

1 **Streams and riparian forests depend on each other: a review with a special focus on** 2 **microbes**

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4 Mari J. Tolkkinen^{1*}, Jani Heino¹, Saija H.K. Ahonen², Kaisa Lehosmaa², and Heikki Mykrä^{1, 2}

5 ¹ Finnish Environment Institute, Freshwater Centre, P.O.Box 413, FI-90014, University of Oulu, Finland

6 ² Ecology and Genetics Research Unit, P.O.Box 8000, FI-90014, University of Oulu, Finland

7 *Corresponding author, e-mail: mari.j.tolkkinen@gmail.com

8 **Highlights**

- 9 • The two-way dependency of streams and their riparian forests is reviewed
- 10 • We focus on biodiversity and ecosystem functions, including microbial processes
- 11 • Land use and climate change effects on riparian and stream ecosystems are discussed
- 12 • Potential management and protection practices are overviewed
- 13 • Future research questions are drawn together

14 **Abstract**

15 In this review, we draw together the research on the two-way connection of streams and their riparian
16 forests of the boreal zone from ecological points of view. Although the knowledge about stream-riparian
17 interactions has increased considerably recently, in practice, riparian zones are still mainly seen as
18 buffers for nutrient and sediment loading. However, recent research has shown that riparian forests
19 disproportionately foster regional biodiversity and maintain stream ecosystem functions and diversity.
20 On the other hand, streams contribute to riparian diversity and ecosystem functions. Microbes are key
21 drivers of global biochemical cycles, and they also interact with plants and animals. The knowledge on
22 microbial communities and understanding of processes they drive has considerably increased due to
23 recent development in microbial profiling methods. However, microbes have been largely neglected in
24 former reviews. Thus, this overview has a special focus on the role of microorganisms in controlling

25 stream-riparian interaction. We also review the land-use pressures that are threatening biodiversity and
26 ecosystem processes of riparian zones in forested landscapes. In addition, we review the possible effects
27 of climate change on stream-riparian interactions. Finally, we outline the research gaps that call for
28 future research.

29

30 **Keywords:** stream-riparian interface, ecosystem functions, biodiversity, riparian vegetation, reciprocal
31 subsidies, microbial processes, flooding, forest management, nature protection, sediment and nutrient
32 retention, decomposition, endophytes

33

34 **1. Introduction**

35 Understanding the tight interlinkage between boreal streams and their riparian forests is necessary in
36 order to preserve or improve the biodiversity of surface waters. The interaction needs to be
37 acknowledged to manage forests in an ecologically sustainable manner near streams. Streams are
38 sources of rivers (Vannote et al. 1980), thereby providing services to rivers by contributing to water
39 quality and providing energy resources and enabling spawning grounds for fish (Freeman et al. 2007,
40 Wipfli et al. 2007, Gomi et al. 2002, Wipfli & Gregovich 2002). Although small in size, streams contribute
41 considerably to regional species pool and may act as reservoirs for river and lake organisms (Besemer et
42 al. 2013, Clarke et al. 2008, Meyer et al. 2007). Riparian forests are transition zones which connect
43 streams to upland forests (Naiman et al. 2005). Given that their occurrence is limited to near-stream
44 locations, the area of riparian forests is small compared to that of upland forests. However, they have a
45 disproportionate influence in maintaining biodiversity and ecosystem processes. First, streams are
46 closely associated with their riparian forests, and the two ecosystems depend on each other
47 hydrologically and ecologically. This is especially true for small headwater streams that rely on riparian-
48 based energy sources. Second, riparian forests often have distinct assemblages of plants and
49 invertebrates, which differ in their composition from upland forest assemblages, increasing regional

50 biodiversity (Kuglerová et al. 2014a, Selonen et al. 2011, Rykken et al. 2007a, Sabo et al. 2005). In
51 addition, streams and their riparian zones serve as dispersal routes and corridors for many terrestrial
52 and aquatic taxa, being integral parts of the landscape in augmenting organisms' movements between
53 sites (Ament et al. 2014, Tonkin et al. 2018).

54
55 The interest in stream-riparian interactions in forested landscapes dates back to 1970's when it was
56 realized that forest management based on clear-cutting severely impacted surface waters and forest soil
57 (e.g. Brown 1973). Although the knowledge about stream-riparian interactions has increased, and the
58 multiple ecosystem services provided by riparian forests are now being acknowledged by scientists,
59 forest managers still mainly see riparian zones as buffers for nutrient and sediment loading. Riparian
60 forests of small streams are not included in international directives and we still lack common protocols
61 for their management. The use of stream riparian areas in some countries is restricted by national acts,
62 yet there is huge variation among nations on how and to what extent riparian forests are considered in
63 legislation (Ring et al. 2017, Lee et al. 2004). Because legislation acknowledges only a small proportion
64 of riparian sites as conservation units, if any, the protection of streamside forests depends heavily on
65 land owners' will. Some countries (e.g. Finland) offer a monetary incentive for the land owner for
66 leaving a predefined stripe of a near-natural riparian forest uncut to enhance the protection of
67 woodland key habitats (Timonen et al. 2010). In addition, forest certificates guide riparian forest
68 management of small streams and even define the width of buffers, but also these buffers vary a lot
69 among countries (Pirainen et al. 2017).

70
71 The close interactions between streams and riparian forests make the two inseparable. In this overview,
72 we aim to highlight the two-way connection of streams and their riparian forests from an ecological
73 point of view. We focus on the boreal zone, although many aspects apply also to temperate streams. By
74 "streams" we mean fluvial channels with up to 100 km² catchment area and which have permanent
75 water-flow. We assumed that a catchment of 100 km² would equal approximately to stream orders 1 to

76 3 (Strahler 1957). We refer to orders 1-2 as headwaters and to order 3 as mid-sized streams. These
77 approximately resemble stream mean width under 2.5 and 7.5 meters, respectively (Downing et al.
78 2012). Some variation, however, may exist in stream order and width depending on regional features
79 (such as the presence of headwater lakes). Large streams from order 4 onward are not considered in
80 this review. Research on stream-riparian interactions has mostly focused on exchange of nutrients and
81 material from land to streams and vice versa. In this overview, we include other processes and aspects
82 of diversity that are important in shaping stream-riparian interactions, such as those including microbes
83 and environmental forces. Although microbial community structure and processes largely drive the
84 diversity and functioning of higher organisms, former reviews about streams or riparian interface have
85 largely neglected the microbial point of view (e.g. Richardson 2019, Wohl 2017, Richardson & Danehy
86 2017, Hjältén et al. 2016). Particularly, a holistic understanding of the drivers of microbial community
87 dynamics and the relationship between biodiversity and functioning of microbes is lacking (e.g. Ledesma
88 et al. 2018). We aim to draw together the main points of stream-forest association and underline the
89 importance of protecting streams and their riparian forests and maintaining the linkage between the
90 two. We further describe in more detail the drivers of riparian biodiversity and how it is affected by
91 anthropogenic pressures. Finally, we draw together the main aspects that should guide riparian
92 management and protection and define future research needs.

94 **2. Ecosystem services provided by riparian forest to streams**

95 In the boreal zone, riparian forest floor is often peat dominated, but the thickness of the peat layer
96 varies due to climate and small-scale environmental variation. Peat layer thickness and vegetation affect
97 the processes on the riparian forest that are the drivers of ecosystem services provided by riparian
98 zones to streams. Sediment, organic matter, nutrient (Pinay et al. 1992) and metal (Lidman et al. 2014)
99 retention capacity of riparian zone depends on soil type, vegetation, topography and hydrology of the
100 riparian area. Streams are hydrologically connected by three-dimensional water flux: within the
101 channels (longitudinally), between riparian zones and channels (laterally) and between surface water

102 and groundwater (vertically; hyporheic flow), all of which affect the fluxes of material in to stream
103 network. In this review, we focus on describing fluxes across the lateral dimension. Riparian zones are
104 situated on low elevation areas in the end of terrestrial hydrological flow paths. They receive and
105 process considerable amounts of water, organic matter (OM), organic carbon (OC), nutrients and
106 elements from the catchment, thus, they are considered as hotspots for biochemical processes (McClain
107 et al. 2003). Microbes are key drivers of biochemical cycles metabolizing elements and organic
108 compounds, which may be stored into plant biomass and bulk soil or carried to the stream channel.

109

110 **2.1 Sediment retention and erosion prevention by riparian zone**

111 Sedimentation is caused by bank erosion or transportation of sediments from riparian or upland forest.
112 Sedimentation may reduce the survival of stream organisms and alter community composition
113 (Tolkkinen et al. 2016), biodiversity (Annala et al. 2014, Izagirre et al. 2009) and productivity (Annala et
114 al. 2014, Cardinale et al. 2002, Parkhill & Gulliver 2002). Roots of plants in the riparian zone stabilize the
115 ground and thus prevent erosion. In forests, natural sedimentation of stream beds is usually low
116 compared to that of less vegetated landscapes, although streams with riparian zones that have thin peat
117 layer can also be sandy in the boreal zone. Further, drought or spring snow melt may significantly
118 increase bank erosion (Wood & Armitage 1999, Naiman 1982).

119

120 **2.2 Organic matter and carbon retention capacity of riparian zone**

121 On a global scale, carbon processing rates in the riparian forests and streams are determined by
122 temperature and precipitation (Tiegs et al. 2019). The hydrology of the riparian zone has a key role in
123 determining the flux of OM and associated OC to the stream (Fiebig et al. 1990). OM may leach to a
124 stream due to land use near the stream or in the catchment. High loads of OM may cause brownification
125 of waters, which may further impair invertebrate diversity (Astorga et al. 2011), microbial community
126 composition and functions (Wagner et al. 2015), and fish abundance (Hedström et al. 2017) locally or at

127 downstream reaches. Therefore, the OM retention capacity of riparian soil, i.e. the capacity to prevent
128 organic substances draining to the stream, is an important ecosystem service needed to maintain
129 stream functioning and biodiversity in a natural state.

130

131 OM retention capacity is maintained by vegetation forming OM traps together with soil microbes and
132 invertebrates decomposing OM into simple particles, which eventually forms soil. Decomposition rate is
133 controlled by soil moisture and temperature (Coûteaux et al. 1995, Singh and Gupta 1977), soil texture
134 (van Deen & Kuikman 1990) and litter quality (Coûteaux et al. 1995). Fungi are often considered as the
135 dominant decomposers on land, especially in acid soils and soils experiencing frequent drying-wetting
136 dynamics (Bapiri et al. 2010, Yuste et al. 2011), while bacteria may overtake decomposition in
137 circumneutral-alkaline and arid soils (Rousk et al. 2010). However, this pattern is not self-evident (see a
138 review by Strickland & Rousk 2010). In riparian forests lower soil carbon:nitrogen (C:N) ratio may give
139 competitive advantage to decomposer bacteria over fungi (Högberg et al. 2007, Fierer et al. 2009,
140 Brockett et al. 2012), although this likely depends on the overall nutritional status of the habitat
141 (Kyaschenko et al. 2017b). In addition to environmental factors, soil fungal community composition has
142 been identified as an important controlling factor of OM storage in humic soil (Kyaschenko et al. 2017a).

143

144 The net balance of C along a stream network depends on terrestrial C gains, biological consumption of C,
145 and inorganic processes such as outgassing of CO² (Dawson et al. 2004). Because groundwater table is
146 shallow near headwater streams, these small streams likely receive terrestrial OC from riparian zone via
147 subsurface pathways rather than from upland sites (Mei et al. 2012). However, upland sites may be
148 principal sources of OC for headwater streams with adjacent hillslopes and those that have shallow
149 bedrock near the channel (Gannon et al. 2015). The amount of OM fluxes may also depend on
150 catchment type as shown by a long-term study from northern Sweden, where fluxes of terrestrial OM at
151 baseflow were positively correlated with the proportion of wetlands in the catchment (Laudon et al.
152 2011). Increased discharge, due to for example heavy rain events, may further increase the flux of

153 riparian OC to streams (Lambert et al. 2011). Differences exist also in inorganic C sources of low and high
154 order streams. Headwater streams may receive most of their inorganic carbon, namely CO₂, from the
155 riparian zone, where it is formed by soil respiration (Winterdahl et al. 2016). Higher order streams, in
156 turn, more likely gain inorganic C from in-stream processes, where DOC is turned into CO₂ in aquatic
157 mineralization processes (Moody et al. 2013).

158

159 **2.3 Riparian-based organic matter in streams**

160 In streams, benthic microbial communities (Kreutzweiser & Capell 2003) together with benthic
161 invertebrates may utilize OM effectively, controlling the flux and concentration of terrestrial OM and OC
162 further downstream (Dawson et al. 2001). Terrestrial OM is important for the biodiversity and
163 ecosystem functions of streams. As implicated by the River Continuum Concept (Vannote et al. 1980),
164 headwater stream invertebrate communities usually depend on allochthonous energy resources
165 (Cummins et al. 1989), which end up to the stream as dissolved and particulate organic matter (DOM
166 and POM, respectively). Main source of coarse POM (CPOM) from riparian forest is leaf litter, but also
167 pieces of other plants and terrestrial invertebrates enter the stream. Benthic invertebrate shredders are
168 the main macroscopic consumers of leaf litter in streams (Cummins et al. 1989, Hieber & Gessner 2002).
169 The major product of decomposition is fine POM (FPOM), which is then carried downstream where it is
170 further consumed by microbes and invertebrates (Webster et al. 1999).

171

172 In addition to shredders, microbes, especially hyphomycete fungi, are important consumers of leaf litter
173 in streams (Hieber & Gessner 2002, Gessner et al. 1999, Bärlocher 1992). Microbial processing is
174 thought to be an essential phase of litter decomposition, because it is assumed to make leaves more
175 palatable for invertebrate consumption due to changes in leaf matrix composition (Graça 2011, Rossi
176 1985). On the other hand, microbes can be seen as potential competitors for shredders as they use same
177 the energy resource (Gessner et al. 1999).

178

179 Moreover, endophytic fungi, which colonize living leaves before abscission, may contribute to litter
180 decomposition on land (Voříšková & Baldrian 2013, Koide et al. 2005) and in streams (Koivusaari et al.
181 2019, Wolfe et al. 2019, Mustonen et al. 2016, LeRoy et al. 2011). This may also hold true for endophytic
182 bacteria, because they too can carry glycoside hydrolases genes, which encode enzymes required for
183 decomposition of OM (Berlemont & Martiny 2016). The contribution of hyphomycete fungi to litter
184 decomposition in streams may depend on hydrological factors. Mustonen et al. (2016) showed that
185 endophytes were the main decomposers of stream litter in slow-flow experimental outdoor channels.
186 Similarly, Wolfe et al. (2019) found litter infected by the endophyte *Rhizisma* decay faster than lesion-
187 free litter in a third-order stream in a mixed conifer and hardwood forest. On the other hand,
188 endophytes have ability to slow down decomposition rates on land (Omacini et al. 2004) and in streams
189 (LeRoy et al. 2011) depending on endophyte identity and/or stream flow velocity. There are various
190 possible ways how endophytes may control litter decomposition (e.g. by inhibiting other microbes), yet
191 the underlying mechanisms are not currently well understood.

192

193 Decomposing biota primarily control decomposition rates, but their efficiency is codetermined by
194 environmental factors such as litter quality (Cornut et al. 2015, Ferreira & Chauvet 2011a, Leroy & Marks
195 2006), trophic state of the stream (Ferreira et al. 2015, Ferreira & Chauvet 2011b), water chemistry
196 (Mykrä et al. 2019, Tolkkinen et al. 2015, Suberkropp & Chauvet 1995) and temperature (Martínez et al.
197 2014, Ferreira & Chauvet 2011a, 2011b). Riparian diversity may affect leaf breakdown rates in streams
198 because litter species composition and quality influences leaf processing rates (Fernandes et al. 2012,
199 Schindler & Gessner 2009, Swan & Palmer 2006, Swan & Palmer 2004). This impact can be mediated
200 through changes in invertebrate (Leroy & Marks 2006) and microbial (Fernandes et al. 2013) diversity or
201 due to differences in riparian forest composition (Kominoski et al. 2011).

202

203 **2.4 Metal retention capacity of riparian zone and toxicity of metals**

204 Drainage of OC and elements to streams are often related, because many elements have high affinity
205 with organic compounds (Lair et al. 2007, Mierle & Ingram 1991). Peat soils may prevent the fluxes of
206 trace metals to streams more effectively than mineral soils (Lidman et al. 2014). Stream water chemistry
207 determines bioavailability and toxicity of metals to organisms. In general, the more acidic and softer
208 (lower concentration of calcium and magnesium) the water is, the lower concentrations of metals are
209 needed to produce toxic effects on organisms (Paquin et al. 2000). Dissolved and particulate OC (DOC
210 and POC, respectively) bind metals decreasing their bioavailability. Thus, in humic streams, organisms
211 may not be as prone to toxic effects as in streams acidified due to, for example, acid sulfate soils or
212 sulfate-rich bedrock. The latter can also decrease water pH more than OC. Ultimately, whether metals
213 produce toxic effect on organisms or not, depends on organisms` sensitivity to metals. Metal
214 contamination due to land-use changes may affect aquatic communities (Tolkkinen et al. 2016) and
215 food-webs (Hogsden & Harding 2012).

216

217 Trace metals, draining from upland or flushing with flood, may accumulate on riparian zone, potentially
218 making the riparian soil toxic for some plants. On the other hand, high affinity of metals with OM may
219 decreases their bioavailability in the riparian zone (Lidman et al. 2017). Some plants, with the help of
220 microbial symbionts, have the ability to accumulate metals in their shoots, thus avoiding toxic effects
221 (Khan et al. 2000). Further, mychorrizal fungi, which form symbiotic relationships with their host plant,
222 have ability to either inhibit (Hildebrandt et al. 2007) or exacerbate (Killham & Firestone 1983) toxicity
223 of metal-polluted soil on the host plant. An example of such metal-tolerant fungus is *Suillus* Gray, 1821
224 from order Boleatus, a common genus in Northern Hemisphere, which contribute to the survival of their
225 host trees (Pinaceae) on metalliferous soils (Colpaert et al. 2011). Forest soil bacterial communities may
226 be able to adapt to metal pollution, presumably via changes in community composition (Pennanen
227 2001), yet their functional activity may decrease despite adaptation (Frey et al. 2006). However,
228 relatively little is known how changes in microbial communities affect their processes.

230 **2.5 Nutrient retention capacity of riparian zone**

231 Because of their position between stream and upland sites, riparian zones play a major role in chemical
232 processing (Ledesma et al. 2013) and controlling stream nutrient status and pH. Because riparian soil in
233 boreal forests is usually rich in OM, it also tends to accumulate nutrients and trace metals. However, as
234 the riparian zone can be a source of OM for streams, especially for small streams, it may be a source of
235 those nutrients that tend to bind with OM (Lidman et al. 2017). The input of alkaline elements may
236 prevent stream from acidification.

237

238 Vegetation and microbes are the primary consumers of soil nitrogen (N) and phosphorous (P), which are
239 the main nutrients controlling ecosystem productivity in terrestrial and freshwater ecosystems (Aerts &
240 Chapin III 1999). Denitrification, is often higher near river channels compared to upland forests (Hill et
241 al. 2000, see also a review by Hill 1996), because the anerobic conditions in the wet ground enable the
242 reduction of nitrate to nitrite and, eventually, to gaseous N forms (Tiedje 1988). Hill (1996) suggests that
243 in watersheds with low drainage of nutrients, riparian forests may act as a nutrient source or sink to the
244 stream depending on the potential redox conditions. In watersheds with relatively high nutrient
245 drainage, riparian zone may act as a nutrient sink (Mulholland 1992).

246

247 Hedin et al. (1998) identified narrow near-stream zone as functionally the most important location for
248 denitrification in riparian zone despite low DOC levels. This may be a consequence of, for example,
249 unexceptionally high root mass in the soil. In their review of microbial “hotspots” and “hot moments”
250 Kuzyakov & Blagodatskaya (2015) go further to microscale and point out that soil microbial activity is
251 highly heterogenous in space and time. In hotspots, such as rhizosphere and detritusphere, microbial
252 activity can be two to 20 times higher than in the bulk soil (Blagodatskaya et al. 2009, Blagodatskaya et
253 al. 2014). Also, seasonal variation may affect the effectiveness of riparian forest to retain nutrients
254 (Pinay et al. 1993), thus studies conducted at different seasons may produce highly variable results.

BOX 1. Microbial community profiling with molecular methods

Microbial communities can be extensively studied with modern molecular methods, so-called 'omics' (see Franzosa et al. 2015 and Knight et al. 2018). In this review we will concentrate on nucleic acid-based methods, i.e. marker gene, metagenome and metatranscriptome sequencing, which can be used for **taxonomic and functional microbial community profiling** answering questions: "who is there?" (using genomic DNA as a template), "who is active?" (ribosomal RNA; rRNA) and "what are they doing?" (messenger RNA; mRNA). Taxonomic studies are usually based on DNA, while functional genomics include both functional potentials (DNA-based metagenomics) and functional activities (RNA-based metatranscriptomics).

Shotgun and amplicon-based marker gene, metagenomic and metatranscriptomic sequencing studies involve extraction of total DNA and/or RNA from the community samples. In RNA-based studies, this is generally followed by mRNA enrichment to remove rRNA (which is around 80% of total RNA) and synthesis of RNA to complementary DNA (cDNA). Typically, amplicon sequencing is based on single gene such as the bacterial 16S and fungal ITS or 18S rRNA gene region, which is amplified in PCR with specific primers. Shotgun sequencing instead gives millions of random genomic fragments from a studied microbial community that can be assembled into longer sequence reads (contigs). Acquired amplicon and shotgun sequence reads are then matched to reference databases and used for downstream analyses.

Challenges in molecular methods: In amplicon-based marker gene analysis, selecting primers that target all the taxa of interest is a challenge, while in shotgun-based studies the challenge is building contigs from complex environmental samples. In both, amplicon and shotgun-based methods, very short sequence reads may not be reliably matched. Still, the biggest problem with the 'omics' is the incomplete databases suffering from the missing reference species and functional genes, as for example 30-50% of the encoded proteins by any given genome are still unknown or incorrectly annotated, especially for taxa found from less well-studied environments. The problem may be even larger with the methods relying on whole genome reference databases or in pathway-reconstruction depending on species-specific databases.

