yates et al., 2007). Der Wichtigkeit der Erhaltung des Weidelandes können wir größtenteils zustimmen, da in unseren Ergebnissen kein direkter Zusammenhang zwischen dem Weideland und der Feinsedimentmenge sowie von Nährstoffen in der Ablagerung bestand. Der relative Anteil an organischer Substanz in der Feinsedimentablagerung hängt zu einem hohen Maße vom Weideland ab, was auf den Eintrag von pflanzlichen Rückständen, beispielsweise nach dem Mähen des Grases, zurückzuführen ist. Mit dem Verlust des Weidelandes wird die Pufferwirkung vermindert und gleichzeitig wird die Freisetzung von Nährstoffen und Feinsediment aufgrund der Verwendung von Düngermittel sowie verstärkter Bodenbearbeitung erhöht.

Generell spielen Gewässerparameter wie die hydromorphologischen und physikochemischen Parameter eine bedeutende Rolle für die chemischen Eigenschaften und das Verhalten des abgelagerten Feinsediments. Gleichzeitig beeinflussen sie die Häufigkeit der Arten und die Zusammensetzung der Makrozoobenthos Gemeinschaft, was die Ergebnisse der Ordinations-, Korrelations- und Regressionsanalysen verdeutlichen (Kapitel 3 und 4). Die Fließparameter sind insbesondere für den Transport sowie die Akkumulationsprozesse von Bedeutung und prägen das Gewässerbett, was der Effekt der Faktoren der Fließgeschwindigkeit und dem relativen Anteil an feinkörnigen Kies im Gewässerbett verdeutlicht (Kapitel 2 und 4). Zudem offenbart das Ergebnis der RDA Analyse, dass sich größere Bereiche mit feinkörnigem Kies negativ auf die Makrozoobenthos Gemeinschaft auswirken können (Kapitel 3). Allerdings können kleinräumige Ablagerungsmuster, welche hinter größeren Barrieren, wie Holzansammlungen oder Steinen entstehen, zur Substratvielfalt beitragen. Das Mosaik an Mikrohabitaten prägt lokale chemische und hydromorphologische Bedingungen, was für die Fauna in den kleinen Quellbächen von Bedeutung ist (z.B. Clarke et al., 2008). Zusätzlich tragen die Diversität an Substraten, Fließparameter und die strukturierte Gewässergerinne zu Transformationsprozessen von Sedimenten und Nährstoffen bei (Peterson et al., 2001; Gomi et al., 2002). Dies spiegelt zum Teil der Zusammenhang zwischen dem C/N Verhältnis und der Fließgeschwindigkeit wider (Kapitel 2).

Die Hauptergebnisse offenbaren, dass die chemische Zusammensetzung und nicht die Menge an Feinsediment einen großen Einfluss auf die Zusammensetzung der Makrozoobenthos Gemeinschaft hat. Das C/N Verhältnis in der Feinsedimentablagerung und die Sauerstoffparameter erklären die Zusammensetzung der benthischen Gemeinschaft (Kapitel 3). Diese Paramater weisen auf eine Nährstoffanreicherung hin, die zur verstärkten biologischen Aktivität und zu Sauerstoffzehrung führen kann. Leider lassen die Ergebnisse keine Differenzierung darüber zu, ob allein die Eutrophierung für die Biozönose maßgebend ist oder eine Interaktion zwischen den Stressoren, Eutrophierung und Sedimentation, auf die Zusammensetzung der Gemeinschaft einwirkt. Generell ist der Einfluss der Sedimentation auf die Besiedelungsdichte ausgewählter Arten gering. Nur die Arten in direkter Verbindung zum Feinsediment, basierend auf den Lebensraumansprüchen und Nahrungspräferenzen, stehen mit Feinsediment im Zusammenhang (Kapitel 4). Wie zum Beispiel die von Organismen besiedelte verschlammte Gewässersohle (z.B. *Ephemera danica*) oder die als Nahrung für *Philopotamus ludificatus* gefangenen Schwebstoffpartikel. Die Häufigkeiten weiterer untersuchter Arten konnten dagegen durch die lokalen Ablagerungsmuster oder die Feinsedimentmenge im Gewässerabschnitt kaum beeinflusst werden. Die durch die Verschlammung verursachte Verringerung der qualitativen Nahrungsquellen oder die Verschiebung des Top-Down Effektes ist vermutlich nicht flächendeckend und kann durch das kleinräumige Auswandern der Arten zu optimalen Mikrohabitaten ausgeglichen werden. Andererseits ist der Eintrag von hohen Feinsedimentmengen nur episodisch, was der hohe mittlere Feinsedimentgehalt, gemessen im Winter nach der Schneeschmelze, belegt (Kapitel 2). Unser annähernder Vergleich des Effektes der Bestandteile von Feinsediment in Hinblick auf die Gemeinschaften in unterschiedlichen Jahreszeiten zeigte allerdings keine Unterschiede (Kapitel 3). Vermutlich können die Larven diese Effekte durch ihre Flucht in Refugialräume im Interstitial oder Emergenz ausgleichen. Um die episodische Wirkung der Sedimentation besser zu erfassen, sollte man die Beprobung an den Wasserstand und extreme Niederschlagsereignisse anpassen.