Recommendations for the future: Combining different 'omic-methods' (including also proteomics and metabolomics) gives enhanced and more reliable results, e.g. by covering some of the weaknesses of the others. These 'multi-omics' studies can be used to acquire a more profound biological understanding and can be used to support new hypotheses. Also, combining traditional cultivation and modern molecular methods could provide new insights into life of microorganisms. However, microbiome studies with molecular methods acquire a careful planning all the way from the study setup, sampling, choosing the most appropriate 'omic-methods' (e.g. primer selection and sequencing platforms) to bioinformatics and statistical analyses.

256 **2.6 Riparian control on stream microbial diversity**

257 Although the development of molecular methods (Box 1) have made microbial profiling much easier,
258 faster and cheaper than before, our knowledge on freshwater bacteria (Zwart et al. 2002) and fungi
259 (Grossart et al. 2006) is still rather scarce compared to that of some other biotic groups, for example,
260 benthic invertebrates. Especially microbial studies linking the aquatic and terrestrial ecosystems are
261 lacking. However, there is evidence that the type of soil-originating DOM can affect aquatic microbial
262 productivity (Berggren et al. 2009), which may be mediated through shifts in bacterial community
263 compositions (Judd et al. 2006). Possibly also aquatic fungi are affected, but they have not been studied
264 in this regard. DOM from the riparian soil originates mostly from plants (Wang et al. 2014). As OM
265 quality and quantity depend on the quality (identity) and quantity of terrestrial plants, riparian
266 vegetation potentially has a strong control of aquatic microbial communities. In addition, genetic
267 variation affects the variability of phenotypic traits in plants having ecosystem-level effects (Hughes et
268 al. 2008). For example, genetic variation can be realized as effects on community structure, species
269 interactions, recovery from disturbance, primary production and decomposition (Hughes et al. 2008,
270 Whitham et al. 2006), and can be detected also in streams (LeRoy et al. 2006).

271

272 Microorganisms originating from land can contribute significantly to richness, and possibly composition,
273 of microbial communities in aquatic ecosystems, especially in streams, which are highly connected to
274 land (Ruiz-Conzales et al. 2015). The relationship between riparian and stream microbial communities is,
275 however, still poorly understood. Plant species (Carney & Matson 2006, Marchner et al. 2001, Borga et
276 al. 1994) and soil properties, such as pH (Moon et al. 2016), can select for certain microbes in terrestrial
277 habitats, and this may also hold true for aquatic environments. For example, certain terrestrial plants
278 can favor fungi over bacteria (Bardgett & Walker 2004), which in turn may play a role in structuring
279 aquatic microbial communities.

280

281 **2.7 Terrestrial invertebrates in stream food-webs**

282 The amounts of terrestrial invertebrates entering the stream are determined by riparian tree
283 composition, especially to the amounts of deciduous trees in riparian forest. Deciduous forests support
284 significantly greater fluxes of invertebrates from land to stream compared to coniferous forests (Inoue
285 et al. 2013, Wipfli 1997). Terrestrial prey input is relevant for stream fish and predatory invertebrates, as
286 they may depend nutritionally on terrestrial subsidies. Food consumed by stream fish may comprise 30-
287 90% of terrestrial invertebrates (Inoue et al. 2013, Wipfli 1997), with a positive feedback on their growth
288 (Gustafsson 2011). The effect may cascade further down the food-web due to predatory-release of
289 aquatic invertebrates. For example, Nakano et al. (1999) experimentally prevented terrestrial
290 invertebrate fluxes to stream, which shifted fish to feed on aquatic grazers, consequently leading to
291 increased periphyton production. England and Rosemond (2004) showed that even a small reduction in
292 riparian forest tree cover may significantly alter the food-web of aquatic consumers that are dependent
293 on terrestrial subsidies.

294

295 **2.8 Physical effects of riparian forest to stream**

296 Riparian forests affect stream biodiversity and functions also physically. Because headwater streams are
297 narrow, they are more shaded than rivers due to more closed canopy cover. Riparian trees thus have a
298 great control on stream water temperature (Richardson & Danehy 2007, Moore et al. 2005). Also,
299 groundwater input from hyporheic zone or the upland forest cools down stream water (Boulton &
300 Hancock 2006). Canopy cover may affect stream diversity by controlling primary production (Mosisch et
301 al. 2008, Hawkins et al. 1982, Murphy et al. 1981), water temperature (Moore et al. 2005) and litter
302 input (Melody & Richardson 2004, Wallace et al 1997). The proximity of trees near streams enable
303 falling of branches and trunks in to the channel. In-stream deadwood originating from riparian forests
304 contributes to decomposition efficiency by trapping and accumulating leaves on the stream bed (Flores
305 et al. 2011), thus extending the retention time of leaves in the stream. Accumulation of leaf litter to the

306 stream bottom may be particularly relevant in northern streams, where ice sheet and snow in the
307 riparian zone prevent fluxes from land to water during winter.

308

309 **3. Riparian forest diversity depends on the stream**

310 Streams can shape riparian diversity by forming a disturbance regime on the riparian zone, by assisting
311 the dispersal of riparian species and by offering subsidies for riparian food-web. Also, groundwater
312 affects riparian diversity and although it is not strictly a mechanism caused by the stream, it is
313 characteristic for stream riparian zones due to their low topographic position in the catchment. We first
314 explain, why riparian diversity differs from that of upland forest and then describe in more detail the
315 mechanisms by which the stream affects riparian diversity. Finally, we discuss the effects of the stream
316 on riparian microbiome.

317

318 **3.1 An overview of riparian diversity**

319 Riparian zones may support more species than the upland landscapes. Studies have shown riparian
320 habitats to be important at least for bird (Bennet et al. 2014, Mosley et al. 2006, Whitaker &
321 Montevecchi 1999, Darveau et al. 1995) and plant (Pollock et al. 1998, Kuglerova et al. 2014a) diversity
322 and dispersal. Even if riparian species richness does not exceed that of upland sites, the biotic
323 communities differ in their composition (Sabo et al. 2005). Riparian zones support species that either
324 prefer or withstand moist conditions, thereby increasing regional species richness (Kuglerová et al.
325 2014a, Selonen et al. 2011, Dynesius et al. 2009, Rykken et al. 2007a, Zinko et al. 2005). Soil can be
326 moist due to groundwater input from upland sites or shallow groundwater table near the stream, or due
327 to inundation by flooding waters. While the role of groundwater is usually more evident in headwater
328 streams, flooding is more important in medium sized streams. In both cases, soil moisture tends to
329 increase near-stream biodiversity, because different species inhabit wetted ground compare to drier
330 sites. The mechanism is different, though. The proximity of groundwater wets the ground year-round

331 and increases pH and N availability (Kuglerová et al. 2014a), thus favoring some species of bryophytes
332 and vascular plants over others. Flooding, on the other hand, causes disturbance and temporal
333 inundation offering habitat for moisture dependent or resistant species that may be poor competitors in
334 more stable conditions. While upland forest may consist of only one to few tree species, riparian zones
335 of typically support a high species richness of trees, especially deciduous ones, which tend to form a
336 zonation from reach to upper forest (Ward et al. 2002), especially in medium-sized streams.

337

338 **3.2 Effects of stream flooding and ice on riparian forest**

339 Stream flooding shapes riparian diversity by creating a disturbance regime in the riparian zone. Climate,
340 stream channel morphology, bank slope, groundwater discharge, and proximity of lakes determine the
341 extent of stream flooding, which is typical for medium-sized (and bigger) streams. Precipitation and
342 seasonal shifts in temperature affect the magnitude and duration of floods and the formation and
343 melting of ice and snow. The effect of floods and ice on riparian zone is significantly different in a V-
344 shaped stream valley with steep bank slopes compared to U-shaped valley with only moderate slope.
345 Flooding can be an important, even fundamental, mediating factor of the diversity of riparian vegetation
346 (Garssen et al. 2015, Lind & Nilsson 2015). As initially hypothesized by Connell (1978), intermediate
347 disturbances should maintain highest biodiversity by promoting competitive release. In theory,
348 intermediate flooding should thus create space for stress-tolerant species with low-competitive abilities
349 and for pioneer species (Lind et al. 2014b). Accordingly, some field studies have found species richness
350 to peak at intermediate flooding (Pollock et al. 1998, Townsend et al. 1997). However, local conditions,
351 especially site productivity, determine the response of communities to disturbances, and thus
352 environmental gradients should be considered when evaluating disturbance effects on diversity (Huston
353 2014). Furthermore, the scale at which diversity effect is evaluated should be considered carefully,
354 because positive diversity effects at intermediate levels of flooding may be detectable more readily on
355 large (hectares) than on small (square meters) scale (Pollock et al 1998). Due to flooding, riparian
356 ecosystems are often highly variable in space and time. Because of frequent disturbances, riparian

357 communities can be considered highly resilient to natural perturbations, but it does not automatically
358 make them resistant or resilient to anthropogenic disturbances, which are usually fundamentally
359 different from natural ones.

360

361 In the northern hemisphere, ice is an important factor mediating riparian diversity (Lind et al. 2014a,
362 Lind et al. 2014b, Engström et al. 2011). About 60% of the major river basins north of the equator
363 experience ice processes during winter (Allard et al. 2011). Thus, the ecological importance of ice cannot
364 be neglected. In small boreal streams, the formation of anchor ice promotes flooding (Beltaos 2008),
365 which in turn can increase riparian vegetation diversity. While detrimental to individual plants, ice
366 creates space for early successional species by ripping off vegetation during ice melt; thus, its effect is
367 similar to that of flooding.

368

369 **3.3 Stream as a dispersal corridor for riparian species**

370 Species richness and assemblage composition in a given stream or riparian location is determined by the
371 sum of environmental preferences, dispersal ability and other traits of the species (Tonkin et al. 2018,
372 Heino et al. 2015, Leyer and Pross 2009, Hérault and Honnay 2005). Stream channel is an important
373 dispersal corridor for passive dispersal of plants and their seeds (Kuglerová et al. 2015, Nilsson et al.
374 2010). Some studies suggest that seeds of riparian plants are more often adapted to floating than
375 upper-forest species (Johansson et al. 1996, Lopez 2001), which implies that their dispersal success may
376 be dependent on the transport capacity of the stream (Merritt & Wohl 2002, Jansson et al. 2000). The
377 potential for transporting seeds and vegetative parts varies among streams due to differences in
378 channel morphology and vegetation cover (van Leeuwen et al. 2014, Riis and Sand-Jensen 2006),
379 magnitude of discharge (Nilsson et al. 2010) and water level (van Leeuwen et al. 2014). Jansson et al.
380 (2005) and Merritt et al. (2010) showed in their studies in Swedish rivers that dispersal by water
381 significantly increased the diversity of riparian plant species. However, hydrochory may be more
382 important for the occurrence of species in larger streams compared to the smallest headwater streams

383 (Kuglerová et al. 2015), presumably because headwater populations do not have source populations
384 upstream, and because they must rely on dispersal modes other than hydrochory. Water dispersal may
385 be also relevant for other riparian organisms (e.g. fungi) as shown by a recent study (LeBrun et al. 2018).
386

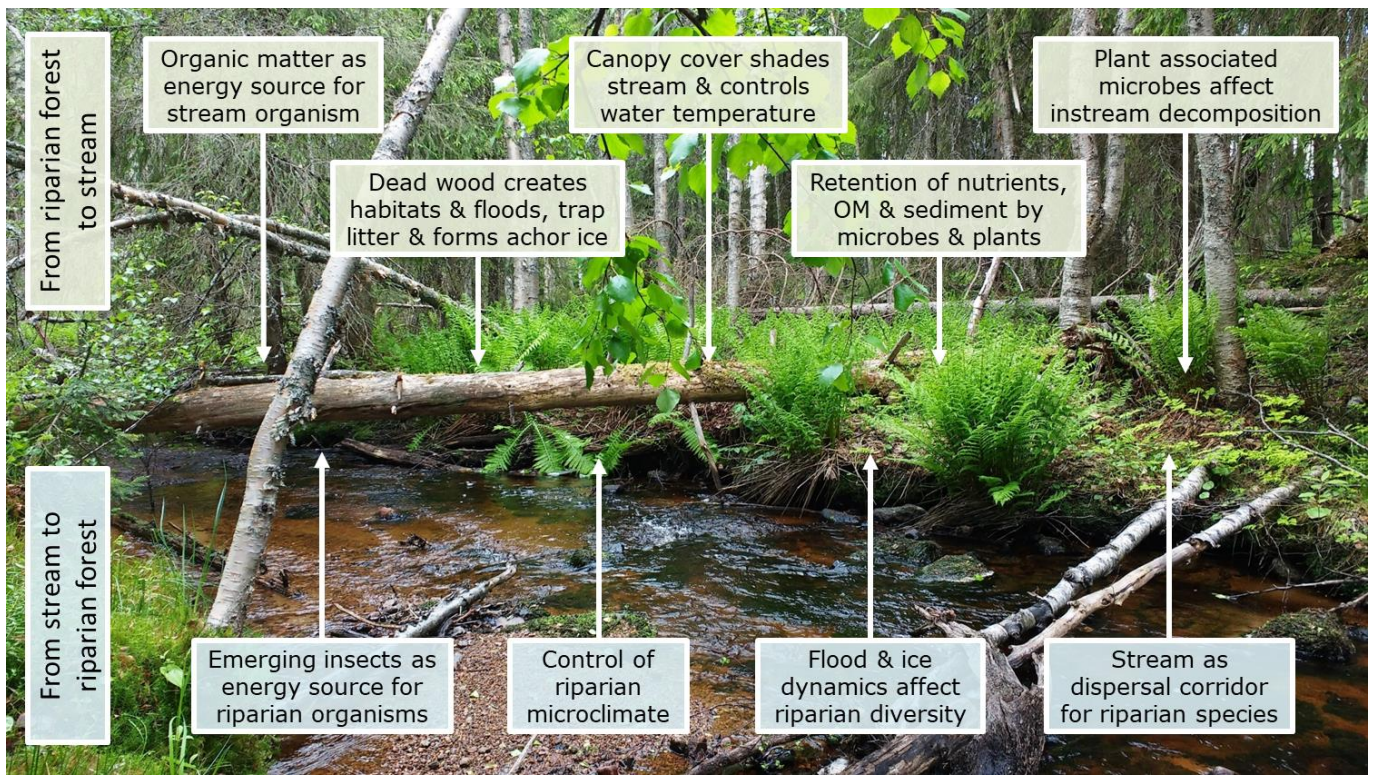
387 **3.4 Subsidies from stream to riparian forest**

388 While terrestrial-to-aquatic subsidies concern mainly the flux of detritus, emerging aquatic insects
389 dominate subsidies from water to riparian zone (Bartels et al. 2012). Insects emerging from the streams
390 are consumed by riparian insectivores, and they are also a nutrient source for riparian plants and micro-
391 organisms (Dryer et al. 2005). Although benthic production of streams exceeds that of lakes, streams
392 and rivers can support significantly lower fluxes of prey to land compared to ponds and lakes (Gratton &
393 Vander Zanden 2009). That said many studies have shown that bottom-up effects initiated by aquatic
394 prey can have major impacts on riparian ecosystems, contributing 25 to 100% of energy sources to
395 spiders, lizards, birds and bats (Baxter et al. 2005). However, most studies are from the temperate zone,
396 and it would thus be beneficial to gain more knowledge from the boreal zone.

397

398 **3.5 Stream effects on riparian microbiome and related processes**

399 Literature about the effects of stream hydrology and ecology on microbial process rates in the riparian
400 zone is scarce, and riparian zones are widely variable regarding to, for example, moisture and nutrient
401 status, which makes generalization difficult. However, biochemical processes in the riparian zone may
402 be more stable than in the upland forest due to closeness of a permanent stream and associated
403 relatively stable microclimate conditions, although we did not find any studies related on the subject.
404 On the other hand, changing hydrology due to land-use change can have unpredictable effects on
405 riparian processes, which may become detectable only in the long term (e.g. Bardgett et al. 2001).
406 Further research is needed on how protecting stream flooding regimes, groundwater discharge and
407 natural vegetation could contribute to the maintenance of biochemical processes in the riparian zone.



408

409 Figure 1. Main reciprocal effects in a stream and its riparian forest. Boxes with arrows indicate the direction of the
 410 effect, either from the riparian forest to the stream (light green boxes) or from the stream to the riparian forest
 411 (light blue boxes).

412

413 **4. Human impact on riparian and stream ecosystems**

414 Extensive land use and modification of stream channels have led to dramatic decline of natural riparian
 415 habitats (Richardson et al. 2007). Multiple pressures due to land management are threatening
 416 biodiversity and ecosystem processes in riparian zones. These pressures include forestry, drainage
 417 ditching, agriculture, grazing and invasion by alien species. Land use has been identified as the most
 418 influential pressure affecting biodiversity (Sala et al. 2000). Streams may be the most sensitive aquatic
 419 ecosystems towards human impact, given their topographically low position in the catchment
 420 (Richardson 2019). Channelization and damming of streams and rivers can affect freshwater and riparian
 421 zone diversity. Anthropogenic land use near streams can change riparian microclimate conditions and
 422 enable invasion by alien species, which translate into changes in species composition and may

423 subsequently affect ecosystem functions. If ecosystem functions are changed, it is possible that the
424 consequences accumulate downstream and extend into riparian forest.

425

426 **4.1 Effects of riparian land use on stream and riparian diversity and ecosystem functions**

427 In this review, we only consider forestry-associated land use effect, and thus urban and agricultural
428 impacts are beyond our consideration, for example. Forestry associated impacts include physical and
429 chemical modification of streams and riparian forests, potentially leading to changes in biotic
430 communities, and eventually to depauperate ecosystem functions.

431

432 *4.1.1 Stream warming*

433 Removing mature trees from riparian zone predisposes streams to warming directly and through
434 warming of exposed spring waters (Kreutzweiser et al. 2009, Brown & Krygier 1970). Possible warming
435 of the stream water depends on the site characters and the weather conditions following the time of
436 logging. Headwater streams that rely on direct input of groundwater may not be as prone to warming
437 (Mellina et al. 2002) as larger streams. On the other hand, wider streams are naturally less shaded than
438 narrow ones, thus the temperature of headwater streams may be more susceptible to forest harvesting
439 compared to higher order streams. The recovery from possible warming following forest harvesting
440 varies a lot among streams and can take up to ten years (Moore et al. 2005). Warming may change the
441 structure of stream communities (Piggott et al. 2015, Ryan & Ryan 2006, Quinn et al. 2004) and
442 eventually the function of the stream. For example, increasing solar radiation accelerates primary
443 production (Kiffney et al. 2004, Boothroyd et al. 2004, Feminella et al. 1989) and decomposition
444 (Ferreira & Canhoto 2015, Ylla et al. 2014, Ferreira & Chauvet 2011), and can result in eutrophication
445 and emission of CO₂ from streams (Acuña et al. 2008).

446

447 4.1.2 *Stream water chemistry*

448 Stream water quality is compromised in forest harvesting, because extensive cutting and site
449 preparation often increase stream DOC levels in headwaters (Schelker et al. 2012). Clear-cutting leads to
450 rapid increase in spring snow melting and runoff potentially increasing nutrient, element and sediment
451 flow to streams (Schelker et al. 2013). In addition, drainage of even-aged peatland forests is a common
452 practice in northern countries. It lowers the groundwater table enhancing tree growth, but at the same
453 time it causes nutrients, suspended solids and sediment load to streams (Nieminen et al. 2017, Stenberg
454 et al. 2015, Marttila & Kløve 2010) leading to depauperate biotic communities due to simplification of
455 habitat structures (Vuori et al. 1998, Vuori & Joensuu 1996), brownification (Hayden et al. 2019, Haaland
456 et al. 2010, Evans et al. 2005) and eutrophication (Hayden et al. 2019, Marttila et al. 2018).
457 Furthermore, ditch network maintenance poses similar threats to streams as new ditches (Nieminen et
458 al. 2018a, Joensuu et al. 2002).

459

460 4.1.3 *Aquatic diversity and functions*

461 Removing trees, especially deciduous ones, from the riparian zone decreases the input of leaf litter and
462 wood to the stream, which means less energy sources for decomposers, less traps for leaf retention and
463 less variable habitat for microbes, algae, plants and invertebrates. These may lead to a decline in
464 diversity, abundance and/or biomass of decomposer communities (Johnson et al. 2003, Wallace et al.
465 1997). Community changes may further decrease ecosystem stability (see the discussion in Bengtsson et
466 al. 2000 and Cardinale et al. 2012) and lead to impaired stream functions, for example, decreased
467 decomposition. In-stream decomposition can be extremely sensitive to land use in the riparian forest
468 (Lecerf & Richardson 2010), but also upland land use changes can be detectable in such processes
469 (Kreutzweiser et al. 2008a). On the other hand, clear-cutting near a stream can increase in-stream
470 decomposition rate with a time lag if it leads to increased deciduous tree abundance in the riparian
471 zone, increased nutrient load to the stream and/or increased mechanical fragmentation of litter due to
472 higher sediment loads (Benfield et al. 2001, McKie & Malmqvist 2008).

473

474 Because riparian plant diversity affects stream microbes (Judd et al. 2006), any change in riparian
475 vegetation – species composition, biomass, age structure and/or species ratio of riparian trees – may
476 change stream assemblage compositions and functions through bottom-up effects on the food-web
477 (Bartels et al. 2012, Inoue et al. 2013, Kominoski & Rosemond 2012, Kominoski et al. 2011, Sweeney et
478 al. 2004).

479

480 *4.1.4 Dispersal of aquatic species with terrestrial adult stages*

481 Catchment-scale vegetation loss may also limit stream-organism dispersal, especially for species that
482 have terrestrial adult stages (Smith et al. 2009), although there is no firm evidence of such from forested
483 catchments. Headwater streams are situated at the top of the river network and suitable source
484 populations are not always found upstream, thus populations may rely on dispersal via land or from
485 source populations downstream (Tonkin et al. 2018). Their colonization success depends on their
486 dispersal abilities and on distance between suitable habitats (Sarremejane et al. 2017). Particularly, the
487 dispersal of caddisflies, stoneflies and mayflies is mostly dependent on adult flying stages (Bunn &
488 Hughes 1997); hence forest habitat fragmentation may impact their population dynamics. Especially
489 populations depending on nearby source populations and dispersal over-land, may be in jeopardy if
490 dispersal is restricted due to land use changes (Heino et al. 2017).

491

492 *4.1.5 Riparian diversity*

493 In theory, riparian organisms may be more adapted to disturbances than upland-dwelling ones, and they
494 may be more effective in re-colonization and re-establishment, because they can more readily take
495 advantage of water-assisted dispersal (Johansson et al. 1996, Lopez 2001). This is especially the case if
496 suitable source populations exist upstream. However, if species disappear after anthropogenic
497 disturbance, they may not be able to recolonize denuded locations (Dynesius et al. 2009). For example,
498 species depending on old-growth forest may not have suitable source populations in nearby areas.

499 Moreover, riparian vegetation removal may be too severe disturbance to overcome, because it reduces
500 suitable habitat for riparian and semi-aquatic species. For example, riparian vegetation loss is a threat to
501 web-spinning spider abundance and diversity because it reduces habitat for web sites (Laeser et al.
502 2005).

503
504 Tree removal in or near the riparian forest leads to drying of microclimate due to exposure to sun and
505 wind (Oldén et al. 2019). Such changes in microclimatic conditions may affect especially species that are
506 specialized to occur in moist riparian habitats, yet this likely depends on species` ecology and site
507 characters. Species attracted to convex surfaces (e.g. logs, stumps or boulders) can have high mortality
508 in uncut buffers due to edge effect caused by clear-cutting (Oldén et al. 2019, Hylander et al. 2005). On
509 the other hand, some riparian organism groups may be more tolerant toward disturbance at sites with
510 rough ground, which have concave surfaces (e.g. stony sites). Species attracted to concave surfaces may
511 be unaffected by edge effect, because of the ability of the uneven ground to maintain moist conditions
512 (Dynesius et al. 2009, Hylander et al. 2005, Hylander et al. 2004). However, in other cases species of
513 concave surfaces have decreased due to logging (Oldén et al. 2019). If soil tillage is practiced in the
514 riparian forest, the potentially beneficial effect of concave forest floor is lost.

515

516 *4.1.6 Riparian microbes and microbial processes*

517 Forest harvesting, especially clear-cutting, may affect microorganisms via changes in nutrient
518 availability, microclimate conditions and root dynamics. Although most research has been conducted in
519 upland forest rather than in the riparian zone, here-in we assume, that the microbial processes are
520 pretty much similar in upland and riparian forests, if the differences in environmental conditions (such
521 as soil moisture and microclimate) are considered. Logging impacts on soil nutrient cycling and flux to
522 streams depends on soil type, site conditions, catchment hydrology, post-logging weather patterns, and
523 type and season of harvesting (Kreutzweiser 2008b). Often soil N, P and possibly potassium (K) are
524 increased after harvesting, because of decreased/ceased tree root nutrient uptake, increased erosion

525 and leaching, and increased mineralization and nitrification rates (Hynes & Germida 2013). However,
526 removing logging residual may lead to negative effects on soil productivity and decrease in soil nutrient
527 pools compared with stem-only harvesting and decrease decomposition (Thiffault et al. 2011). Also,
528 clear-cutting effects on microbial dynamics vary among sites. While microbial biomass may not be
529 directly affected by forest harvesting (Taylor et al. 1999), it may decrease due to reduced litter input and
530 changes in microclimate (Hassett & Zak 2005) and soil moisture (Taylor et al. 1999) following clear-cut
531 harvest. Furthermore, microbial community composition may change after harvesting (Hynes &
532 Germida 2013, Lazaruk et al. 2005, Hagerman et al. 1999). Presumably fungi are more sensitive to forest
533 harvesting than bacteria (Bååth et al. 1999), because the changes in root dynamics affect root-
534 associated (mycorrhizal) fungi (Kyashcenko et al. 2017b, Bååth 1980). This contradicts to natural
535 disturbances, such as wildfires, which usually act above ground rather having little or no effect
536 underground (Jonsson et al. 1999). Moreover, wildfire and forest harvesting have distinct impact on soil
537 chemical composition, which potentially induces differing microorganismal responses (Thiffault et al.
538 2008). However, as Hynes & Germida (2013) point out, changes in microbial composition, or even
539 biomass, do not necessarily resemble changed microbial functions - rather it may reflect ability of the
540 community to adjust to changed conditions and keep up functions.

541

542 Harvesting-induced changes in soil moisture can affect microbiota. Soil moisture can either decrease or
543 increase due to forest harvesting depending on the hydrological connectivity of the stream and the
544 catchment (Smerdon et al. 2009). Typically, boreal streams are in the receiving end of groundwater flow
545 path, and thus groundwater table more likely rises near the stream reach rather than decreases.
546 Groundwater level tends to rise due to removal of trees, which absorb water from the ground. This may
547 make the soil more wet in places, where groundwater table is shallow, for example, near streams,
548 especially headwaters. When the forest begins to regenerate, groundwater table may decrease back or
549 close to basic level (Smerdon et al. 2009). Site preparation for a new tree generation can override
550 harvesting effects on groundwater level. Full-cutting in peatlands may be accompanied with drainage

551 ditching, which is intended to lower the groundwater level, and thus soil may not get wetter. In
552 addition, removing shading trees leads to drying of microclimate (e.g. Oldén et al. 2019) including
553 topsoil. Thus, the effect of forestry practices on microbial communities and processes may be very
554 different depending on which soil profile is being considered. Disentangling the effects of forestry-
555 related changes in the soil is difficult, because tree harvesting affects simultaneously so many
556 phenomena, which potentially induce changes to microbial biomass, composition and/or processes.
557 These include, for example, soil moisture and chemistry, soil bulk density, organic matter content and
558 fine root biomass. Also, the effect on soil properties may vary depending on the harvesting method (e.g.
559 partial-cut harvesting, green tree retention patches and strip-cut corridors; Lindo & Visser 2003).

560

561 **4.2 Management of riparian forests and protection of streams**

562 Streams and riparian forests are important areas for biodiversity and ecosystem processes, and at the
563 same time they are sensitive to land-use changes needing special attention in management. We now
564 discuss potential ways to protect streams and riparia from harmful effects of forestry. We use the terms
565 “protection” and “preservation” interchangeably to mean the protection of near-natural habitats and
566 species (but not necessarily to restrict all human use of the habitat). By “conservation” we mean
567 ecologically sustainable use of nature and natural resources.

568

569 Riparian communities are highly dependent on the microclimatic conditions of near-stream forest
570 (Pollock et al. 1998, Kuglerová et al. 2014a). Higher resilience of riparian compared to upland
571 communities can occur if flooding and groundwater discharge maintain moist conditions (Dynesius et al.
572 2009). Promoting flooding by adding wood and boulders in the stream (Turunen et al. 2017) or by
573 allowing colonization by beaver (Pollock et al. 2014) could mitigate harmful effects of catchment land-
574 use, at least in given locations. However, if flooding significantly increases nutrient input to the riparian
575 forest, it may pose a threat to riparian diversity (Lamers et al. 2006). This could happen if, for example,

576 nutrients from a heavily ditched catchment drain to the stream and are flushed on to the riparia by
577 floods. To our knowledge this is a novel idea and we are no aware of any research studying this aspect
578 of flooding. Also, due to their disturbance regime, riparian habitats may be easily invaded by alien
579 species (Catford & Jansson 2014, Richardson et al. 2007, Planty-Tabacchi et al. 1996).

580

581 There are only few means of reducing harmful effects of ditch maintenance (Nieminen et al. 2018a).
582 Integration of drainage with biodiversity conservation (Löhmus et al. 2015), and a site-specific
583 evaluation of the real need for ditch maintenance coupled with careful planning (Hasselquist et al.
584 2018), should be the primary approaches to avoid unnecessary disturbance to waters. In addition,
585 considering continuous cover forestry in peatland sites (Nieminen et al. 2018b) and near streams could
586 be a way to overcome the problem that ditches pose. Leaving trees and/or the shrub layer on the
587 riparian zone mitigates heating of the stream (Mellina et al. 2002, Brosofske et al. 1997), although in
588 some cases even partial harvesting of riparian trees may result in significant warming of water (Moore
589 et al. 2005). Other potential management practices reducing the need for ditches include, for example,
590 gap canopy harvesting and strip felling (see also Kuglerová et al. 2017).

591

592 If intensive land management is practiced in the watershed, a buffer is usually needed to prevent
593 nutrient and sediments draining to stream. No ground-disturbance should be practiced on the buffer,
594 but partial tree-harvesting may be allowed. Riparian forests have been acknowledged as effective
595 nutrient sinks in agricultural watersheds (Lowrance et al. 1984, Peterjohn & Corell 1984), and at the
596 same time they are able to maintain stream biodiversity (Turunen et al. 2019). They also have a great
597 stream protection potential with forestry-associated land fertilization (Vowell & Frydenborg 2004). In
598 order to function effectively, the buffer needs to be wide enough. Today, riparian researches
599 recommend varying-width buffers (Kuglerová et al. 2017, Richardson et al. 2017). This is because
600 riparian forest itself is varying width, if it is defined by its most important characters: microclimate and
601 soil moisture. Also, the nutrient and sediment retention capacity of riparian forest is site specific

602 depending on soil characters and topography (Gundersen et al. 2010). However, in practice buffers are
603 still usually designed as fixed-width. This is probably because fixed-width buffers were formerly the
604 center of research (e.g. Pinay et al. 1993) and management tend to change slowly, and because fixed-
605 widths are easier to design and implement compared to varying-width buffers. Nature-caring forest
606 management would benefit from considering new ways of implementing riparian buffers.

607

608 Buffers can also be used for biodiversity protection, but it is essential to define what the protection is
609 targeted for (see Gundersen et al. 2010 and references therein). While relatively narrow buffer strip
610 may (or may not; Vuori & Joensuu 1996) protect the stream from sedimentation, few rows of trees
611 unlikely provide effective protection for natural values on the riparian zone. Furthermore, forestry-
612 associated ground disturbance can affect aquatic food webs despite buffers (Erdozain et al. 2019). If the
613 aim is to develop a dispersal corridor, then the buffer zone should be long and continuous, but not
614 necessarily wide (see Gundersen 2010). The width of effective dispersal corridor depends on the target
615 species: in general, the larger the target species is the wider the buffer should be. If the aim is to protect
616 moisture-dependent species or certain habitat types, the buffer zones should be set wide enough where
617 the targeted conditions prevail. This can be achieved by incorporating variable width buffers with wider
618 buffers left where specific natural values occur and narrower buffers elsewhere (Kuglerová et al. 2014b).
619 In general, however, wider buffer strips are usually better than narrow ones from the ecological point of
620 view (Sweeney et al. 2004). The exception to this rule may be sites that have changed significantly
621 because of former land-use practices, for example, riparian forest, which have become spruce-
622 monocultures. Such sites may benefit from partial harvesting or management that emulates natural
623 disturbances on the riparian forest (Sibley et al. 2012), because making space for other species can
624 foster biodiversity and direct the plant communities towards more natural-like assemblages.

625

626 Leaving riparian forests uncut may benefit most forest species because they can use riparian zones as
627 refuges from clear-cutting and as dispersal corridors. Preserving natural riparian forests can also benefit

628 stream biodiversity and red-listed aquatic species (Suurkuukka et al. 2014). Particularly, protecting
629 natural riparian and stream habitats could secure aquatic, semi-aquatic and terrestrial insects whose
630 abundance has declined dramatically in the past decades (e.g. Hallman et al. 2017). In addition,
631 preserving the functional diversity of the microbial community may sustain long-term timber and soil
632 production, and diversity of plants, by retaining the capacity of symbiotic fungi and decomposing
633 microbes. It is not clear, though, whether refugees cause unintended pressures on riparian buffers, for
634 example due to increased rate of herbivory. Introduction of small herbivorous mammals, for example,
635 may cause changes in the vegetation community composition and affect nutrition dynamics in riparian
636 forest (Sirotnak & Huntly 2000).

637

638 Intermediate disturbances may increase functional diversity in the riparian forest (Biswas & Mallik
639 2010). It has been suggested that selective logging could be practiced on riparian buffers to emulate
640 natural disturbances (Kuglerová et al. 2017). However, because clear-cutting itself is such a big
641 disturbance that fundamentally differs from natural disturbances (Bergeron et al. 1999), more research
642 and careful landscape-level planning is needed before any additional disturbance can be recommended.
643 Overall, protection should not aim to increase local biodiversity, but rather the natural-like habitats and
644 associated species. For example, harvesting riparian trees increases light availability and temperature,
645 decreases near-ground air humidity and creates open space. Such environmental changes are likely to
646 initiate community changes by allowing the establishment of pioneer species and species adapted to
647 more open forest and concurrently losing species adapted to moist and/or shadow habitats. Especially
648 communities colonizing moist parts of riparian forest are at risk (Oldén et al. 2019, Kuglerová et al.
649 2014b). While partial logging may promote local biodiversity, at the same time, it can decrease or
650 increase beta diversity (Anderson et al. 2011) among sites, depending on the identity and number of
651 winners and losers. Regional (gamma) diversity will decrease if species specialized to riparian habitats
652 are lost. Considering the intensity of current forestry, gaps (clear-cuts) are well established in forests. It
653 is the old-growth forest and associated species that need protection, that is, species typically found in

654 undisturbed natural forests, for example those associated to dead wood, but at the same time forest
655 management needs to consider species of all successional stages (Spence 2001). However, it is not clear
656 how different management practices affect rare or endangered species, which most urgently need
657 protection.

658

659 The impact of selective logging on diversity depends on the width of the buffer, because the edge effect
660 causes additional warming and drying of riparian microclimate (Oldén et al. 2019, Steward & Mallik
661 2006). Thus, some logging might be allowed in buffers, that are wide-enough to overcome the edge
662 effect, without jeopardizing natural values. In boreal forests, a 30-45 m buffer without selective logging
663 on both sides of the stream is needed to prevent changes in microclimate (air humidity, temperature)
664 and moss communities in riparian forest that are considered hotspots of diversity (Oldén et al. 2019,
665 Selonen et al. 2013, Rykken et al. 2007a, Steward & Mallik 2006). Similarly, a >30 m forested buffer is
666 needed in between the stream and the clear-cut to prevent the stream from significant warming and
667 biological changes (Sweeney & Newbold 2014). Continuous cover forestry near streams could be one
668 way to dodge the issue of wide buffers. Currently, there is no research on how combining continuous
669 cover forestry and selective logging in riparian forest affects riparian or stream populations and
670 communities.

671

672 As much as riparian forests need protection, it is not an easy task if the forest must be deployed for
673 timber production at the same time. In most forests, riparian habitats cannot be wholly preserved
674 without any economic losses to forest owners. Therefore, effective and extensive riparian protection
675 requires that the forest owners understand the value of biodiversity and riparian ecosystem services.
676 However, even awareness of natural values may not be enough, because forest owners may have a
677 conflict of interest, for example, among biodiversity, climate change mitigation and economic values
678 (Eriksson & Klapwijk 2019, Norlund & Westin 2011) and because the demand of forest products forces
679 to more extensive logging. On the other hand, sustainable forestry makes sense not only from

680 ecological, but also from economical point of view (Balmford et al. 2002). Thus, efforts should be put
681 into finding a sustainable compromise between biodiversity protection and forestry. This can be
682 achieved by targeting additional protection to biodiversity hotspots, such as riparian forests, while
683 guaranteeing large enough forest areas for preserving overall biodiversity.

684

685 Especially nature prioritizing forest management would benefit from further research, but also
686 economic gains from tree harvest and other ecosystem services depend on nature-caring forestry. It is
687 important to maintain diversity of both micro- and macroorganisms at a level that enables communities
688 to reject perturbations and adjust to changing conditions, that is, maintain the resilience potential of
689 communities. For example, extensive clear-cutting has a negative effect on ectomycorrhizal fungal
690 abundance (Kyashcenko et al. 2017b) and diversity (Lazaruk et al. 2005, Hagerman et al. 1999),
691 decomposition (Ussiri and Johnson 2007), and the community of decomposing microbes through
692 changes in organic carbon pool (Bååth et al. 1995) and vegetation (De Graaff et al. 2010). Thus, in the
693 long run, alternative forest management practices (e.g. Lazaruk et al. 2005, Hagerman et al. 1999) could
694 be beneficial for the maintenance of biodiversity and ecosystem services in riparian forests.

695

696 **4.3 Climate change effects on stream and riparian ecosystem processes**

697 Mitigation of climate change on rivers and their watersheds is a challenge that calls for optimized
698 management practices. Climate change models predict increasing mean annual temperatures, more
699 frequent drought and extreme rainfall events, decreasing water table levels, and in the boreal zone
700 elongated thawed time and more frequent freezing-thawing cycles (Pachauri et al. 2014). Overall, wet
701 areas become wetter and dry areas drier (Dore 2005). Streamflow dynamics may change, for example, it
702 is predicted to increase in the winter and decrease in the summer in the northern hemisphere (Fortsieri
703 et al. 2013, Stahl et al. 2010, Wilson et al. 2010, Zhang et al. 2001). It is likely that biotic communities
704 and processes on streams and riparian areas will be affected due to changes in hydrology and
705 environmental factors related to warming (Heino et al. 2009).

706

707 Nilsson et al. (2013) reviewed climate change effects on riparian vegetation on the boreal zone. Shortly,
708 they conclude that decreased area of moist riparian zone due to increased summer-time drought and
709 smaller spring floods may decrease local species richness. It is worth noting, that climate change can
710 increase hydrological drought (van Loon 2015) due to increased evaporation, even if meteorological
711 drought does not increase (an Lanen et al. 2013, Wong et al. 2013, Wong & Beldring 2011). The rate of
712 formation and melting of ice in boreal streams has accelerated during recent decades and as the climate
713 keeps warming the ice formation will become rarer (Tolonen et al. 2019). Increased ice dynamics may
714 promote the formation of more species rich communities. Dead wood in streams creates similar
715 flooding effects (Turunen et al. 2017) as ice (Prowse & Beltaos 2002) and, on the other hand, wood
716 enhances the formation of anchor ice (Lind & Nilsson 2015). Promoting the amounts of dead wood
717 could thus keep up the ice-like dynamics in streams under climate change. The dispersal of invasive
718 species to higher latitudes will increase with climate warming, which poses further thread to native
719 plant communities (Nilsson et al. 2013).

720

721 Microbes play a key role in immobilizing C from atmosphere to soil and biomass. Thus, understanding
722 drivers of microbial processes are essential for climate change mitigation. Because water drains from
723 upland area to riparian zones, their soils receive and process remarkable proportion of C and N from the
724 drainage area, and they can be considered hotspots of C and N cycling and transformation (Vidon et al.
725 2010). Accelerated freezing-thawing, increased thawed time, and a decrease in water table and/or
726 frozen soil depth may affect C (Groffman et al. 2001) and N (Groffman et al. 2001, Mitchell et al. 1996,
727 Goodroad & Keeney 1984) cycling. Although decomposition relates to soil temperature on a local scale
728 (Kirschbaum 2006), increased decomposition rates at higher temperatures and at increased freezing-
729 thawing dynamics seems to relate to changes in soil moisture and substrate quality rather than warming
730 per se (Giardina & Ryan 2000). Changes in decomposition rates occur through changes in microbial
731 community composition (Haei et al. 2011, Nielsen et al. 2011, Zogg et al. 1997). Decomposition

732 efficiency may be related, for example, to the differences in the C processing or growth efficiency of the
733 microbial species (Zogg et al. 1997).

734

735 There is the possibility that climate change will cause a positive feedback that would increase the
736 emissions of greenhouse gases from riparian soils (Davidson & Janssens 2006) and drying stream beds
737 (Shumilova et al. 2019). When soils dry and then become rewetted, there is a burst of decomposition,
738 mineralization and release of inorganic N and CO₂ (Jarvis et al. 2007). Also, decreased snow cover can
739 change C and N cycling, for example increase the fluxes of N₂O from forests (Groffman et al 2006). Given
740 the extent of streams and their riparian areas and the fact that a relatively modest change in soil C
741 stocks are assumed to have major consequences for atmospheric CO₂ concentrations and climate
742 change (Nielsen et al. 2011), changes in the decomposition of riparian areas can have major
743 consequences on C cycling. Further, N-cycling is predominantly determined by soil condition (Brenzinger
744 et al. 2017), and significant emissions of N₂O from the soil due to climate change induced changes in
745 microbial communities and/or their functions (Chen et al. 2015, Baggs 2011) would further enhance
746 climate warming.

747

748 Global change is modifying microbial composition and functional potential in soil ecosystems (Amend et
749 al. 2016). Based on the hypotheses of Wallenstein and Hall (2012) microbial communities are better able
750 to adapt to changing temperature and precipitation condition in regions and habitats that naturally
751 experience relatively rapid temporal temperature and moisture variation. In line with this theory,
752 aquatic microbial communities would be less capable adapting to climate change than terrestrial
753 communities, because temperature changes are typically more subtle in aquatic than in terrestrial
754 habitats. Following this reasoning, biological communities in high latitudes would be more conservative
755 towards climate change impacts than those at temperate regions. This is because natural temperature
756 changes during a year are more pronounced in high compared to low latitudes. However, this is only
757 theoretic, and the actual realization of climate change impacts on biotic communities can be

758 unpredictable. Furthermore, adaptation at the community level does not mean that processes do not
759 change. In fact, adaptation of microbial communities to changing climate can have major impacts on
760 biochemical processes (Wallenstein & Hall 2012).

761

762 According to Ferreira & Chauvet (2011a) water temperature is the major environmental factor
763 controlling the structure of aquatic hyphomycete communities. Increase in water temperature due to
764 climate change may thus affect species composition of and decomposition by aquatic hyphomycetes
765 (Ferreira & Chauvet 2011b). Bacteria may be affected similarly. Reason may be the fact that microbial
766 processes are driven by enzymes (Berlemont & Martiny 2016), the performance of which depends on
767 temperature or that biomass production increases with temperature in both stream fungi and bacteria
768 (Suberkropp & Weyers 1996). Significant changes may be detectable only after a substantial stream
769 warming (e.g. 10 °C). On the other hand, warming may interact with increased nutrient loads (due to
770 climate change or land use) exacerbating the effects on microbial communities and processes (Ferreira
771 & Chauvet 2011b). Climate induced increase in flood dynamics also may increase the export of detrital
772 material downstream. Thus, only little material may be left for decomposer consumption, which may
773 lead to food depletion especially for invertebrate shredders (Buzby & Perry 2000).