Basierend auf unseren Ergebnissen können wir folgende Schlussfolgerungen bezüglich der Auswirkung der Sedimentation auf das Makrozoobenthos ziehen:

Die Wirkung der Sedimentation ist im Untersuchungsgebiet vorhanden, aber aufgrund des Untersuchungsdesigns konnte sie nicht genau ermittelt werden. Die vorliegende Fallstudie stellt ein bestimmtes Untersuchungsgebiet in den Vordergrund. In einer homogen genutzten Landschaft können diffuse Einträge flächendeckend wirken. Als Reaktion auf eine dauerhafte Belastung können sensible Arten keine intakte Population aufbauen und fehlen somit in diesen Abschnitten. Als Folge kann es dazu führen, dass der Gradient im Feinsedimentgehalt zwischen den Probestellen zu gering war, um deutliche Effekte auf die Biozonöse zu erzielen und physikalische Schwellenwerte zu ermitteln. Auf diese Tatbestände weist auch Benoy et al. (2012) in einer aktuellen Studie hin.

Ferner kann die Eutrophierung den Effekt von Sedimentation in kleinen Mittelgebirgsquellbächen generell verstärken. Die Wirkung der Sedimentation erstreckt sich vor allem auf Organismen, die Mikrohabitate in direkter Verbindung mit dem Feinsediment besiedeln. In den letzten Jahren wurde in landwirtschaftlich geprägten Einzugsgebieten die synergetische Wirkung beider Stressoren bzw. die Wirkung einzelner Stressoren auf das Makrozoobenthos immer häufiger erforscht (Matthaei et al., 2006; Ormerod et al., 2010; Wagenhoff et al., 2011). Bisherige Studien behaupten, dass der einzelne Effekt der Sedimentation einen stärkeren Einfluss auf die Biozönose als die Eutrophierung hat (Townsend et al., 2008; Wagenhoff et al., 2011; Wagenhoff et al., 2012). In unserer Studie konnten wir allerdings die Auswirkung beider Stressoren nicht voneinander trennen, weil hierfür das permanente bzw. dauerhafte Monitoring der Wasserchemie, begleitend zur Sediment- und Makrozoobenthos Probenahme notwendig ist.

In unserem Untersuchungsgebiet hat die Eutrophierung, als Folge von Nährstoffeinträgen aus der Landwirtschaft, einen stärkeren Einfluss auf die benthischen Organismen als die Sedimentation. Der Einfluss der Abwässer konnte für unsere Probestellen überwiegend ausgeschlossen werden. Lediglich vier von 29

Stellen waren hiervon betroffen. Unsere Behauptungen basieren auf den Ergebnissen der Kapitel 2 und 3, die den Zusammenhang zwischen der Wasserchemie und dem C/N Verhältnis im Feinsediment sowie zwischen dem C/N Verhältnis und der benthischen Biozönose bestätigen und stützen uns im oben erwähnten Bericht auf die Ergebnisse über die nachgewiesenen höheren Stickstoffverbindungen im Wasser (Hall et al., 2010).

6.4 Ausblick

Die ökologischen Wirkungsmechanismen des erhöhten Feinsedimenteintrags im Fließgewässer sind wenig bekannt. Eine Ursache dafür ist das Fehlen der standarisierten Methoden zur quantitativen Erfassung des auf der Gewässersohle akkumulierten Feinsediments. Hierzu haben wir eine neue Probenahmetechnik, die zur Quantifizierung der auf der Gewässersohle abgelagerten Schwebstoffpartikel in kleinen Bächen von Nutzen sein kann entwickelt und erfolgreich angewendet. Ob diese Methode für größere Fließgewässer geeignet ist muss in zukünftigen Studien getestet werden, da durch höhere Pegelstände ein längerfristiges Exponieren der Kunstrasenstücke und eine Entnahme der Proben problematisch sein könnte.

Durch eine große Auswahl an Probestellen konnte genau gezeigt werden, dass der Eintrag von Feinsediment in einigen Abschnitten sehr hoch war. Da der Bodenabtrag besonders stark von episodischen Niederschlagsereignissen im Winter und Frühjahr abhängig ist, werden für die landwirtschaftliche Praxis bodenschonende Bewirtschaftungsmaßnahmen beziehungsweise das Bepflanzen des Vegetationsrandstreifens an den Hangrändern als Schutz vor Bodenerosion empfohlen. Um weitere Maßnahmen zur Reduzierung der Sediment- und Nährstofffreisetzung im Einzugsgebiet mit hoher Erosion besser konzipieren zu können, sollten in Zukunft die lokale Geländeneigung und die Bodenbewirtschaftung sowie eine größere Länge und Breite der Vegetation im Umfeld beachtet werden.