774

775 Due to their high diversity, microbes can be expected to have higher functional redundancy compared
776 to most other biotic groups (but see Mayfield et al. 2010). However, their communities consist of high
777 proportions of rare species, which may make microbial processes vulnerable to climate or land use
778 change because rare species can disproportionately increase functional diversity (Jousset et al. 2017,
779 Mouillot et al. 2013). If low temperatures become less important in constraining decomposition, others,
780 such as soil moisture and substrate quality, will become more important (Giardina & Ryan 2000).
781 Therefore, prioritizing the protection efforts on maintaining natural hydrological conditions and riparian
782 vegetation would benefit mitigation of climate change effects on streams and riparian zone microbial
783 related processes.

785 **5. Future research**

786 In the world of increasing anthropogenic impacts, we need to evaluate the state of habitats and to point
787 out the pressures threatening biodiversity and ecosystem functions of streams and riparian forests. In
788 order to be able to mitigate the harmful effects on ecosystems, research should focus on comparing
789 “what is there” to “what should there be”. This means, that the reference sites should represent the
790 natural state of the studied ecosystem as well as possible. As the footprint of anthropogenic actions can
791 be nowadays seen everywhere on the Earth, researchers must define what is “a pristine enough”
792 reference site to cover their study questions. For example, in Finland, almost all forests have been clear-
793 cut at some point of history, and even if not recently clear-cut (e.g. 100 years), they often have been
794 partially harvested and/or their drainage basin has been ditched. Furthermore, climate crisis is now
795 affecting all ecosystems around the world, thus we must accept that our new “reference” is forced
796 under anthropogenic pressure. From conservation point of view, “what should there be” may also refer
797 to future conditions rather than the past. Should we aim to protect the species and habitats as they
798 have occurred before human interventions or should we conserve and restore for the future (Choi et al.
799 2008)? If the latter is the aim, long-term ecological studies (“knowledge of the past”) may be needed to
800 set future conservation goals (Willis et al. 2007).

801

802 Furthermore, headwater streams are often highly variable, and soil and forest types differ according to
803 the geographical and topographical position. Thus, it can be difficult to control for among stream
804 variation in statistical tests and interpretation of results. Studies focusing on biodiversity are needed to
805 detect the effects of land management along riparian corridors and streams. Both qualitative and
806 quantitative criteria should be used to evaluate biodiversity. Including multiple biological groups may
807 enhance the detection of responses that can be seen in some organism groups but not the others
808 (Mykrä et al. 2017, Annala et al. 2014, Williams et al. 2014). In addition, beta diversity should be
809 included in biodiversity studies, but with a caution because habitat fragmentation or degradation may

810 lead to increased beta diversity (Mykrä et al. 2017, Hawkins et al. 2015). We now draw together main
811 gaps in knowledge on riparian ecosystems that call for future research (Table 1.).

812

813 The interaction between terrestrial and aquatic microbiome is poorly understood. Deep understanding
814 of circulation of energy and substances requires detailed knowledge of the interaction of different
815 microbial processes. The role of endophytic fungi and bacteria on decomposition in streams should be
816 studied more carefully. For example, the functional potential of decomposer microbes, including
817 prokaryotes and eukaryotes, and the impact of interactions between fungi and bacteria on
818 decomposition deserve further attention. Research would benefit from studying fungi and bacteria
819 simultaneously, because responses may be detectable in one group but not the other and interaction
820 between fungi and bacteria likely affect their functioning but are poorly understood. Environmental
821 filtering strongly determines microbial community composition, and co-occurrence patterns among
822 microbial groups are weak (Mykrä et al. 2017, Williams et al. 2014), which further emphasizes the
823 importance of including multiple biological groups in studies. Furthermore, some microbial groups, such
824 as archaea and fungi (e.g. Horner-Devine et al. 2007), are underrepresented in ecological studies and
825 the relationship between riparian and stream microbial communities is still imperfectly understood.
826 Simultaneous research on aquatic and terrestrial communities is necessary to understand the diversity
827 and functioning of and the linkage between streams and riparian forests.

828

829 Riparian forests often contribute to OM cycling (McClain et al. 2003) and storage (Sutfin et al. 2016,
830 Hazlett et al. 2015, Jaramillo et al. 2003) relatively more than upland forest. Further research is needed
831 on how preserving stream flooding regimes, groundwater discharge and natural vegetation contribute
832 on maintaining OM cycling on riparian zone. Also, most brownification studies are from lakes, and
833 effects of brownification on lotic waters should thus be studied. As drainage ditching is a common
834 practice in peatland-dominated forests, a question rises whether nutrient loads due to intensive
835 drainage ditching at an upstream site can impact riparian diversity at downstream sites, if floods pass

836 nutrients to riparian forest. Furthermore, as the studies on the sensitivity of riparian zones towards
837 disturbances are scarce and inconsistent, more research is needed to clarify the sensitivity of riparian
838 zones to human disturbance and their importance as dispersal corridors (Gundersen et al. 2010).

839

840 The effect of habitat-specific microbial communities on OM decomposition and nutrient cycling
841 deserves further studying. Especially fungi are an understudied group. Different fungal guilds have
842 differing functional potential, which can be studied with novel sequencing techniques and applying
843 analysis tools such as FUNGuild (Nguyen et al. 2016; and correspondingly PICRUSt2 for bacteria, Douglas
844 et al. 2019; see Box 1.). For example, ectomycorrhizal fungi may compete for N with free-living
845 decomposer microbes decreasing C cycling rate (Averill & Hawkes 2016) and increasing soil C storage
846 (Averill et al. 2014, Orwin et al. 2011). Also, fungi have greater potential for stocking C in their biomass
847 than bacteria (Godbold et al. 2006) and they are considered the main decomposers in aquatic
848 ecosystems (Fabian et al. 2017). Functional potential (DNA-based) and activity (RNA-based) of stream-
849 riparian microbiome can be studied, for example, with metatranscriptomics and metagenomics,
850 respectively (see Box 1.). However, if the aim is to study the active fraction of microbiome, relic DNA
851 should be taken into consideration when planning the sampling and analyses. Relic DNA, which can exist
852 in high amounts in soil (Fierer et al. 2017, Carini et al. 2016), can obscure the detection of active vs.
853 inactive microbes. Thus, it should be removed from the samples or optionally RNA-based methods can
854 be used instead or together with DNA-based methods.

855

856 Preserving shading vegetation in the riparian zone could be one way to prevent warming of surface
857 waters by maintaining shading trees and shrubs near streams and around groundwater discharge spots.
858 Almost every permanent stream is somewhat dependent on groundwater hydrologically (Boulton &
859 Hancock 2006), but groundwater discharge is also important for riparian diversity (Jansson et al. 2007,
860 Zinko et al. 2005). However, the role of groundwater in mitigating harmful effects of forest harvesting,
861 climate change and their interactions call for further research (Dwire et al. 2018).

862

863 While the importance of riparian forest to species diversity of many organism groups is relatively well
864 established, there are many biological groups uncovered. What is the meaning of riparian zones to
865 mammals, reptiles, frogs, insects, mollusks, fungi, bacteria and others and how does forest management
866 affect them? The implementation of forest buffers is still a question of debate: how should they be
867 planned and what management practices can or cannot be conducted in or near them if the aim is to
868 protect the riparian ecosystem as well as the stream? It is not clear how riparian zones respond to
869 different kinds of anthropogenic pressures, interactions of stressors, and which aspects of biological
870 diversity are most sensitive or resistant towards disturbances. And further, how sensitive are different
871 kinds of riparian zones to anthropogenic pressures and what kind of protection do they need?
872 Addressing these questions would further help the development of better forest management practices
873 that consider simultaneously the protection of the streams and their riparian forests.

874

875

876 Table 1. Future research needs concerning streams and their riparian forests, and the interaction of the two.

Ecosystem	Subject	Specific research question/approach
Streams	Ecosystem functions	Role of endophytic micro-organisms in aquatic decomposition and underlying mechanisms
	Ecosystem functions and diversity	Symbiosis of differing microorganism groups in aquatic decomposition Effects of brownification
Stream-riparian linkage	Diversity and ecosystem functions	Reciprocal exploration of aquatic and terrestrial communities: e.g. to what extent does terrestrial microbial diversity drive the diversity and ecosystem functions of streams and vice versa?
		Variation in beta diversity and community composition
		Importance of functional and phylogenetic diversity
Riparian forest	Diversity	Combined effect of drainage ditching and flooding on riparian diversity
		Sensitivity to human induced disturbance
		Sensitivity of headwater riparian forests to invasions by alien species
		Effect of forest management practices (buffer widths, selective logging on upland and riparian forests, continuous cover forestry)
		Importance for regional diversity (especially for groups other than birds and plants)
	Ecosystem functions	Contribution of flooding on carbon cycling
		Contribution of groundwater discharge on carbon cycling
		Contribution of natural vs. non-natural vegetation on carbon cycling
		The stability of biochemical processes in the riparian zone compared to upland forest
	Other ecological relevance	Meaning of headwater riparian forests as dispersal corridors

877

878

879 **Declaration of Competing Interest**

880 The authors declare that they have no known competing financial interests or personal relationships

881 that could have appeared to influence the work reported in this paper.

882

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886

887 **Literature**

888

889 Acuña, V., Wolf, A., Uehlinger, U. & Tockner, K. 2008. Temperature dependence of stream benthic
890 respiration in an Alpine river network under global warming. *Freshwater Biology* 53: 2076-2088.

891 <https://doi.org/10.1111/j.1365-2427.2008.02028.x>

892

893 Aerts, R. & Chapin III, F.S. 1999. The mineral nutrition of wild plants revisited: a re-evaluation of
894 processes and patterns. *Advances in Ecological Research* 30: 1-67. <https://doi.org/10.1016/S0065->

895 [2504\(08\)60016-1](https://doi.org/10.1016/S0065-2504(08)60016-1)

896

897 Allard, G., Buffin-Bélanger, T. & Bergeron, N. 2011. Analysis of frazil ice as a geomorphic agent in a frazil
898 pool. *River Research and Applications* 27: 1136-1148. <https://doi.org/10.1002/rra.1490>

899

900 Amend, A.S., Martiny, A.C., Allison, S.D., Berlemont, R., Goulden, M.L., Lu, Y., Treseder, K.K., Weihe, C. &
901 Martiny, J.B.H. 2016. Microbial response to simulated global change is phylogenetically conserved and
902 linked with functional potential. *The ISME Journal* 10: 109-118. <https://doi.org/10.1038/ismej.2015.96>

903

904 Ament, R., Callahan, R., McClure, M. Reuling, M. & Tabor, G. 2014. *Wildlife Connectivity: Fundamentals*
905 *for Conservation Action*. Center for Large Landscape Conservation. Bozeman, Montana.

906 <https://doi.org/10.13140/RG.2.1.3958.0561>

907

908 Anderson, M.J., Crist, T.O., Chase, J.M., Vellend, M. , Inouye, B.D., Freestone, A.L., Sanders, N.J., Cornell,
909 H.V., Comita, L.S., Davies, K.F., Harrison, S.P., Kraft, N.J., Stegen, J.C. & Swenson, N.G. 2011. Navigating
910 the multiple meanings of β diversity: a roadmap for the practicing ecologist. *Ecology Letters* 14: 19-28.

911 <https://doi.org/10.1111/j.1461-0248.2010.01552.x>

912

913 Annala, M., Mykrä, H., Tolkkinen, M., Kauppila, T. & Muotka, T. 2014. Are biological communities in
914 naturally unproductive streams resistant to additional anthropogenic stressors? *Ecological Applications*
915 24: 1887-1897. <https://doi.org/10.1890/13-2267.1>
916

917 Astorga, A., Heino, J., Luoto, M. & Muotka, T. 2011. Freshwater biodiversity at regional extent:
918 determinants of macroinvertebrate taxonomic richness in headwater streams. *Ecography* 34: 705-713.
919 <https://doi.org/10.1111/j.1600-0587.2010.06427.x>
920

921 Averill, C., Turner, B.L. & Finzi, A.C. 2014. Mycorrhiza-mediated competition between plants and
922 decomposers drives soil carbon storage. *Nature* 505: 543-545. <https://doi.org/10.1038/nature12901>
923

924 Averill, C. & Hawkes, C.V. 2016. Ectomycorrhizal fungi slow soil carbon cycling. *Ecology letters* 19: 937-
925 947. <https://doi.org/10.1111/ele.12631>
926

927 Bapiri, A., Bååth, E. & Rousk, J. 2010. Drying-rewetting cycles affect fungal and bacterial growth
928 differently in an arable soil. *Microbial Ecology* 60: 419-428. <https://doi.org/10.1007/s00248-010-9723-5>
929

930 Baggs, E.M. 2011. Soil microbial sources of nitrous oxide: recent advances in knowledge, emerging
931 challenges and future direction. *Current Opinion in Environmental Sustainability* 3: 321-327.
932 <https://doi.org/10.1016/j.cosust.2011.08.011>
933

934 Balmford, A., Bruner, A., Cooper, P., Costanza, R., Farber, S., Green, R. E., Jenkins, M., Jefferiss, P.,
935 Jessamy, V., Madden, J., Munro, K., Myers, N., Naeem, S., Paavola, J., Rayment, M., Rosendo, S.,
936 Roughgarden, J., Trumper, K. & Turner, R. K. 2002. Economic reasons for conserving wild nature. *Science*
937 297: 950-953. <https://doi.org/10.1126/science.1073947>
938

939 Bardgett, R.D., Anderson, J.M., Behan-Pelletier, V., Brussaard, L., Coleman, D.C., Ettema, C., Moldenke,
940 A., Schimel, J.P. & Wall, D.H. 2001. The influence of soil biodiversity on hydrological pathways and the
941 transfer of materials between terrestrial and aquatic ecosystem. *Ecosystems* 4: 421-429.
942 <https://doi.org/10.1007/s10021-001-0020-5>
943
944 Bardgett, R.D. & Walker, L.R. 2004. Impact of colonizer plant species on the development of
945 decomposer microbial communities following deglaciation. *Soil Biology & Biochemistry* 36: 555-559.
946 <https://doi.org/10.1016/j.soilbio.2003.11.002>
947
948 Bartels, P., Cucherousset, J., Steger, K., Eklov, P., Tranvik, L.J. & Hillebrand, H. 2012. Reciprocal subsidies
949 between freshwater and terrestrial ecosystems structure consumer resource dynamics. *Ecology* 93:
950 1173-1182. <https://doi.org/10.1890/11-1210.1>
951
952 Baxter, C. V., Fausch, K. D. & Saunders, W. C. 2005. Tangled webs: reciprocal flows of invertebrate prey
953 link streams and riparian zones. *Freshwater Biology* 50: 201-220. [https://doi.org/10.1111/j.1365-](https://doi.org/10.1111/j.1365-2427.2004.01328.x)
954 [2427.2004.01328.x](https://doi.org/10.1111/j.1365-2427.2004.01328.x)
955
956 Beltaos, S. 2008. Progress in the study and management of river ice jams. *Cold Regions Science and*
957 *Technology* 51: 2-19. <https://doi.org/10.1016/j.coldregions.2007.09.001>
958
959 Benfield, E.F., Webster, J.R., Tank, J.L. & Hutchens, J.J. 2001. Long-term patterns in leaf breakdown in
960 streams in response to watershed logging. *International Review of Hydrobiology* 86: 467-474.
961 [https://doi.org/10.1002/1522-2632\(200107\)86:4/5<467::AID-IROH467>3.0.CO;2-1](https://doi.org/10.1002/1522-2632(200107)86:4/5<467::AID-IROH467>3.0.CO;2-1)
962

963 Bengtsson, J., Nilsson, S.G., Franc, A. & Menozzi, P. 2000. Biodiversity, disturbances, ecosystem function
964 and management of European forests. *Forest Ecology and Management* 132: 39-50.
965 [https://doi.org/10.1016/S0378-1127\(00\)00378-9](https://doi.org/10.1016/S0378-1127(00)00378-9)
966

967 Bennet, A.F. Nimmo, D.G. & Radford, J.Q. 2014. Riparian vegetation has disproportionate benefits for
968 landscape-scale conservation of woodland birds in highly modified environments. *Journal of Applied*
969 *Ecology* 51: 514-523. <https://doi.org/10.1111/1365-2664.12200>
970

971 Bergeron, Y., Harvey, B., Leduc, A. & Gauthier, S. 1999. Forest management guidelines based on natural
972 disturbance dynamics: Stand- and forest-level considerations. *The Forestry Chronicle* 75: 49-54.
973 <https://doi.org/10.5558/tfc75049-1>
974

975 Berggren, M., Laudon, H. & Jansson, M. 2009. Hydrological Control of Organic Carbon Support for
976 Bacterial Growth in Boreal Headwater Streams. *Microbial Ecology* 57: 170-178. <https://doi.org/doi:10.1007/s00248-008-9423-6>
977
978

979 Berlemont, R. & Martiny, A.C. 2016. Glycoside hydrolases across environmental microbial communities.
980 *PLoS Comput Biol* 12(12):e1005300. <https://doi.org/10.1371/journal.pcbi.1005300>
981

982 Besemer, K., Singer, G., Quince, C., Bertuzzo, E., Sloan, W. & Battin, T.J. 2013. Headwaters are critical
983 reservoirs of microbial diversity for fluvial networks. *Proceeding of the Royal Society*: B20131760.
984 <https://doi.org/10.1098/rspb.2013.1760>
985

986 Bishop, K., Buffam, I., Erlandsson, M., Fölster, J., Laudon, H., Seibert, J. & Temnerud, J. 2008. *Aqua*
987 *Incognita*: the unknown headwaters. *Hydrological Processes* 22: 1239-1242.
988 <https://doi.org/10.1002/hyp.7049>

989

990 Biswas, S.R. & Mallik, A.U. 2010. Disturbance effects on species diversity and functional diversity in
991 riparian and upland plant communities. *Ecology* 91: 28-35. <https://doi.org/10.1890/08-0887.1>

992

993 Blagodatskaya, E.V., Blagodatsky, S.A., Anderson, T.H. & Kuzyakov, Y. 2009. Contrasting effects of
994 glucose, living roots and maize straw on microbial growth kinetics and substrate availability in soil.
995 *European Journal of Soil Science* 60: 186e197. <https://doi.org/10.1111/j.1365-2389.2008.01103.x>

996

997 Blagodatskaya, E., Blagodatsky, S., Anderson, T.H. & Kuzyakov, Y. 2014. Microbial growth and carbon use
998 efficiency in the rhizosphere and root-free soil. *Plos One* 9: e93282.

999 <https://doi.org/10.1371/journal.pone.0093282>

1000

1001 Boothroyd, I.K.G., Quinn, J.M., Langer, E.R.L., Costley, K.J., Steward, G. 2004. Riparian buffers mitigate
1002 effects of pine plantation logging on New Zealand streams: 1. Riparian vegetation structure, stream
1003 geomorphology and periphyton. *Forest Ecology and Management* 197: 199-213.

1004 <https://doi.org/10.1016/j.foreco.2004.02.018>

1005

1006 Borga, P., Nilsson, M. & Tunlid, A. 1994. Bacterial communities in peat in relation to botanical
1007 composition as revealed by phospholipid fatty acid analysis. *Soil Biology and Biochemistry* 26: 841-848.

1008 [https://doi.org/10.1016/0038-0717\(94\)90300-X](https://doi.org/10.1016/0038-0717(94)90300-X)

1009

1010 Boulton, A.J. & Hancock, P.J. 2006. Rivers as groundwater-dependent ecosystems: a review of degrees of
1011 dependency, riverine processes and management implications. *Australian Journal of Botany* 54: 133-

1012 144. <https://doi.org/10.1071/BT05074>

1013

1014 Brenzinger, K., Kujala, K., Horn, M.A., Moser, G., Guillet, C., Kammann, C., Müller, C. & Braker, G. 2017.
1015 Soil condition rather than long-term exposure to elevated CO₂ affect soil microbial communities
1016 associated with N-cycling. *Frontiers in Microbiology* 8: 1976. <https://doi.org/10.3389/fmicb.2017.01976>
1017

1018 Brockett, B.F.T., Prescott, C.E. & Grayston, S.J. 2012. Soil moisture is the major factor influencing
1019 microbial community structure and enzyme activities across seven biogeoclimatic zones in western
1020 Canada. *Soil Biology & Biochemistry* 44: 9-20. <https://doi.org/10.1016/j.soilbio.2011.09.003>
1021

1022 Brosofske, K. D., Chen, J., Naiman, R. J. & Franklin, J. F. 1997. Harvesting effects on microclimatic
1023 gradients from small streams to uplands in Western Washington. *Ecological Applications* 7: 1188-1200.
1024 [https://doi.org/10.1890/1051-0761\(1997\)007\[1188:HEOMGF\]2.0.CO;2](https://doi.org/10.1890/1051-0761(1997)007[1188:HEOMGF]2.0.CO;2)
1025

1026 Brown, G. W. & Krygier, J. T. 1970. Effects of clear-cutting on stream temperature. *Water Resources*
1027 *Research* 6: 1133-1139. <https://doi.org/10.1029/WR006i004p01133>
1028

1029 Brown, G.W. 1973. The impact of timber harvest on soil and water resources. Extension Bulletin 827.
1030 Oregon State University Extension Service.
1031

1032 Bunn, S.E. & Hughes, J.M. 1997. Dispersal and recruitment in streams: evidence from genetic studies.
1033 *Journal of the North American Benthological Society* 16: 338–346. <https://doi.org/10.2307/1468022>
1034

1035 Buzby, K. M. & Perry, S. A. 2000. Modeling the potential effects of climate change on leaf pack
1036 processing in central Appalachian streams. *Canadian Journal of Fisheries and Aquatic Sciences* 57: 1773-
1037 1783. <https://doi.org/10.1139/f00-113>
1038

1039 Bååth, E. 1980. Soil fungal biomass after clear-cutting of a pine forest in central sweden. *Soil Biology and*
1040 *Biochemistry* 12: 495-500. [https://doi.org/10.1016/0038-0717\(80\)90086-3](https://doi.org/10.1016/0038-0717(80)90086-3)

1041

1042 Bååth, E., Frostegård, Å., Pennanen, T. & Fritze, H. 1995. Microbial community structure and pH
1043 response in relation to soil organic matter quality in wood-ash fertilized, clear-cut or burned coniferous
1044 forest soils. *Soil Biology and Biochemistry* 27: 229-240. [https://doi.org/10.1016/0038-0717\(94\)00140-V](https://doi.org/10.1016/0038-0717(94)00140-V)

1045

1046 Bååth, E., Frostegård, Å., Pennanen, T. & Fritze, H. 1999. Microbial community structure and pH response
1047 in relation to soil organic matter quality in wood-ash fertilized, clear-cut or burned coniferous forest
1048 soils. *Soil Biology and Biochemistry* 27: 229-240. [https://doi.org/10.1016/0038-0717\(94\)00140-V](https://doi.org/10.1016/0038-0717(94)00140-V)

1049

1050 Bärlocher, F. 1992. Community organization, in: Bärlocher, F. (Ed.), *The Ecology of Aquatic*
1051 *Hyphomycetes*. *Ecological Studies*, Vol. 94. Springer-Verlag, Berlin, pp. 38–76.

1052

1053 Cardinale, B.J., Palmer, M.A., Swan, C.M., Brooks, S. & Poff, N. L. 2002. The influence of substrate
1054 heterogeneity on biofilm metabolism in a stream ecosystem. *Ecology* 83: 412-422.
1055 [https://doi.org/10.1890/0012-9658\(2002\)083\[0412:TIOSHO\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2002)083[0412:TIOSHO]2.0.CO;2)

1056

1057 Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M.,
1058 Tilman, D., Wardle, D.A., Kinzig, A.P., Daily, G.C., Loreau, M., Grace, J.B., Larigauderie, A., Srivastava, D.S.
1059 & Naeem, S. 2012. Biodiversity loss and its impact on humanity. *Nature* 486: 59-67.
1060 <https://doi.org/10.1038/nature11148>

1061

1062 Carini, P., Marsden, P.J., Leff, J.W., Morgan, E.E., Strickland, M., and Fierer, N. 2017. Relic DNA is
1063 abundant in soil and obscures estimates of soil microbial diversity. *Nature Microbiology* 2: 16242.
1064 <https://doi.org/dx.doi.org/10.1101/043372>

1065

1066 Carney, K.M. & Matson, P.A. 2006. The influence of tropical plant diversity and composition on soil
1067 microbial communities. *Microbial Ecology* 52: 226-238. <https://doi.org/10.1007/s00248-006-9115-z>

1068

1069 Catford, J. A. & Jansson, R. 2014. Drowned, buried and carried away: effects of plant traits on the
1070 distribution of native and alien species in riparian ecosystems. *New Phytologist* 204: 19-36.
1071 <https://doi.org/10.1111/nph.12951>

1072

1073 Chen, H., Mothapo, N.V. & Shi, W. 2015. Soil moisture and pH control relative contributions of fungi and
1074 bacteria to N₂O production. *Microbial Ecology* 69: 180-191. <https://doi.org/10.1007/s00248-014-0488-0>

1075

1076 Choi, Y. D., Temperton, V. M., Allen, E. B., Grootjans, A. P., Halassy, M., Hobbs, R. J., Naeth M. A. &
1077 Torok, K. 2008. Ecological restoration for future sustainability in a changing environment. *Écoscience* 15:
1078 53-64. [https://doi.org/10.2980/1195-6860\(2008\)15\[53:ERFFSI\]2.0.CO;2](https://doi.org/10.2980/1195-6860(2008)15[53:ERFFSI]2.0.CO;2)

1079

1080 Clarke, A., Mac Nally, R., Bond, N. & Lake, P.S. 2008. Macroinvertebrate diversity in headwater streams:
1081 a review. *Freshwater Biology* 53: 1707-1721. <https://doi.org/10.1111/j.1365-2427.2008.02041.x>

1082

1083 Colpaert, J. V., Wevers, J. H. L., Krznicar, E. & Adriaensen, K. 2011. How metal-tolerant ecotypes of
1084 ectomycorrhizal fungi protect plants from heavy metal pollution. *Annals of Forest Science* 68: 17-24.
1085 <https://doi.org/10.1007/s13595-010-0003-9>

1086

1087 Connell, J.H. 1978. Diversity in Tropical Rain Forests and Coral Reefs. *Science* 199: 1302-1310.
1088 <https://doi.org/10.1126/science.199.4335.1302>

1089

1090 Cornut, J., Ferreira, V., Gonçalves, A.L., Chauvet, E. & Canhoto, C. 2015. Fungal alteration of the
1091 elemental composition of leaf litter affects shredder feeding activity. *Freshwater Biology* 60: 1755-1771.
1092 <https://doi.org/10.1111/fwb.12606>
1093
1094 Coûteaux, M.-M., Bottner, P. & Berg, B. 1995. Litter decomposition, climate and litter quality. *Trends in*
1095 *ecology and evolution* 10: 63-66. [https://doi.org/10.1016/S0169-5347\(00\)88978-8](https://doi.org/10.1016/S0169-5347(00)88978-8)
1096
1097 Darveau, M., Beauchesne, P., Bélanger, L., Huot, L. & Larue, P. 1995. Riparian forest strips as habitat for
1098 breeding birds in boreal forest. *The Journal of Wildlife Management* 59: 67-78.
1099 <https://doi.org/10.2307/3809117>
1100
1101 Davidson, E.A. & Janssens, I.A. 2006. Temperature sensitivity of soil carbon decomposition and feedback
1102 to climate change. *Nature* 440: 165-173. <https://doi.org/doi:10.1038/nature04514>
1103
1104 Dawson, J. J. C., Bakewell, C. & Billett, M. F. 2001. Is in-stream processing an important control on spatial
1105 changes in carbon fluxes in headwater catchments? *Science of The Total Environment* 265: 153-167.
1106 [https://doi.org/10.1016/S0048-9697\(00\)00656-2](https://doi.org/10.1016/S0048-9697(00)00656-2)
1107
1108 Dawson, J. J. C., Billett, M. F., Hope, D., Palmer, S. M. & Deacon, C. M. 2004 Sources and sinks of aquatic
1109 carbon in a peatland stream continuum. *Biochemistry* 70: 71-92.
1110 <https://doi.org/10.1023/B:BI0G.0000049337.66150.f1>
1111
1112 De Graaff, M.-A., Classen, A.T., Castro, H.F. & Schadt, C.W. 2010. Labile soil carbon inputs mediate the
1113 soil microbial community composition and plant residue decomposition rates. *New Phytologist* 188:
1114 1055-1064. <https://doi.org/10.1111/j.1469-8137.2010.03427.x>
1115

1116 Dore, M.H.I. 2005. Climate change and changes in global precipitation patterns: What do we know?
1117 Environmet International 31: 1167-1181. <https://doi.org/10.1016/j.envint.2005.03.004>
1118
1119 Douglas, G.M., Maffei, V.J., Zaneveld, J., Yurgel, S.N., Brown, J.R., Taylor, C.M., Huttenhower, C. &
1120 Langille, M.G. I. 2019. PICRUSt2: An improved and extensible approach for metagenome inference.
1121 BioRxiv: 672295. <https://doi.org/10.1101/672295>
1122
1123 Downing, J. A., Cole, J. J., Duarte, C. M., Middelburg, J. J., Melack, J. M., Prairie, Y. T., Kortelainen, P.,
1124 Striegl, R. G., McDowell, W. H. & Tranvik, L. J. 2012. Global abundance and size distribution of streams
1125 and rivers. Inland Waters 2: 229-236. <https://doi.org/10.5268/IW-2.4.502>
1126
1127 Dreyer, J., Townsend, P.A., Hook III, J.C., Hoekman, D., Vander Zanden, M.J. & Gratton, C. 2015.
1128 Quantifying aquatic insect deposition from lake to land. Ecology, 96: 499–509.
1129 <https://doi.org/10.1890/14-0704.1>
1130
1131 Dwire, K.A., Mellmann-Brown, S. & Gurrieri, J.T. 2018. Potential effects of climate change on riparian
1132 areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon USA. Climate
1133 Services 10: 44-52. <https://doi.org/10.1016/j.cliser.2017.10.002>
1134
1135 Dynesius, M., Hylander, K. & Nilsson, C. 2009. High resilience of bryophyte assemblages in streamside
1136 compared to upland forests. Ecology 90: 1042-1052. <https://doi.org/10.1890/07-1822.1>
1137
1138 Erdozain, M., Kidd, K., Kreutzweiser, D. & Sibley, P. 2019. Increased reliance of stream
1139 macroinvertebrates on terrestrial food sources linked to forest management intensity. Ecological
1140 Applications 29: e01889. <https://doi.org/10.1002/eap.1889>
1141

1142 Engström, J., Jansson, R., Nilsson, C. & Weber, C. 2011. Effects of river ice on riparian vegetation.
1143 *Freshwater Biology* 56: 1095-1105. <https://doi.org/10.1111/j.1365-2427.2010.02553.x>
1144
1145 England, L.E. & Rosemond, A.D. 2004. Small reductions in forest cover weaken terrestrial-aquatic
1146 linkages in headwater streams. *Freshwater Biology* 49: 721-734. <https://doi.org/10.1111/j.1365-2427.2004.01219.x>
1147
1148
1149 Eriksson, L. & Klapwijk, M.J. 2019. Attitudes towards biodiversity conservation and carbon substitution
1150 in forestry: a study of stakeholders in Sweden. *Forestry* 00: 1-11.
1151 <https://doi.org/10.1093/forestry/cpz003>
1152
1153 Evans, C.D., Monteith, D.T. & Cooper, D.M. 2005. Long-term increases in surface water dissolved organic
1154 carbon: Observations, possible causes and environmental impacts. *Environmental Pollution* 137: 55-71.
1155 <https://doi.org/10.1016/j.envpol.2004.12.031>
1156
1157 Fabian, J., Zlatanovic, S., Mutz, M., Premke, K. 2017. Fungal–bacterial dynamics and their contribution to
1158 terrigenous carbon turnover in relation to organic matter quality. *The ISME Journal* 11: 415-425.
1159 <https://doi.org/10.1038/ismej.2016.131>
1160
1161 Feminella, J.W., Power, M.E. & Resh, V.H. 1989. Periphyton responses to invertebrate grazing and
1162 riparian canopy in three northern California coastal streams. *Freshwater Biology* 22: 445-457.
1163 <https://doi.org/10.1111/j.1365-2427.1989.tb01117.x>
1164
1165 Fernandes, I., Pascoal, C., Guimarães, H., Pinto, R., Sousa, I. & Cássio, F. 2012. Higher temperature
1166 reduces the effects of litter quality on decomposition by aquatic fungi. *Freshwater Biology* 57: 2306-
1167 2317. <https://doi.org/10.1111/fwb.12004>

1168

1169 Fernandes, I., Duarte, S., Cássio, F. & Pascoal, C. 2013. Effects of riparian plant diversity loss on aquatic
1170 microbial decomposers become more pronounced with increasing time. *Microbial Ecology* 66: 763-772.
1171 <https://doi.org/10.1007/s00248-013-0278-0>

1172

1173 Ferreira, V. & Canhoto, C. 2015. Future increase in temperature may stimulate litter decomposition in
1174 temperate mountain streams: evidence from a stream manipulation experiment. *Freshwater Biology* 60:
1175 881-892. <https://doi.org/10.1111/fwb.12539>

1176

1177 Ferreira, V. & Chauvet, E. 2011a. Future increase in temperature more than decrease in litter quality can
1178 affect microbial litter decomposition in streams. *Oecologia* 167: 279-291.
1179 <https://doi.org/10.1007/s00442-011-1976-2>

1180

1181 Ferreira, V. & Chauvet, E. 2011b. Synergistic effects of water temperature and dissolved nutrients on
1182 litter decomposition and associated fungi. *Global Change Biology* 17: 551-564.
1183 <https://doi.org/10.1111/j.1365-2486.2010.02185.x>

1184

1185 Ferreira, V., Castagnyrol, B., Koricheva, J., Gulis, V., Chauvet, E. & Graça, A.S. 2015. A meta-analysis of
1186 the effects of nutrient enrichment on litter decomposition in streams. *Biological Reviews* 90: 669-688.
1187 <https://doi.org/10.1111/brv.12125>

1188

1189 Fiebig, D. M., Lock, M. A. & Neal, C. 1990. Soil water in the riparian zone as a source of carbon for a
1190 headwater stream. *Journal of Hydrology* 116: 217-237. [https://doi.org/10.1016/0022-1694\(90\)90124-G](https://doi.org/10.1016/0022-1694(90)90124-G)

1191

1192 Fierer, N. 2017. Embracing the unknown: disentangling the complexities of the soil microbiome. *Nature*
1193 *Reviews Microbiology* 15: 579–590. <https://doi.org/10.1038/nrmicro.2017.87>

1194

1195 Fierer, N., Strickland, M.S., Liptzin, D., Bradford, M.A. & Cleveland, C.C. 2009. Global patterns in
1196 belowground communities. *Ecology Letters* 12: 1238-1249. [https://doi.org/10.1111/j.1461-](https://doi.org/10.1111/j.1461-0248.2009.01360.x)
1197 [0248.2009.01360.x](https://doi.org/10.1111/j.1461-0248.2009.01360.x)

1198

1199 Flores, L., Larrañaga, A., Díez, J., Elosegi, A. 2011. Experimental wood addition in streams: effects on
1200 organic matter storage and breakdown. *Freshwater Biology* 56: 2156-2167.
1201 <https://doi.org/10.1111/j.1365-2427.2011.02643.x>

1202

1203 Fortsieri, G., Feyen, L., Rojas, R., Flörke, M., Wimmer, F. & Bianchi, A. 2013. Ensemble projections of
1204 future streamflow droughts in Europe. *Hydrology and Earth System Sciences Discussions* 10: 10719-
1205 10774. <https://doi.org/10.5194/hessd-10-10719-2013>

1206

1207 Franzosa, E.A., Hsu, T., Sirota-Madi, A., Shafquat, A., Abu-Ali, G., Morgan, X.C. & Huttenhower, C. 2015.
1208 Sequencing and beyond: integrating molecular 'omics' for microbial community profiling. *Nature*
1209 *Reviews Microbiology* 13: 360-372. <https://doi.org/10.1038/nrmicro3451>

1210

1211 Freeman, M.C., Pringle, C.M. & Jackson, C.R. 2007. Hydrologic connectivity and the contribution of
1212 stream headwaters to ecological integrity at regional scales. *Journal of the American Water Resources*
1213 *Association* 43: 5-14. <https://doi.org/10.1111/j.1752-1688.2007.00002.x>

1214

1215 Frey, B., Stemmer, M., Widmer, F., Luster, J. & Sperisen, C. 2006. Microbial activity and community
1216 structure of a soil after heavy metal contamination in a model forest ecosystem. *Soil Biology and*
1217 *Biochemistry* 38: 1745-1756. <https://doi.org/10.1016/j.soilbio.2005.11.032>

1218

1219 Gannon, J. P., Bailey, S. W., McGuire, K. J. & Shanley, J. B. 2015. Flushing of distal hillslopes as an
1220 alternative source of stream dissolved organic carbon in a headwater catchment. *Water Resources*
1221 *Research* 51: 8114-8128. <https://doi.org/10.1002/2015WR016927>
1222

1223 Garsen, A.G., Baattrup-Pedersen, A., Voesenek, L.A.C.J., Verhoeven, J.T.A. & Soons, M.B. 2015. Riparian
1224 plant community responses to increased flooding: a meta-analysis. *Global Change Biology* 21: 2881-
1225 2890. <https://doi.org/10.1111/gcb.12921>
1226

1227 Gessner, M.O., Chauvet, E. & Dobson, M. 1999. A perspective on leaf litter breakdown in streams. *Oikos*
1228 85: 377-384. <https://www.jstor.org/stable/3546505>
1229

1230 Giardina, C.P. & Ryan, M.G. 2000. Evidence that decomposition rates of organic carbon in mineral soil do
1231 not vary with temperature. *Nature* 404: 858-861. <https://doi.org/10.1038/35009076>
1232

1233 Godbold, D.L., Hoosbeek, M.R., Lukac, M., Cotrufo, M.F., Janssens, I.A., Ceulemans, R., Polle, A.,
1234 Velthorst, E.J., Scarascia-Mugnozza, G., De Angelis, P., Miglietta, F. & Peressotti, A. 2006. Mycorrhizal
1235 hyphal turnover as a dominant process for carbon input into soil organic matter. *Plant and Soil* 281: 15-
1236 24. <https://doi.org/10.1007/s11104-005-3701-6>
1237

1238 Gomi, T., Sidle, R.C. & Richardson, J.S. 2002. Understanding processes and downstream linkages of
1239 headwater systems: Headwaters differ from downstream reaches by their close coupling to hillslope
1240 processes, more temporal and spatial variation, and their need for different means of protection from
1241 land use. *BioScience* 52: 905-916.
1242

1243 Goodroad, L.L. & Keeney, D.R. 1984. Nitrous oxide emissions from soils during thawing. *Canadian*
1244 *Journal of Soil Sciences* 64: 187-194. <https://doi.org/10.4141/cjss84-020>

1245

1246 Graça, M.A.S. 2011. The role of invertebrates on leaf litter decomposition in streams – a review.

1247 Hydrobiologia 86: 383-393. [https://doi.org/10.1002/1522-2632\(200107\)86:4/5<383::AID-](https://doi.org/10.1002/1522-2632(200107)86:4/5<383::AID-)

1248 IROH383>3.0.CO;2-D

1249

1250 Gratton, C. & Vander Zanden, M.J. 2009. Flux of aquatic insect productivity to land: comparison of lentic

1251 and lotic ecosystems. Ecology 90: 2689–2699. <https://doi.org/10.1890/08-1546.1>

1252

1253 Groffman, P.M., Driscoll, C.T., Fahey, T.J., Hardy, J.P., Fitzhugh, R.D. & Tierney, G.L. 2001. Colder soils in a

1254 warmer world: A snow manipulation study in a northern hardwood forest ecosystem. Biochemistry: 56:

1255 135-150. <https://doi.org/10.1023/A:1013039830323>

1256

1257 Groffman, P.M., Hardy, J.P, Driscoll, C.T. & Fahey, T.J. 2006. Snow depth, soil freezing, and fluxes of

1258 carbon dioxide, nitrous oxide and methane in a northern hardwood forest. Global Change Biology 12:

1259 1748-1760. <https://doi.org/10.1111/j.1365-2486.2006.01194.x>

1260

1261 Grossart, H.-P. & Rojas-Jimenez, K. 2016. Aquatic fungi: targeting the forgotten in microbial ecology.

1262 Current Opinion in Microbiology 31: 140-145. <https://doi.org/10.1016/j.mib.2016.03.016>

1263

1264 Gundersen, P., Laurén, A., Finér, L., Ring, E., Koivusalo, H., Sætersdal, M., Weslien, J.-O., Sigurdsson, B.D.,

1265 Högbom, L., Laine, J. & Hansen, K. 2010. Environmental services provided from the riparian forests in the

1266 Nordic countries. Ambio. DOI: 10.1007/s13280-010-0073-9.

1267

1268 Gustafsson, P. 2011. Forest – stream linkages: Brown trout (*Salmo trutta*) responses to woody debris,

1269 terrestrial invertebrates and light. Dissertation. Faculty of Social and Life Sciences, Department of

1270 Biology, Karlstad University Studies. diva2:387321

1271

1272 Haaland, S., Hongve, D., Laudon, H., Riise, G. & Vodt, R.D. 2010. Quantifying the drivers of the increasing
1273 colored organic matter in boreal surface waters. *Environmental Science & Technology* 44: 2975-2980.
1274 <https://doi.org/10.1021/es903179j>

1275

1276 Haei, M., Rousk, J., Ilstedt, U., Öquist, M., Bååth, E & Laudon, H. 2011. Effects of soil frost on growth,
1277 composition and respiration of the soil microbial decomposer community. *Soil Biology and Biochemistry*
1278 43: 2069-2077. <https://doi.org/10.1016/j.soilbio.2011.06.005>

1279

1280 Hagerman, S.M., Jones, M.D., Bradfield, G.E., Gillespie, M. & Durall, D.M. 1999. Effects of clear-cut
1281 logging on the diversity and persistence of ectomycorrhizae at a subalpine forest. *Canadian Journal of*
1282 *Forest Research* 29: 124-134. <https://doi.org/10.1139/x98-186>

1283

1284 Hallmann, C.A., Sorg, M. Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A.,
1285 Sumser, H., Hörren, T., Goulson, D. & de Kroon, H. 2017. More than 75 percent decline over 27 years in
1286 total flying insect biomass in protected areas. *PLoS ONE* 12: e0185809.
1287 <https://doi.org/10.1371/journal.pone.0185809>

1288

1289 Hasselquist, E.M., Lidberg, W., Sponseller, R.A., Ågren, A. & Laudon, H. 2017. Identifying and assessing
1290 the potential hydrological function of past artificial forest drainage. *Ambio*.
1291 <https://doi.org/10.1007/s13280-017-0984-9>.

1292

1293 Hassett, J. E. & Zak, D. R. 2005. Aspen harvest intensity decreases microbial biomass, extracellular
1294 enzyme activity, and soil nitrogen cycling. *Soil Science Society of America Journal* 69: 227-235.