Es wurde aufgezeigt, dass die Veränderungen der Artengemeinschaften hauptsächlich mit der chemischen Zusammensetzung des Feinsediments zusammenhängen. Daher sollten weitere Freilandstudien, besonders in landwirtschaftlich geprägten Regionen, die Wirkung der Sedimentation von den Nährstoffeinträgen besser differenzieren, z.B. durch begleitendes Wassermonitoring der Stickstoff- und Sauerstoffparameter. Zusätzlich wäre es bei feineren Fraktionen wie z.B. Schluff (2 - 63 µm) oder Ton (< 2 µm) aufgrund der starken Bindungsaffinitäten an partikulären Stoffen oder Nährstoffen von Bedeutung, die Phosphat- bzw. Schwermetallbelastungen zu erfassen.

Unsere Ergebnisse zeigten, dass die Gewässerhydraulik (z.B. Strömungsparameter) eine wichtige Rolle sowohl für das Sedimentverhalten als auch für die Biozönosen im Fließgewässer spielt und in Zukunft aufgrund der prognostizierten Niederschlagsereignisse einer stärkerer Schwankung ausgesetzt sein wird. Für künftige Studien wäre es interessant, die Auswirkung der Extremsituationen nach Hochwasser und Niedrigwasserständen auf die Sedimentation und die Biozönose zu überprüfen. Dadurch könnten zeitlich limitierende Wirkungen genauer erfasst werden. In diesem Zusammenhang ist eine Verschiebung der Sedimentmenge in den kolmatierten bzw. verschlammten Bereichen sowie eine Veränderung in der Artenzusammensetzung durch die Drift bzw. langzeitige Deposition von Sedimentation zu erwarten.

Bei der Bewertung der Sedimentationseffekte mit Indikatorarten oder biologischen Indizes sollten möglichst viele funktionale Faktoren beachtet werden. Da die autökologischen Eigenschaften die Effekte der Sedimentation beeinflussen können, ist es möglich, dass z.B. die Larven der Kriebelmücken (Simuliiden), die zu den passiven Filtrierern gehören, anders als die Vertreter der gleichen trophischen Gilde, *Philopotamus ludificatus,* reagieren, da Simuliidae der Feinsedimentfracht aufgrund ihrer Habitatansprüche stärker ausgesetzt sind. Zudem sollten die Lebensansprüche einiger im Sediment eingebetteter Arten, insbesondere Muscheln, in Freiland- oder Laborexperimenten ausführlicher untersucht werden, um die Wechselwirkungen zwischen Umweltparamatern im Gewässerbett und in der fließenden Welle genauer zu überprüfen.

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Appendix

The Appendix is submitted as data files on a CD, which is attached to this page of the document.

Appendix I	Description of samples sites.
Appendix I-A	Location of sites, hydromorphological variables, land use in the catchment and riparian zone.
Appendix I-B	Abbreviations.
Appendix II	Environmental variables recorded during the sediment sampling.
Appendix III	Macroinvertebrate data and environmental variables recorded in autumn 2008 and in spring 2009.
Appendix III-A	Macroinvertebrate data recorded in autumn 2008 and in spring 2009 used in chapter 3.
Appendix III-B	Flow velocity and fine sediment cover recorded for individual samples in spring 2009 used in chapter 4.
Appendix IV	Macroinvertebrate data recorded in spring 2010.
Appendix IV-A	Macroinvertebrate data recorded in spring 2010 used in chapter 4.
Appendix IV-B	Morphometric variables recorded for samples used in chapter 4.
Appendix V	Physicochemical variables.

Curriculum Vitae

Der Lebenslauf ist in der Online-Version aus Gründen des Datenschutzes nicht enthalten.

Erklärung:
Hiermit erkläre ich, gem. § 6 Abs. (2) f) der Promotionsordnung der Fakultäten für Biologie, Chemie und Mathematik zur Erlangung der Dr. rer. nat., dass ich das Arbeitsgebiet, dem das Thema ***„The impact of deposited fine sediment on benthic macroinvertebrates in small headwater streams in Luxembourg“*** zuzuordnen ist, in Forschung und Lehre vertrete und den Antrag von ***Marta G. von Bertrab*** befürworte und die Betreuung auch im Falle eines Weggangs, wenn nicht wichtige Gründe dem entgegenstehen, weiterführen werde.

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Erklärung:
Hiermit erkläre ich, gem. § 7 Abs. (2) c) + e) der Promotionsordnung Fakultäten für Biologie, Chemie und Mathematik zur Erlangung des Dr. rer. nat., dass ich die vorliegende Dissertation selbständig verfasst und mich keiner anderen als der angegebenen Hilfsmittel bedient habe.
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Hiermit erkläre ich, gem. § 7 Abs. (2) d) + f) der Promotionsordnung der Fakultäten für Biologie, Chemie und Mathematik zur Erlangung des Dr. rer. nat., dass ich keine anderen Promotionen bzw. Promotionsversuche in der Vergangenheit durchgeführt habe und dass diese Arbeit von keiner anderen Fakultät/Fachbereich abgelehnt worden ist.
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