1295

1296 Hawkins, C.P., Murphy, M.L. & Anderson, N.H. 1982. Effects of canopy, substrate composition, and
1297 gradient on the structure of macroinvertebrate communities in Cascade Range streams of Oregon.
1298 Ecology 63: 1840-1856. <https://doi.org/10.2307/1940125>
1299

1300 Hawkins, C.P., Mykrä, H., Oksanen, J. & Vander Laan, J.J. 2015. Environmental disturbance can increase
1301 beta diversity of stream macroinvertebrate assemblages. Global Ecology and Biogeography 24: 483-494.
1302 <https://doi.org/10.1111/geb.12254>
1303

1304 Hayden, B. , Harrod, C. , Thomas, S.M., Eloranta, A.P., Myllykangas, J. , Siwertsson, A. , Præbel, K. ,
1305 Knudsen, R. , Amundsen, P. & Kahilainen, K.K. 2019. From clear lakes to murky waters – tracing the
1306 functional response of high-latitude lake communities to concurrent ‘greening’ and ‘browning’.
1307 Ecological Letters 22: 807-816. <https://doi.org/10.1111/ele.13238>
1308

1309 Hazlett, P.W., Gordon, A.M., Dibley, P.K. & Nuttle, J.M. 2005. Stand carbon stocks and soil carbon and
1310 nitrogen storage for riparian and upland forests of boreal lakes in northeast Ontario. Forest Ecology and
1311 Management 219: 56-68. <https://doi.org/10.1016/j.foreco.2005.08.044>
1312

1313 Hedin, L.O., von Fischer, J.C., Ostrom, N.E., Kennedy, B.P., Brown, M.G. & Robertson, G.P. 1998.
1314 Thermodynamic constraints on nitrogen transformations and other biogeochemical processes at soil-
1315 stream interfaces. Ecology 79: 684-703.
1316

1317 Hedström, P., Bystedt, D., Karlsson, J., Bokma, F. & Byström, P. 2017. Brownification increases winter
1318 mortality in fish. Oecologia 183: 587-595.
1319

1320 Heino, J., Virkkala, R. & Toivonen, H. 2009. Climate change and freshwater biodiversity: detected
1321 patterns, future trends and adaptations in northern regions. *Biological Reviews* 84: 39-54.
1322 <https://doi.org/10.1111/j.1469-185X.2008.00060.x>
1323

1324 Heino, J., Melo, A.S., Siqueira, T., Soininen, J., Valanko, S. & Bini, L.M. 2015. Metacommunity
1325 organisation, spatial extent and dispersal in aquatic systems: patterns, processes and prospects.
1326 *Freshwater Biology* 60: 845-869. <https://doi.org/10.1111/fwb.12533>
1327

1328 Heino, J., Alahuhta, J., Ala-Hulkko, T., Antikainen, H., Bini, L.M., Bonada, N., Datry, T., Erős, T., Hjort, J.,
1329 Kotavaara, O., Melo, A.S. & Soininen, J. 2017. Integrating dispersal proxies in ecological and
1330 environmental research in the freshwater realm. *Environmental Reviews* 25: 334-349.
1331 <https://doi.org/10.1139/er-2016-0110>
1332

1333 Hérault, B. & Honnay, O. 2005. The relative importance of local, regional and historical factors
1334 determining the distribution of plants in fragmented riverine forests: an emergent group approach.
1335 *Journal of Biogeography* 32: 2069-2081. <https://doi.org/10.1111/j.1365-2699.2005.01351.x>
1336

1337 Hieber, M. & Gessner, M.O. 2002. Contribution of stream detritivores, fungi, and bacteria to leaf
1338 breakdown based on biomass estimates. *Ecology* 83: 1026–1038. [https://doi.org/10.1890/0012-9658\(2002\)083\[1026:COSEFA\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2002)083[1026:COSEFA]2.0.CO;2)
1339
1340

1341 Hildebrandt, U., Regvar, M. & Bothe, H. 2007. Arbuscular mycorrhiza and heavy metal tolerance.
1342 *Phytochemistry* 68: 139-146. <https://doi.org/10.1016/j.phytochem.2006.09.023>
1343

1344 Hill, A.R. 1996. Nitrate removal in stream riparian zone. *Journal of Environmental Quality* 25: 743-755.
1345 <https://doi.org/10.2134/jeq1996.00472425002500040014x>

1346

1347 Hill, A.R., Devito, K.J., Camagnolo, S. & Sanmugadas, K. 2000. Subsurface denitrification in a forest
1348 riparian zone: Interactions between hydrology and supplies of nitrate and organic carbon.
1349 *Biogeochemistry* 51: 193-223. <https://doi.org/10.1023/A:1006476514038>

1350

1351 Hogsden, K. L. & Harding, J. S. 2012. Anthropogenic and natural sources of acidity and metals and their
1352 influence on the structure of stream food webs. *Environmental Pollution* 162: 466-474.
1353 <https://doi.org/10.1016/j.envpol.2011.10.024>

1354

1355 Horner-Devine, M.C., Silver, J.M., Leibold, M.A., Bohannon, B.J.M., Colwell, R.K., Fuhrman, J.A., Green,
1356 J.L., Kuske, C.R., Martiny, J.B., Muyzer, G., Øvreås, L., Reysenbach, A.-L. & Smith, V.H. 2007. A
1357 comparison of taxon co-occurrence patterns for macro- and microorganisms. *Ecology* 88: 1345-1353.
1358 <https://doi.org/10.1890/06-0286>

1359

1360 Hughes, A.R., Inouye, B.D., Johnson, M.T.J., Underwood, N. & Vellend, M. 2008. Ecological consequences
1361 of genetic diversity. *Ecology Letters* 11: 609-623. <https://doi.org/10.1111/j.1461-0248.2008.01179.x>

1362

1363 Huston, M.A. 2014. Disturbance, productivity, and species diversity: empiricism vs. logic in ecological
1364 theory. *Ecology* 95: 2382-2396. <https://doi.org/10.1890/13-1397.1>

1365

1366 Hylander, K., Dynesius, M., Jonsson, B.G. & Nilsson, C. 2005. Substrate form determines the fate of
1367 bryophytes in riparian buffer strips. *Ecological Applications*, 15: 674-688. [https://doi.org/10.1890/04-](https://doi.org/10.1890/04-0570)
1368 0570

1369

1370 Hylander, K., Nilsson, C. & Göthner, T. 2004. Effects of buffer-strip retention and clearcutting on land
1371 snail in boreal riparian forests. *Conservation Biology* 18: 1052-1062. [https://doi.org/10.1111/j.1523-](https://doi.org/10.1111/j.1523-1739.2004.00199.x)
1372 [1739.2004.00199.x](https://doi.org/10.1111/j.1523-1739.2004.00199.x)
1373
1374 Hynes, H. M. & Germida, J. J. 2013. Impact of clear cutting on soil microbial communities and
1375 bioavailable nutrients in the LFH and Ae horizons of Boreal Plain forest soils. *Forest Ecology &*
1376 *Management* 306: 88-95. <https://doi.org/10.1016/j.foreco.2013.06.006>
1377
1378 Högberg, M.N., Högberg, P. & Myrold, D.D. 2007. Is microbial community composition in boreal forest
1379 soils determined by pH, C-to-N ratio, the trees, or all three? *Oecologia* 150: 590-601.
1380 <https://doi.org/10.1007/s00442-006-0562-5>
1381
1382 Inoue, M., Sakamoto, S. & Kikuchi, S. 2013. Terrestrial prey inputs to streams bordered by deciduous
1383 broadleaved forests, conifer plantations and clear-cut sites in southwestern Japan: effects on the
1384 abundance of red-spotted masu salmon. *Ecology of Freshwater Fish* 22: 335-347.
1385 <https://doi.org/10.1111/eff.12029>
1386
1387 IPCC 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the*
1388 *Fifth Assessment Report of the Intergovernmental Panel on Climate Change / R. Pachauri and L. Meyer*
1389 *(Eds.)*, Geneva, Switzerland, IPCC, 151 p., ISBN: 978-92-9169-143-2.
1390 <https://epic.awi.de/id/eprint/37530/>
1391
1392 Izagirre, O., Serra, A., Guasch, H. & Elosegui, A. 2009. Effects of sediment deposition on periphytic
1393 biomass, photosynthetic activity and algal community structure. *Science of The Total Environment* 407:
1394 5694-5700. <https://doi.org/10.1016/j.scitotenv.2009.06.049>
1395

1396 Jansson, R., Nilsson, C. & Renöfält, B. 2000. Fragmentation of riparian floras in rivers with multiple dams.
1397 Ecology 81: 899-903. [https://doi.org/10.1890/0012-9658\(2000\)081\[0899:FORFIR\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2000)081[0899:FORFIR]2.0.CO;2)
1398
1399 Jansson, R., Zinko, U., Merritt, D.M. & Nilsson, C. 2005. Hydrochory increases riparian plant species
1400 richness: a comparison between a free-flowing and a regulated river. Journal of Ecology 93: 1094-1103.
1401 <https://doi.org/10.1111/j.1365-2745.2005.01057.x>
1402
1403 Jansson, R., Laudon, H., Johansson, E. & Augspurger, C. 2007. The importance of groundwater discharge
1404 for plant species number in riparian zones. Ecology 88: 131–139. [https://doi.org/10.1890/0012-9658\(2007\)88\[131:TIOGDF\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2007)88[131:TIOGDF]2.0.CO;2)
1405
1406
1407 Jaramillo, V.J., Kauffman, J.B., Rentería-Rodríguez, L., Cummings, D.L. & Ellingson, L.J. 2003. Biomass,
1408 carbon, and nitrogen pools in Mexican tropical dry forest landscape. Ecosystems 6: 609-629.
1409 <https://doi.org/10.1007/s10021-002-0195-4>
1410
1411 Jarvis, P., Rey, A., Petsikos, C., Wingate, L., Rayment, M., Pereira, J., Banza, J., David, J., Miglietta, F.,
1412 Borghetti, M., Manca, G. & Valentini, R. 2007. Drying and wetting of Mediterranean soils stimulates
1413 decomposition and carbon dioxide emission: the “Birch effect”. Tree Physiology 27: 929-940.
1414 <https://doi.org/10.1093/treephys/27.7.929>
1415
1416 Joensuu, S., Ahti, E. & Vuollekoski, M. 2002. Effects of ditch network maintenance on the chemistry of
1417 run-off water from peatland forests. Scandinavian Journal of Forest Research 17: 238-247.
1418 <https://doi.org/10.1080/028275802753742909>
1419
1420 Johansson, M.E., Nilsson, C. & Nilsson, E. 1996. Do rivers function as corridors for plant dispersal?
1421 Journal of Vegetation Science 7: 593-598. <https://doi.org/10.2307/3236309>

1422

1423 Johnson, B.R., Cross, W.F. & Wallace J.B. 2003. Long-term resource limitation reduces insect detritivore
1424 growth in a headwater stream. *Journal of the North American Benthological Society* 22: 565-574.
1425 <https://doi.org/10.2307/1468353>

1426

1427 Jonsson, L., Dahlberg, A., Nilsson, M.-C., Zackrisson, O. & Kåren, O. 1999. Ectomycorrhizal fungal
1428 communities in late-successional Swedish boreal forests, and their composition following wildfire.
1429 *Molecular Ecology* 8: 205-215. <https://doi.org/10.1046/j.1365-294x.1999.00553.x>

1430

1431 Jousset, A., Bienhold, C., Chatzinotas, A., Gallien, L., Gobet, A., Kurm, V., Küsel, K., Rilling, M. C., Rivett, D.
1432 W., Salles, J. F., van der Heijden, M. G. A., Youssef, N. H., Zhang, X., Wei, Z. & Hol, W. H. G. 2017. Where
1433 less may be more: how the rare biosphere pulls ecosystems strings. *The ISME Journal* 11: 853-862.
1434 <https://doi.org/10.1038/ismej.2016.174>

1435

1436 Judd, K.E., Crump, B.C. & Kling, G., W. 2006. Variation in dissolved organic matter controls bacterial
1437 production and community composition. *Ecology* 87: 2068-2079. [https://doi.org/10.1890/0012-9658\(2006\)87\[2068:VIDOMC\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2006)87[2068:VIDOMC]2.0.CO;2)

1439

1440 Khan, A. G., Kuek, C., Chaudhry, T. M., Khoo, C. S. & Hayes, W. J. 2000. Role of plants, mycorrhizae and
1441 phytochelators in heavy metal contaminated land remediation. *Chemosphere* 41: 197-207.
1442 [https://doi.org/10.1016/S0045-6535\(99\)00412-9](https://doi.org/10.1016/S0045-6535(99)00412-9)

1443

1444 Kiffney, P.M., Richardson, J.S. & Bull, J.P. 2004. Establishing light as a causal mechanism structuring
1445 stream communities in response to experimental manipulation of riparian buffer width. *Journal of North*
1446 *American Benthological Society* 23: 542–555. [https://doi.org/10.1899/0887-3593\(2004\)023<0542:ELAACM>2.0.CO;2](https://doi.org/10.1899/0887-3593(2004)023<0542:ELAACM>2.0.CO;2)

1448

1449 Killham, K. & Firestone, M. K. 1983. Vesicular arbuscular mycorrhizal mediation of grass response to
1450 acidic and heavy metal depositions. *Plant and Soil* 72: 39-48. <https://doi.org/10.1007/BF02185092>

1451

1452 Kirschbaum, M.U.F. 2006. The temperature dependence of organic-matter decomposition – still a topic
1453 of debate. *Soil Biology & Biochemistry* 38: 2510-2518. <https://doi.org/10.1016/j.soilbio.2006.01.030>

1454

1455 Knight, R., Vrbanac, A., Taylor, B.C., Aksenov, A., Callewaert, C., Debelius, J., et al. 2018. Best practices
1456 for analysing microbiomes. *Nature Reviews Microbiology* 16: 410-422. [https://doi.org/10.1038/s41579-](https://doi.org/10.1038/s41579-018-0029-9)
1457 [018-0029-9](https://doi.org/10.1038/s41579-018-0029-9)

1458

1459 Koide, K., Osonoro, T. & Takeda, H. 2005. Colonization and lignin decomposition of *Camellia japonica*
1460 leaf litter by endophytic fungi. *Mycoscience* 46: 280-286. <https://doi.org/10.1007/S10267-005-0247-7>

1461

1462 Koivusaari, P., Tejesvi, M.V., Tolkkinen, M., Markkola, AM., Mykrä, H. & Pirttilä, A.M. 2019. Fungi
1463 originating from tree leaves contribute to fungal diversity of litter in streams. *Frontiers in Microbiology*
1464 10:651. <https://doi:10.3389/fmicb.2019.00651>

1465

1466 Kominoski, J.S. & Rosemond, A.D. 2012. Conservation from the bottom up: forecasting effects of global
1467 change on dynamics of organic matter and management needs for river networks. *Freshwater Science*
1468 31: 51-68. <https://doi.org/10.1899/10-160.1>

1469

1470 Kominoski, J.S., Marczak, L.B. & Richardson, J.S. 2011. Riparian forest composition affects stream litter
1471 decomposition despite similar microbial and invertebrate communities. *Ecology* 92: 151-159.
1472 <https://doi.org/10.1890/10-0028.1>

1473

1474 Kreutzweiser, D. P. & Capell, S. S. 2003. Benthic microbial utilization of differential
1475 dissolved organic matter sources in a forest headwater stream. *Canadian Journal of Forest Research* 33:
1476 1444-1451. <https://doi.org/10.1139/X03-030>
1477

1478 Kreutzweiser, D. P., Good, K. P., Capell, S. S. & Holmes, S. B. 2008a. Leaf-litter decomposition and
1479 macroinvertebrate communities in boreal forest streams linked to upland logging disturbance. *Journal*
1480 *of North American Benthological Society* 27: 1-15. <https://doi.org/10.1899/07-034R.1>
1481

1482 Kreutzweiser, D. P., Hazlett, P. W. & Gunn, J. M. 2008b. Logging impacts on the biogeochemistry of
1483 boreal forest soils and nutrient export to aquatic systems: A review. *Environmental Reviews* 16: 157-
1484 179. <https://doi.org/10.1139/A08-006>
1485

1486 Kreutzweiser, D.P., Capell, S.S. & Holmes, S.B. 2009. Stream temperature responses to partial-harvest
1487 logging in riparian buffers of boreal mixedwood forest watershed. *Canadian Journal of Forest Research*
1488 39: 497-506. <https://doi.org/10.1139/X08-191>
1489

1490 Kuglerová, L., Jansson, R., Ågren, A., Laudon, H. & Malm-Renöfält, B. 2014a. Groundwater discharge
1491 creates hotspots of riparian plant species richness in a boreal forest stream network. *Ecology* 95: 715-
1492 725. <https://doi.org/10.1890/13-0363.1>
1493

1494 Kuglerová, L., Ågren, A., Jansson, R. & Laudon, H. 2014b. Towards optimizing riparian buffer zones:
1495 Ecological and biogeochemical implications for forest management. *Forest Ecology and Management*
1496 334: 74-84. <https://doi.org/10.1016/j.foreco.2014.08.033>
1497

1498 Kuglerová, L., Jansson, R., Sponseller, R. A., Laudon, H. & Malm-Renöfält, B. 2015. Local and regional
1499 processes determine plant species richness in a river-network metacommunity. *Ecology* 96: 381-391.
1500 <https://doi.org/10.1890/14-0552.1>
1501
1502 Kuglerová, L., Hasselquist, E.M., Richardson, J.S., Sponseller, R.A., Kreuzweiser, D.P. & Laudon, H. 2017.
1503 Management perspective on *Aqua incognita*: Connectivity and cumulative effects of small natural and
1504 artificial streams in boreal forests. *Hydrological Processes* 31: 4268-4244.
1505 <https://doi.org/10.1002/hyp.11281>
1506
1507 Kuzyakov, Y. & Blagodatskaya, E. 2015. Microbial hotspots and hot moments in soil: Concept & review.
1508 *Soil Biology & Biochemistry* 83: 184-199. <https://doi.org/10.1016/j.soilbio.2015.01.025>
1509
1510 Kyachenko, J., Clemmensen, K.E., Karlton, E. & Lindahl, B.D. 2017a. Below-ground organic matter
1511 accumulation along a boreal forest fertility gradient relates to guild interaction within fungal
1512 communities. *Ecology Letters* 20: 1546-1555. <https://doi.org/10.1111/ele.12862>
1513
1514 Kyachenko, J., Clemmensen, K.E., Hagenbo, A., Karlton, E. & Lindahl, B.D. 2017b. Shift in fungal
1515 communities and associated enzyme activities along an age gradient of managed *Pinus sylvestris* stands.
1516 *The ISME Journal* volume 11: 863–874. <https://doi.org/doi:10.1038/ismej.2016.184>
1517
1518 Laeser, S.R., Baxter, C.V. & Fausch, K.D. 2005. Riparian vegetation loss, stream channelization, and web-
1519 weaving spiders in northern Japan. *Ecological Research* 20: 646-651. [https://doi.org/10.1007/s11284-](https://doi.org/10.1007/s11284-005-0084-3)
1520 [005-0084-3](https://doi.org/10.1007/s11284-005-0084-3)
1521
1522 Lair, G. J., Gerzabek, M. H. & Haberhauer, G. 2007. Sorption of heavy metals on organic and inorganic
1523 soil constituents. *Environmental Chemistry Letters* 5: 23-27. <https://doi.org/10.1007/s10311-006-0059-9>

1524

1525 Lambert, T., Pierson-Wickmann, A.-C., Gruau, G., Thibault, J.-N. & Jaffrezic, A. 2011. Carbon isotopes as
1526 tracers of dissolved organic carbon sources and water pathways in headwater catchments. *Journal of*
1527 *Hydrology* 402: 228-238. <https://doi.org/10.1016/j.jhydrol.2011.03.014>

1528

1529 Lamers, L.P.M., Loeb, R., Antheunisse, A.M., Miletto, M., Lucassen, E.C.H.E.T., Boxman, A.W., Smolders,
1530 A.J.P. & Roelofs, J.G.M. 2006. Biogeochemical constraints on the ecological rehabilitation of wetland
1531 vegetation in river floodplains. *Hydrobiologia* 565: 165-186. <https://doi.org/10.1007/s10750-005-1912-8>

1532

1533 Laudon, H., Berggren, M., Ågren, A., Buffam, I., Bishop, K., Grabs, T., Jansson, M. & Köhler, S. 2011.
1534 Patterns and dynamics of dissolved organic carbon (doc) in boreal streams: the role of processes,
1535 connectivity, and scaling. *Ecosystems* 14: 880-893. <https://doi.org/10.1007/s10021-011-9452-8>

1536

1537 Lazaruk, L.W., Kernaghan, G., Macdonald, S.E. & Khasa, D. 2005. Effects of partial cutting on the
1538 ectomycorrhizae of *Picea glauca* forests in northwestern Alberta. *Canadian Journal of Forest Research*
1539 35: 1442-1454. <https://doi.org/10.1139/x05-062>

1540

1541 LeBrun, E.S., Taylor, D.L., King, R.S., Back, J.A. & Kang, S. 2018. Rivers may constitute an overlooked
1542 avenue of dispersal for terrestrial fungi. *Fungal Ecology* 32: 72-79.
1543 <https://doi.org/10.1016/j.funeco.2017.12.003>

1544

1545 Lecerf, A. & Richardson, J. S. 2010. Litter decomposition can detect effects of high and moderate levels
1546 of forest disturbance on stream condition. *Forest Ecology and Management* 259: 2433-2443.
1547 <https://doi.org/10.1016/j.foreco.2010.03.022>

1548

1549 Ledesma, J. L. J., Grabs, T., Futter, M. N., Bishop, K. H., Laudon, H. & Köhler, S. J. 2013. Riparian zone
1550 control on base cation concentration in boreal streams. *Biogeosciences* 10: 3849-3868.
1551 <https://doi.org/10.5194/bg-10-3849-2013>
1552
1553 Ledesma, J. L. J., Futter, M. N., Blackburn, M., Lidman, F., Grabs, T., Sponseller, R. A., Laudon, H., Bishop,
1554 K. H. & Köhler, S. J. 2018. Towards an improved conceptualization of riparian zones in boreal forest
1555 headwaters. *Ecosystems* 21: 297-315. <https://doi.org/10.1007/s10021-017-0149-5>
1556
1557 Lee, P., Smyth, C. & Boutin, S. 2004. Quantitative review of riparian buffer width guidelines from Canada
1558 and the United States. *Journal of Environmental Management* 70: 165-180.
1559 <https://doi.org/10.1016/j.jenvman.2003.11.009>
1560
1561 LeRoy, C.J. & Marks, J.C. 2006. Litter quality, stream characteristics and litter diversity influence
1562 decomposition rates and macroinvertebrates. *Freshwater Biology* 51: 605-617.
1563 <https://doi.org/10.1111/j.1365-2427.2006.01512.x>
1564
1565 LeRoy, C.J., Whitham, T.G., Keim, P. & Marks, J.C. 2006. Plant genes link forests and streams. *Ecology* 87:
1566 255-261. <https://doi.org/10.1890/05-0159>
1567
1568 LeRoy, C., Fischer, D.G., Halstead, K., Pryor, M., Bailey, J.K. & Schweitzer, J.A. 2011. A fungal endophyte
1569 slows litter decomposition in streams. *Freshwater Biology* 56: 1426-1433.
1570 <https://doi.org/10.1111/j.1365-2427.2011.02581.x>
1571
1572 Leyer, I. & Pross, S. 2009. Do seed and germination traits determine plant distribution patterns in
1573 riparian landscapes? *Basic and Applied Ecology* 10: 113-121. <https://doi.org/10.1016/j.baae.2008.01.002>
1574

1575 Lidman, F., Köhler, S. J., Mörth, C.-M. & Laudon, H. 2014. Metal transport in the boreal landscape—the
1576 role of wetlands and the affinity for organic matter. *Environmental Science & Technology* 48: 3783-
1577 3790. <https://doi.org/10.1021/es4045506>
1578

1579 Lidman, F., Boily, Å., Laudon, H. & Köhler, S. J. 2017. From soil water to surface water – how the riparian
1580 zone controls element transport from a boreal forest to a stream. *Biogeosciences* 14: 3001-3014.
1581 <https://doi.org/10.5194/bg-14-3001-2017>
1582

1583 Lind, L., Nilsson, C., Polvi, L.E. & Weber, C. 2014a. The role of ice dynamics in shaping vegetation in
1584 flowing waters. *Biological Reviews* 89: 791-804. <https://doi.org/10.1111/brv.12077>
1585

1586 Lind, L., Nilsson, C. & Weber, C. 2014b. Effects of ice and flooding on vegetation in streams in cold
1587 regions: implications for climate change. *Ecology and Evolution* 4: 4173-4184.
1588 <https://doi.org/10.1002/ece3.1283>
1589

1590 Lind, L. & Nilsson, C. 2015. Vegetation patterns in small boreal streams relate to ice and winter floods.
1591 *Journal of Ecology* 103: 431–440. <https://doi.org/10.1111/1365-2745.12355>
1592

1593 Lindo, Z. & Visser, S. 2003. Microbial biomass, nitrogen and phosphorus mineralization, and mesofauna
1594 in boreal conifer and deciduous forest floors following partial and clear-cut harvesting. *Canadian Journal*
1595 *of Forest Research* 33: 1610-1620. <https://doi.org/10.1139/X03-080>
1596

1597 Lõhmus, A., Remm, L. & Rannap, R. 2015. Just a ditch in forest? Reconsidering draining in the context of
1598 sustainable forest management. *BioScience* 65: 1066-1076. <https://doi.org/10.1093/biosci/biv136>
1599

1600 Lopez, O.R. 2001. Seed flotation and postflooding germination in tropical *terra firme* and seasonally
1601 flooded forest species. *Functional Ecology* 15: 763-771. [https://doi.org/10.1046-](https://doi.org/10.1046/j.0269-8463.2001.00586.x)
1602 [8463.2001.00586.x](https://doi.org/10.1046/j.0269-8463.2001.00586.x)
1603
1604 Lowrance, R., Todd, R., Fail Jr., J., Hendrickson, Jr., O., Leonard, R. & Asmussen, L. 1984. Riparian forests
1605 as nutrient filters in agricultural watersheds. *BioScience* 34: 374-377. <https://doi.org/10.2307/1309729>
1606
1607 Marchner, P., Yang, C.-H., Lieberei, R. & Crowley, D.E. 2001. Soil and plant specific effects on bacterial
1608 community composition in the rhizosphere. *Soil Biology & Biochemistry* 33: 1437-1445.
1609 [https://doi.org/10.1016/S0038-0717\(01\)00052-9](https://doi.org/10.1016/S0038-0717(01)00052-9)
1610
1611 Martínez, A., Larrañaga, A., Pérez, J., Descals, E., Pozo, J. & Notes, A. 2014. Temperature affects leaf
1612 litter decomposition in low-order forest streams: field and microcosm approaches. *FEMS Microbiology*
1613 *Ecology* 87: 257-267. <https://doi.org/10.1111/1574-6941.12221>
1614
1615 Marttila, H., Karjalainen, S.-M., Kuoppala, M., Nieminen, M.L., Ronkanen, A.-K., Kløve, B. & Hellsten, S.
1616 2018. Elevated nutrient concentrations in headwaters affected by drained peatland. *Science of the Total*
1617 *Environment*. 643: 1304-1313. <https://doi.org/10.1016/j.scitotenv.2018.06.278>
1618
1619 Marttila, H. & Kløve, B. 2010. Dynamics of erosion and suspended sediment transport from drained
1620 peatland forestry. *Journal of Hydrology* 388: 414-425. <https://doi.org/10.1016/j.jhydrol.2010.05.026>
1621
1622 Mayfield, M.M., Bonser, S.P., Morgan, J.W., Aubin, I., McNamara, S. & Vesk, P.A. 2010. What does
1623 species richness tell us about functional trait diversity? Predictions and evidence for responses of
1624 species and functional trait diversity to land-use change. *Global Ecology and Biogeography* 19: 423-431.
1625 <https://doi.org/10.1111/j.1466-8238.2010.00532.x>

1626

1627 McClain, M.E., Boyer, E.W., Dent, C.L., Gergel, S.E., Grimm, N.B., Groffman, P.M., Hart, S.C., Harvey, J.W.,
1628 Johnson, C.A., Mayorga, E., McDowell, W.H. & Pinay, G. 2003. Biogeochemical hot spots and hot
1629 moments at the interface of terrestrial and aquatic ecosystems. *Ecosystems* 6: 301-312.
1630 <https://doi.org/10.1007/s10021-003-0161-9>

1631

1632 McKie, B.G. & Malmqvist, B. 2008. Assessing ecosystem functioning in streams affected by forest
1633 management: increased leaf decomposition occurs without changes to the composition of benthic
1634 assemblages. *Freshwater Biology* 54: 2086–2100. <https://doi.org/10.1111/j.1365-2427.2008.02150.x>

1635

1636 Mei, Y., Hornberger, G. M., Kaplan, L. A., Newbold, J. D. & Aufdenkampe, A. K. 2012. Estimation of
1637 dissolved organic carbon contribution from hillslope soils to a headwater stream. *Water Resources*
1638 *Research* 48: W09514. <https://doi.org/10.1029/2011WR010815>

1639

1640 Mellina, E., Moore, R. D., Hinch, S. G., Macdonald, J. S. & Pearson, G. Stream temperature responses to
1641 clearcut logging in British Columbia: the moderating influences of groundwater and headwater lakes.
1642 *Canadian Journal of Fisheries and Aquatic Sciences* 59: 1886-1900.

1643

1644 Melody, K.J. & Richardson, J.S. 2004. Responses of invertebrates and algae of a boreal coniferous forest
1645 stream to experimental manipulation of leaf litter inputs and shading. *Hydrobiologia* 519: 197-206.
1646 <https://doi.org/10.1023/B:HYDR.0000026506.16929.e1>

1647

1648 Merritt, D.M. & Wohl, E.E. 2002. Plant dispersal along rivers fragmented by dams. *River Research and*
1649 *Applications* 22: 1-26. <https://doi.org/10.1002/rra.890>

1650

1651 Merrit, D.M., Nilsson, C. & Jansson, R. 2010. Consequences of propagule dispersal and river
1652 fragmentation for riparian plant community diversity and turnover. *Ecological Monographs* 80: 609-626.
1653 <https://doi.org/10.1890/09-1533.1>
1654
1655 Meyer, J.L., Strayer, D.L., Wallace, J.B., Eggert, S.L., Helfman, G.S. & Leonard, N.E. 2007. The contribution
1656 of headwater streams to biodiversity in river networks. *Journal of the American Water Resources*
1657 *Association* 43: 86-103. <https://doi.org/10.1111/j.1752-1688.2007.00008.x>
1658
1659 Mierle, G. & Ingram, R. 1991. The role of humic substances in the mobilization of mercury from
1660 watersheds. *Water, Air & Soil Pollution* 56: 349-357. <https://doi.org/10.1007/BF00342282>
1661
1662 Mitchell, M.J., Driscoll, C.T., Kahl, J.S., Likens, G.E., Murdoch, P.S. & Pardo, L.H. 1996. Climatic control of
1663 nitrate loss from forested watershed in the northeast United States. *Environmental Science &*
1664 *Technology* 30: 2609-2612. <https://doi.org/10.1021/es9600237>
1665
1666 Moody, C. S., Worrall, F., Evans, C. D. & Jones, T. G. 2013. The rate of loss of dissolved organic carbon
1667 (DOC) through a catchment. *Journal of Hydrology* 492: 139-150.
1668 <https://doi.org/10.1016/j.jhydrol.2013.03.016>
1669
1670 Moon, J.B., Wardrop, D.H., Bruns, M.A.V., Miller, R.M. & Naithani, K.J. 2016. Land-use and land-cover
1671 effects on soil microbial community abundance and composition in headwater riparian wetlands. *Soil*
1672 *Biology & Biochemistry* 97: 215-233. <https://doi.org/10.1016/j.soilbio.2016.02.021>
1673
1674 Moore, R.D., Spittlehouse, D.L. & Story, A. 2005. Riparian microclimate and stream temperature
1675 response to forest harvesting: a review. *Journal of the American Water Resources Association* 41: 813-
1676 834. <https://doi.org/10.1111/j.1752-1688.2005.tb03772.x>

1677

1678 Mosisch, T.D., Bunn, S.E. & Davies, P.M. 2008. The relative importance of shading and nutrients on algal
1679 production in subtropical streams. *Freshwater Biology* 46: 1269-1278.

1680 <https://doi.org/10.1046/j.1365-2427.2001.00747.x>

1681

1682 Mosley, E., Holmes, S.B. & Nol, E. 2006. Songbird diversity and movement in upland and riparian
1683 habitats in the boreal mixedwood forest of northeastern Ontario. *Canadian Journal of Forest Research*
1684 36: 1149-1164. <https://doi.org/10.1139/x06-010>

1685

1686 Mouillot, D., Bellwood, D.R., Baraloto, C., Chave, J., Galzin, R., Harmelin-Vivien, M., Kulbicki, M.,
1687 Lavergne, S., Lavorel, S., Mouquet, N., Paine, C.E.T., Renaud, J. & Thuiller, W. 2013. Rare species support
1688 vulnerable functions in high-diversity ecosystems. *PLOS Biology* 11: e1001569.

1689 <https://doi.org/10.1371/journal.pbio.1001569>

1690

1691 Mulholland, P.J. 1992. Regulation of nutrient concentrations in a temperate forest stream: Roles of
1692 upland, riparian, and instream processes. *Limnology and Oceanography* 37: 1512-1526.

1693 <https://doi.org/10.4319/lo.1992.37.7.1512>

1694

1695 Murphy, M.L., Hawkins, C.P. & Anderson, N.H. 1981. Effects of canopy modification and accumulated
1696 sediment on stream communities. *Transactions of the American Fisheries Society* 110: 469-478.

1697 [https://doi.org/10.1577/1548-8659\(1981\)110<469:EOCMAA>2.0.CO;2](https://doi.org/10.1577/1548-8659(1981)110<469:EOCMAA>2.0.CO;2)

1698

1699 Mustonen, K.-R., Mykrä, H., Louhi, P., Markkola, AM., Tolkkinen, M., Huusko, A., Alioravainen, N.,
1700 Lehtinen, S. & Muotka, T. 2016. Sediments and flow have mainly independent effects on multitrophic
1701 stream communities and ecosystem functions. *Ecological Applications* 26: 2116-2129.

1702 <https://doi.org/10.1890/15-1841.1>

1703

1704 Mykrä, H., Tolkkinen, M. & Heino, J. 2017. Environmental degradation results in contrasting changes in
1705 the assembly processes of stream bacterial and fungal communities. *Oikos* 126: 1291-1298.

1706 <https://doi.org/10.1111/oik.04133>

1707

1708 Mykrä, H., Sarremejane, R., Laamanen, T., Karjalainen, S.M., Markkola, A., Lehtinen, S., Lehosmaa, K. &
1709 Muotka, T. 2019. Local geology determines responses of stream producers and fungal decomposers to
1710 nutrient enrichment: A field experiment. *Ambio* 48: 100-110. [https://doi.org/10.1007/s13280-018-1057-](https://doi.org/10.1007/s13280-018-1057-4)

1711 4

1712

1713 Naiman, R. J. 1982. Characteristics of sediment and organic carbon export from pristine boreal forest
1714 watersheds. *Canadian Journal of Fisheries and Aquatic Sciences* 39: 1699-1718.

1715 <https://doi.org/10.1139/f82-226>

1716

1717 Naiman, R.J., Décamps, H. & McClain, M.E. 2005. *Riparia – Ecology, conservation, and management of*
1718 *streamside communities*. Elsevier Academic Press, China. 430 p.

1719

1720 Nakano, S., Miyasaka, H. & Kuhara, N. 1999. Terrestrial-aquatic linkages: Riparian arthropod inputs alter
1721 trophic cascades in a stream food web. *Ecology* 80: 2435-2441. [https://doi.org/10.1890/0012-](https://doi.org/10.1890/0012-9658(1999)080[2435:TALRAI]2.0.CO;2)

1722 9658(1999)080[2435:TALRAI]2.0.CO;2

1723

1724 Nguyen, N.H., Song, Z., Bates, S.T., Branco, S., Tedersoo, L., Menke, J., Schilling, J.S., Kennedy, P.G. 2016.
1725 FUNGuild: an open annotation tool for parsing fungal community datasets by ecological guild. *Fungal*

1726 *Ecology* 20: 241-248. <https://doi.org/10.1016/j.funeco.2015.06.006>

1727

1728 Nielsen, U.N., Ayres, E., Wall, D.H. & Bardgett, R.D. 2011. Soil biodiversity and carbon cycling: a review
1729 and synthesis of studies examining diversity–function relationships. *European Journal of Soil Science* 62:
1730 105-116. <https://doi.org/10.1111/j.1365-2389.2010.01314.x>
1731

1732 Nieminen, M., Piirainen, S., Sikström, U., Löfgren, S., Marttila, H., Sarkkola, S., Laurén, A. & Finer, L.
1733 2018a. Ditch network maintenance in peat-dominated boreal forests: Review and analysis of water
1734 quality management options. *Ambio* 47: 535-545. <https://doi.org/10.1007/s13280-018-1047-6>
1735

1736 Nieminen, M., Hökkä, H., Laiho, R., Juutinen, A., Ahtikoski, A., Pearson, M., Kojola, S., Sarkkola, S.,
1737 Launiainen, S., Valkonen, S., Penttilä, T., Lohila, A., Saarinen, M., Haahti, K., Mäkipää, R., Miettinen, J. &
1738 Ollikainen, M. 2018b. Could continuous cover forestry be an economically and environmentally feasible
1739 management option on drained boreal peatlands? *Forest Ecology and Management* 424: 78-84.
1740 <https://doi.org/10.1016/j.foreco.2018.04.046>
1741

1742 Nieminen, M., Sarkkola, S. & Laurén, A. 2017. Impacts of forest harvesting on nutrient, sediment and
1743 dissolved organic carbon exports from drained peatlands: A literature review, synthesis and suggestions
1744 for the future. *Forest Ecology and Management* 392: 13-20.
1745 <https://doi.org/10.1016/j.foreco.2017.02.046>
1746

1747 Nilsson, C., Brown, R. L., Jansson, R. & Merritt, D. M. 2010. The role of hydrochory in structuring riparian
1748 and wetland vegetation. *Biological Reviews* 85: 837-858. <https://doi:10.1111/j.1469-185X.2010.00129.x>
1749

1750 Nilsson, C., Jansson, R., Kuglerová, L., Lind, L. & Ström, L. 2013. Boreal riparian vegetation under climate
1751 change. *Ecosystems* 16: 401-410. <https://doi.org/10.1007/s10021-012-9622-3>
1752

1753 Norlund, A. & Westin, K. 2011. Forest values and forest management attitudes among private forest
1754 owners in Sweden. *Forests* 2: 30-50. <https://doi.org/10.3390/f2010030>
1755

1756 Oldén, A., Selonen, V.A.O., Lehkonen, E. & Kotiaho, J.S. 2019. The effect of buffer strip width and
1757 selective logging on streamside plant communities. *BMC Ecology* 19:9 [https://doi.org/10.1186/s12898-](https://doi.org/10.1186/s12898-019-0225-0)
1758 [019-0225-0](https://doi.org/10.1186/s12898-019-0225-0)
1759

1760 Omacini, M., Chaneton, E.J., Ghera, C.M. & Otero, P. 2004. Do foliar endophytes affect grass litter
1761 decomposition? A microcosm approach using *Lolium multiflorum*. *Oikos* 104: 581-590.
1762 <https://doi.org/10.1111/j.0030-1299.2004.12915.x>
1763

1764 Orwin, K.H., Kirschbaum, M.U.F., St John, M.G. & Dickie I.A. 2011. Organic nutrient uptake by
1765 mycorrhizal fungi enhances ecosystem carbon storage: a model-based assessment. *Ecology Letters* 14:
1766 493-502. <https://doi.org/10.1111/j.1461-0248.2011.01611.x>
1767

1768 Ostrofsky, M.L. 1997. Relationship between chemical characteristics of autumn-shed leaves and aquatic
1769 processing rates. *Journal of American Benthological Society* 16: 750-759.
1770 <https://doi.org/10.2307/1468168>
1771

1772 Parkhill, K.L.P. & Gulliver, J.S. 2002. Effects of inorganic sediment on whole-stream productivity.
1773 *Hydrobiologia* 472: 5-17. <https://doi.org/10.1023/A:1016363228389>
1774

1775 Pennanen, T. 2001. Microbial communities in boreal coniferous forest humus exposed to heavy metals
1776 and changes in soil pH—a summary of the use of phospholipid fatty acids, Biolog® and ³H-thymidine
1777 incorporation methods in field studies. *Geoderma* 100: 91-126. [https://doi.org/10.1016/S0016-](https://doi.org/10.1016/S0016-7061(00)00082-3)
1778 [7061\(00\)00082-3](https://doi.org/10.1016/S0016-7061(00)00082-3)

1779

1780 Peterjohn, W.T. & Corell, D.L. 1984. Nutrient dynamics in an agricultural watershed: Observations on the
1781 role of a riparian forest. *Ecology* 65: 1466-1475. <https://doi.org/10.2307/1939127>

1782

1783 Planty-Tabacchi, A.-M., Tabacchi, E., Naiman, R.J., Deferrari, C. & Décamps, H. 1996. Invasibility of
1784 species-rich communities in riparian zones. *Conservation Biology* 10: 598-607.

1785 <https://doi.org/10.1046/j.1523-1739.1996.10020598.x>

1786

1787 Piggot, J.J., Townsend, C.R. & Matthaei, C.D. 2015. Climate warming and agricultural stressors interact to
1788 determine stream macroinvertebrate community structure. *Global Change Biology* 21: 1887-1906.

1789 <https://doi.org/10.1111/gcb.12861>

1790

1791 Piirainen, S., Finér, L., Andersson, E., Belova, O., Čiuldienė, D., Futter, M., Gil, W., Glazko, Z., Hiltunen, T.,
1792 Högbom, L., Janek, M., Joensuu, S., Jägerud, L., Libiète, Z., Lode, E., Löfgren, S., Pierzgalski, E., Ring, E.,

1793 Zarins, J. & Thorell, D. 2017. Management of riparian forests for good water quality in the Baltic Sea

1794 Region countries – current knowledge, methods and areas for development. EU Baltic Sea Region

1795 Interreg – WAMBAF. <http://jukuri.luke.fi/handle/10024/540296>

1796

1797 Pinay, G., Fabre, A., Vervier, Ph. & Gazelle, F. 1992. Control of C, N, P distribution in soils of riparian
1798 forests. *Landscape Ecology* 6: 121-132. <https://doi.org/10.1007/BF00130025>

1799

1800 Pinay, G., Roques, L. & Fabre, A. 1993. Spatial and temporal patterns of denitrification in a riparian
1801 forest. *Journal of Applied Ecology* 30: 581-591. <https://doi.org/10.2307/2404238>

1802

1803 Pollock, M.M., Naiman, R.J. & Hanley, T.A. 1998. Plant species richness in riparian wetlands – A test of
1804 biodiversity theory. *Ecology* 79: 94-105. [https://doi.org/10.1890/0012-](https://doi.org/10.1890/0012-9658(1998)079[0094:PSRIRW]2.0.CO;2)
1805 [9658\(1998\)079\[0094:PSRIRW\]2.0.CO;2](https://doi.org/10.1890/0012-9658(1998)079[0094:PSRIRW]2.0.CO;2)
1806
1807 Pollock, M.M., Beechie, T.J., Wheaton, J.M., Jordan, C.E., Bouwes, N., Weber, N. & Volk, C. 2014. Using
1808 Beaver dams to restore incised stream ecosystems. *BioScience* 64: 279-290.
1809 <https://doi.org/10.1093/biosci/biu036>
1810
1811 Prowse, T.D. & Beltaos, S. 2002. Climatic control of river-ice hydrology: a review. *Hydrological processes*
1812 16: 805-822. <https://doi.org/10.1002/hyp.369>
1813
1814 Quinn, J.M., Boothroyd, I.K.G. & Smith, B.J. 2004. Riparian buffers mitigate effects of pine plantation
1815 logging on New Zealand streams: 2. Invertebrate communities. *Forest Ecology and Management* 191:
1816 129-146. <https://doi.org/10.1016/j.foreco.2003.11.013>
1817
1818 Richardson, J.S. & Danehy, R.J. 2007. A synthesis of the ecology of headwater streams and their riparian
1819 zones in temperate forests. *Forest Science* 53: 131-147. <https://doi.org/10.1093/forestscience/53.2.131>
1820
1821 Richardson, D.M., Holmes, P.M., Esler, K.J., Galatowitsch, S.M., Stromberg, J.C., Kirkman, S.P., Pyšek, P.
1822 & Hobbs, R.J. 2007. Riparian vegetation: degradation, alien plant invasions, and restoration prospects.
1823 *Diversity and Distribution* 13: 126-139. <https://doi.org/10.1111/j.1366-9516.2006.00314.x>
1824
1825 Richardson, J. S., Naiman, R. J. & Bisson, P. A. 2017. How did fixed-width buffers become standard
1826 practice for protecting freshwater and their riparian areas from forest harvest practices? *Freshwater*
1827 *Science* 31: 232-238.
1828

1829 Richardson, J. S. 2019. Biological diversity in headwater streams. *Water* 11: 366.
1830 <https://doi.org/10.3390/w11020366>
1831

1832 Riis, T. & Sand-Jensen, K. 2006. Dispersal of plant fragments in small streams. *Freshwater Biology* 51:
1833 274-286. <https://doi.org/10.1111/j.1365-2427.2005.01496.x>
1834

1835 Ring, E., Johansson, J., Sandström, C., Bjarnadóttir, B., Finér, L., Ļībiete, Z., Lode, E., Stupak, I. &
1836 Sætersdal, M. 2017. Mapping policies for surface water protection zones in forest land in the Nordic-
1837 Baltic region: Large differences in prescriptiveness and zone width. *Ambio* 46: 878-893.
1838 <https://doi.org/10.1007/s13280-017-0924-8>
1839

1840 Rossi, L. 1985. Interactions between invertebrates and microfungi in freshwater ecosystems. *Oikos* 44:
1841 175-184. <https://www.jstor.org/stable/3544059>
1842

1843 Rousk, J., Brookes, P.C. & Bååth, E. 2010. Investigating the mechanisms for the opposing pH relationship
1844 of fungal and bacterial growth in soil. *Soil Biology and Biochemistry* 42: 926-934.
1845 <https://doi.org/10.1016/j.soilbio.2010.02.009>
1846

1847 Ruiz-Conzález, C., Niño-Gracia, J.P. & del Giorgio, P.A. 2015. Terrestrial origin of bacterial communities in
1848 complex boreal freshwater networks. *Ecology Letters*. <https://doi.org/10.1111/ele.12499>
1849

1850 Ryan, P.A. & Ryan, A.P. 2006. Impacts of global warming on New Zealand freshwater organisms: a
1851 preview and review. *New Zealand Natural Sciences* 31: 43-57.
1852

1853 Rykken, J.J., Moldenke, A.R. & Olson, D.H. 2007. Headwater riparian forest-floor invertebrate
1854 communities associated with alternative forest management practices. *Ecological Applications* 17: 1168-
1855 1183. <https://doi.org/10.1890/06-0901>
1856
1857 Sabo, J.L., Sponseller, R., Dixon, M., Gade, K., Harms, T., Heffernan, J., Jani, A., Katz, G., Soykan, C.,
1858 Watts, J. & Welter, J. 2005. Riparian zones increase regional species richness by harboring different, not
1859 more, species. *Ecology* 86: 56–62. <https://doi.org/10.1890/04-0668>
1860
1861 Sala, O.E., Chapin III, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E.,
1862 Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D. M., Mooney, H.A., Oesterheld, M., Poff,
1863 N. LR., Sykes, M. T., Walker, B.H., Walker, M. & Wall, D.H. 2000. Global biodiversity scenarios for the
1864 year 2100. *Science* 287: 1770-1774. <https://doi.org/10.1126/science.287.5459.1770>
1865
1866 Sarremejane, R., Mykrä, H., Bonada, N., Aroviita, J. & Muotka, T. 2017. Habitat connectivity and
1867 dispersal ability drive the assembly mechanisms of macroinvertebrate communities in river networks.
1868 *Freshwater Biology* 62: 1073-1082. <https://doi.org/10.1111/fwb.12926>
1869
1870 Shelker, J., Eklöf, K., Bishop, K. & Laudon, H. 2012. Effects of forestry operations on dissolved organic
1871 carbon concentrations and export in boreal first-order streams. *Journal of Geophysical Research* 117:
1872 G1. <https://doi.org/10.1029/2011JG001827>
1873
1874 Schelker, J., Kuglerová, L., Eklof, K., Bishop, K. & Laudon, H. 2013. Hydrological effects of clear-cutting in
1875 a boreal forest – Snowpack dynamics, snowmelt and streamflow responses. *Journal of Hydrology* 484:
1876 105-114. <https://doi.org/10.1016/j.jhydrol.2013.01.015>
1877

1878 Schindler, M.H. & Gessener, M.O. 2009. Functional leaf traits and biodiversity effects on litter
1879 decomposition in a stream. *Ecology* 90: 1641-1649. <https://doi.org/10.1890/08-1597.1>
1880
1881 Shumilova, O., et al. 2019. Simulating rewetting events in intermittent rivers and ephemeral streams: A
1882 global analysis of leached nutrients and organic matter. *Global Change Biology* 25: 1591-1611.
1883 <https://doi.org/10.1111/gcb.14537>
1884
1885 Selonen, V.A.O., Mussaari, M., Toivanen, T. & Kotiaho, J.S. 2011. The conservation potential of brook-
1886 side key habitats in managed boreal forests. *Silva Fennica* 45: 1041-1052.
1887 <http://www.metla.fi/silvafennica/full/sf45/sf4551041.pdf>
1888
1889 Selonen, V.A.O. & Kotiaho, J.S. 2013. Buffer strips can pre-empt extinction debt in boreal streamside
1890 habitats. *BMC Ecology* 13: 24. <https://doi.org/10.1186/1472-6785-13-24>
1891
1892 Sibley, P. K., Kreuzweiser, D. P., Naylor, B. J., Richardson, J. S. & Gordon, A. M. 2012. Emulation of
1893 natural disturbance (END) for riparian forest management: synthesis and recommendations. *Freshwater*
1894 *Science* 3: 258-264. <https://doi.org/10.1899/11-094.1>
1895
1896 Singh, J.S. & Gupta, S.R. 1977. Plant decomposition and soil respiration in terrestrial ecosystems.
1897 *Botanical Review* 43: 449-528. <https://doi.org/10.1007/BF02860844>
1898
1899 Sirotnak, J.M. & Huntly, N.J. 2000. Direct and indirect effects of herbivores on nitrogen dynamics: voles
1900 in riparian areas. *Ecology* 81: 78-87. [https://doi.org/10.1890/0012-9658\(2000\)081\[0078:DAIEOH\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2000)081[0078:DAIEOH]2.0.CO;2)
1901
1902

1903 Smerdon, B. D., Redding, T. E. & Beckers, J. 2009. An overview of the effects of forest management on
1904 groundwater hydrology. *BC Journal of Ecosystems and Management* 10: 22–44.
1905 www.forrex.org/publications/jem/ISS50/vol10_no1_art4.pdf
1906
1907 Smith, R.F., Alexander, L.C. & Lamp, W.O. 2009. Dispersal by terrestrial stages of stream insects in urban
1908 watersheds: a synthesis of current knowledge. *Freshwater Science* 28: 1022-1037.
1909 <https://doi.org/10.1899/08-176.1>
1910
1911 Spence, J. R. 2001. The new boreal forestry: adjusting timber management to accommodate
1912 biodiversity. *Trends in Ecology & Evolution* 16: 591-593. [https://doi.org/10.1016/S0169-5347\(01\)02335-](https://doi.org/10.1016/S0169-5347(01)02335-7)
1913 [7](https://doi.org/10.1016/S0169-5347(01)02335-7)
1914
1915 Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L., van Lanen, H., Sauquet, E., Demuth, S., Fendekova, M. &
1916 Jordar, J. Streamflow trends in Europe: evidence from a dataset of near-natural catchments. *Hydrology*
1917 *and Earth System Sciences* 14: 2367-2382. <https://doi.org/10.5194/hess-14-2367-2010>
1918
1919 Stenberg, L., Tuukkanen, T., Finér, L., Marttila, H., Piirainen, S., Kløve, B. & Koivusalo, H. 2015. Ditch
1920 erosion processes and sediment transport in a drained peatland forest. *Ecological Engineering* 75: 421-
1921 433. <https://doi.org/10.1016/j.ecoleng.2014.11.046>
1922
1923 Steward, K.J. & Mallik, A.U. 2006. Bryophyte responses to microclimatic edge effects across riparian
1924 buffers. *Ecological Applications* 16: 1474-1486. [https://doi.org/10.1890/1051-](https://doi.org/10.1890/1051-0761(2006)016[1474:BRTMEE]2.0.CO;2)
1925 [0761\(2006\)016\[1474:BRTMEE\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2006)016[1474:BRTMEE]2.0.CO;2)
1926
1927 Strahler, A. N. 1957. Quantitative analysis of watershed geomorphology. *Transactions American*
1928 *Geophysical Union* 38: 913-920.

1929

1930 Strickland, M.S. & Rousk, J. 2010. Considering fungal:bacterial dominance in soils – Methods, controls,
1931 and ecosystem implications. *Soil Biology and Biochemistry* 42: 1385-1395.

1932 <https://doi.org/10.1016/j.soilbio.2010.05.007>

1933

1934 Suberkropp, K. & Chauvet, E. 1995. Regulation of leaf breakdown by fungi in streams: influences of
1935 water chemistry. *Ecology* 76: 1433-1445. <https://doi.org/10.2307/193814>

1936

1937 Suberkropp, K. & Weyers, H. 1996. Application of fungal and bacterial production methodologies to
1938 decomposing leaves in stream. *Applied and Environmental Microbiology* 62: 1610-1615.

1939 <https://aem.asm.org/content/62/5/1610.short>

1940

1941 Sutfin, N.A., Wohl, E.E. & Dwire, K.A. 2016. Banking carbon: a review of organic carbon storage and
1942 physical factors influencing retention in floodplains and riparian ecosystems. *Earth Surface Processes*
1943 *and Landforms* 41: 38-60. <https://doi.org/10.1002/esp.3857>

1944

1945 Suurkuukka, H., Virtanen, R., Suorsa, V., Soininen, J., Paasivirta, L. & Muotka, T. 2014. Woodland key
1946 habitats and stream biodiversity: Does small-scale terrestrial conservation enhance the protection of
1947 stream biota? *Biological Conservation* 170: 10-19. <https://doi.org/10.1016/j.biocon.2013.10.009>

1948

1949 Swan, C.M. & Palmer, M.A. 2004. Leaf diversity alters litter breakdown in a Piedmont stream. *Journal of*
1950 *North American Benthological Society* 23: 15-28. <https://doi.org/10.1899/0887->

1951 [3593\(2004\)023<0015:LDALBI>2.0.CO;2](https://doi.org/10.1899/0887-3593(2004)023<0015:LDALBI>2.0.CO;2)

1952

1953 Swan, C.M. & Palmer, M.A. 2006. Composition of speciose leaf litter alters stream detritivore growth,
1954 feeding activity and leaf breakdown. *Oecologia* 147: 469-478. [https://doi.org/10.1007/s00442-005-](https://doi.org/10.1007/s00442-005-0297-8)
1955 0297-8
1956
1957 Sweeney, B.W., Bott, T.L., Jackson, J.K., Kaplan, L.A., Newbold, J.D., Standley, L.J., Hession, W.C. &
1958 Horwitz, R.J. 2004. Riparian deforestation, stream narrowing, and loss of stream ecosystem services.
1959 *PNAS* 101: 14132-14137. <https://doi.org/10.1073/pnas.0405895101>
1960
1961 Sweeney, B.W. & Newbold, J.D. 2014. Streamside forest buffer width needed to protect stream water
1962 quality, habitat, and organisms: A literature review. *Journal of the American Water Resources*
1963 *Association* 50: 560-584. <https://doi.org/10.1111/jawr.12203>
1964
1965 Taylor, L. A., Arthur, M. A. & Yanai, R. D. Forest floor microbial biomass across a northern hardwood
1966 successional sequence. *Soil Biology and Biochemistry* 31: 431-439. [https://doi.org/10.1016/S0038-](https://doi.org/10.1016/S0038-0717(98)00148-5)
1967 0717(98)00148-5
1968
1969 Tiegs, S. D. et al. 2019. Global patterns and drivers of ecosystem functioning in rivers and riparian zones.
1970 *Science Advances* 5: eaav0486. <https://doi.org/10.1126/sciadv.aav0486>
1971
1972 Thiffault, E., Hannam, K. D., Quideau, S. A., Paré, D., Bélanger, N., Oh, S.-W. & Munson, A. D. 2008.
1973 Chemical composition of forest floor and consequences for nutrient availability after wildfire and
1974 harvesting in the boreal forest. *Plant and Soil* 308: 37-53. <https://doi.org/10.1007/s11104-008-9604-6>
1975
1976 Thiffault, E., Hannam, K. D., Paré, D., Titus, B. D., Hazlett, P. W., Maynard, D. G. & Brais, S. 2011. Effects
1977 of forest biomass harvesting on soil productivity in boreal and temperate forests — A review.
1978 *Environmental Reviews* 19: 278-309. <https://doi.org/10.1139/A11-009>

1979

1980 Tiedje, J. M. 1988. Ecology of denitrification and dissimilatory nitrate reduction to ammonium. p. 179-

1981 244. *In* Zehnder, A. J. B. (ed.), *Environmental Microbiology of Anaerobes*. John Wiley and Sons, New

1982 York.

1983

1984 Timonen, J., Siitonen, J., Gustafsson, L., Kotiaho, J.S., Stokland, J.N., Sverdrup-Thygeson, A. &

1985 Mönkkönen, M. 2010. Woodland key habitats on northern Europe: concepts, inventory and protection.

1986 *Scandinavian Journal of Forest Research* 25: 309-324. <https://doi.org/10.1080/02827581.2010.497160>

1987

1988 Tolkkinen, M., Mykrä, H., Annala, M., Markkola, A.M., Vuori, K. M. & Muotka, T. 2015. Multi-stressor

1989 impacts on fungal diversity and ecosystem functions in streams: natural vs. anthropogenic stress.

1990 *Ecology* 96: 672-683. <https://doi.org/10.1890/14-0743.1>

1991

1992 Tolkkinen, M.J., Mykrä, H., Virtanen, R., Tolkkinen, M., Kauppila, T., Paasivirta, L. & Muotka, T. 2016.

1993 Land use impacts on stream community composition and concordance along a natural stress gradient.

1994 *Ecological Indicators* 62: 14-21. <https://doi.org/10.1016/j.ecolind.2015.11.015>

1995

1996 Tolonen, K.E., Picazo, F., Vilmi, A., Datry, T., Stubbington, R., Pařil, P., Perez Rocha, M. & Heino, J. 2019.

1997 Parallels and contrasts between intermittently freezing and drying streams: from individual adaptations

1998 to biodiversity variation. *Freshwater Biology* 64: 1679-1691. <https://doi.org/10.1111/fwb.13373>

1999

2000 Tonkin, J.D., Altermatt, F., Finn, D., Heino, J., Olden, J.D., Pauls, S.U. & Lytle, D.A. 2018. The role of

2001 dispersal in river network metacommunities: patterns, processes, and pathways. *Freshwater Biology* 63:

2002 141-163. <https://doi.org/10.1111/fwb.13037>

2003

2004 Townsend, C.R., Scarsbrook, M.R. & Dolédec, S. 1997. The intermediate disturbance hypothesis, refugia,
2005 and biodiversity in streams. *Limnology and Oceanography* 42: 938-949.
2006 <https://doi.org/10.4319/lo.1997.42.5.0938>
2007
2008 Turunen, J. Markkula, J., Rajakallio, M. & Aroviita, J. 2019. Riparian forests mitigate harmful ecological
2009 effects of agricultural diffuse pollution in medium-sized streams. *Science of the Total Environment* 649:
2010 495-503. <https://doi.org/10.1016/j.scitotenv.2018.08.427>
2011
2012 Turunen, J., Aroviita, J., Marttila, H., Louhi, P., Laamanen, T., Tolkkinen, M., Luhta P.-L., Klove, B. &
2013 Muotka, T. 2017. Differential responses by stream and riparian biodiversity to restoration of forestry-
2014 impacted streams. *Journal of Applied Ecology* 54: 1505-1514. <https://doi.org/10.1111/1365-2664.12897>
2015
2016 Ussiri, D.A.N. & Johnson, C.E. 2007. Organic matter composition and dynamics in a northern hardwood
2017 forest ecosystem 15 years after clear-cutting. *Forest Ecology and Management* 240: 131-142.
2018 <https://doi.org/10.1016/j.foreco.2006.12.017>
2019
2020 van Deen, J. A. & Kuikman, P. J. 1990. Soil structural aspects of decomposition of organic matter by
2021 micro-organisms. *Biochemistry* 11: 213-233. <https://www.jstor.org/stable/1468641>
2022
2023 van Lanen, H.A.J., Wanders, N., Tallaksen, L.M. & Van Loon, A.F. 2013. Hydrological drought across the
2024 world: impact of climate and physical catchment structure. *Hydrology and Earth System Sciences* 17:
2025 1715-1732. <https://doi.org/10.5194/hess-17-1715-2013>
2026
2027 van Leeuwen, C.H.A., Sarneel, J.M., van Paassen, J., Rip, W.J. & Bakker, E.S. 2014. Hydrology, shore
2028 morphology and species traits affect seed dispersal, germination and community assembly in shoreline
2029 plant communities. *Journal of Ecology* 102: 998-1007. <https://doi.org/10.1111/1365-2745.12250>

2030

2031 van Loon, A.F. 2015. Hydrological drought explained. *WIREs Water* 2: 359-392.

2032 <https://doi.org/10.1002/wat2.1085>

2033

2034 Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. & Cushing C.E. 1980. The river continuum

2035 concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37: 130-137. <https://doi.org/10.1139/f80->

2036 017

2037

2038 Vidon, P., Allan, G., Burns, D., Duval, T.P., Gurwick, N., Inamdar, S., Lowrance, R., Okay, J., Scott, D. &

2039 Sebestyen, S. 2010. Hot spots and hot moments in riparian zones: potential for improved water quality

2040 management. *Journal of the American Water Resources Association* 46: 278-298.

2041 <https://doi.org/10.1111/j.1752-1688.2010.00420.x>

2042

2043 Voříšková, J. & Baldrian, P. 2013. Fungal community on decomposing leaf litter undergoes rapid

2044 successional changes. *The ISME Journal* 7: 477-486. <https://doi.org/10.1038/ismej.2012.116>

2045

2046 Vowell, J.L. & Frydenborg, R.B. 2004. A biological assessment of best management practices

2047 effectiveness during intensive silviculture and forest chemical application. *Water, Air and Soil Pollution:*

2048 *Focus*: 4: 297-307. <https://doi.org/10.1023/B:WAFO.0000012812.90967.7a>

2049

2050 Vuori, K.-M. & Joensuu, I. 1996. Impact of forest drainage on the macroinvertebrates of a small boreal

2051 headwater stream: do buffer zones protect lotic biodiversity? *Biological Conservation* 77: 87-95.

2052 [https://doi.org/10.1016/0006-3207\(95\)00123-9](https://doi.org/10.1016/0006-3207(95)00123-9)

2053

2054 Vuori, K.-M., Joensuu, I., Latlava, J., Jutila, E. & Ahvonen, A. 1998. Forest drainage: a threat to benthic
2055 biodiversity of boreal headwater streams? *Aquatic Conservation* 8: 745-759.
2056 [https://doi.org/10.1002/\(SICI\)1099-0755\(1998110\)8:6<745::AID-AQC310>3.0.CO;2-X](https://doi.org/10.1002/(SICI)1099-0755(1998110)8:6<745::AID-AQC310>3.0.CO;2-X)
2057

2058 Wagner, K., Besemer, K., Burns, N. R., Battin, T.J. & Bengtsson, M.M. 2015. Light availability affects
2059 stream biofilm bacterial community composition and function, but not diversity. *Environmental*
2060 *Microbiology* 17: 5036-5047. <https://doi.org/10.1111/1462-2920.12913>
2061

2062 Wallace, J.B., Eggert, S.L., Meyer, J.L. & Webster, J.R. 1997. Multiple trophic levels of a forest stream
2063 linked to terrestrial litter inputs. *Science* 277: 102-104. <https://doi.org/10.1126/science.277.5322.102>
2064

2065 Wallenstein, M.D. & Hall, E.K. 2012. A trait-based framework for predicting when and where microbial
2066 adaptation to climate change will affect ecosystem functioning. *Biogeochemistry* 109: 35-47.
2067 <https://doi.org/10.1007/s10533-011-9641-8>
2068

2069 Wang, Y., Yang, C., Li, J. & Shen, S. 2014. The chemical composition and source identification of soil
2070 dissolved organic matter in riparian buffer zones from Chongming Island, China. *Chemosphere* 111: 505-
2071 512. <https://doi.org/10.1016/j.chemosphere.2014.04.056>
2072

2073 Ward, J.V., Tockner, K., Arscott, D.B. & Claret, C. 2002. Riverine landscape diversity. *Freshwater Science*
2074 47: 517-539. <https://doi.org/10.1046/j.1365-2427.2002.00893.x>
2075

2076 Webster, J.R., Benfield, E.F., Ehrman, T.P., Schaeffer, M.A., Tank, J.L., Hutchens, J.J. & D'angelo, D.J.
2077 1999. What happens to allochthonous material that falls into streams? A synthesis of new and published
2078 information from Coweeta. *Freshwater Biology* 41: 687-705. [https://doi.org/10.1046/j.1365-](https://doi.org/10.1046/j.1365-2427.1999.00409.x)
2079 [2427.1999.00409.x](https://doi.org/10.1046/j.1365-2427.1999.00409.x)

2080

2081 Whitaker, D.M. & Montevecchi, W.A. 1999. Breeding bird assemblages inhabiting riparian buffer strips
2082 in Newfoundland, Canada. *Journal of Wildlife Management* 63: 167-179.

2083 <https://doi.org/10.2307/3802498>

2084

2085 Whitham, T.G., Bailey, J.K., Schweitzer, J.A., Shuster, S.M., Bangert, R.K., LeRoy, C.J., Lonsdorf, E.V.,
2086 Allan, G.J., DiFazio, R.K., Potts, B.M., Fischer, D.G., Gehring, C.A., Lindroth, R.L., Marks, J.C., Hart, S.C.,
2087 Wimp, G.M. and Wooley, S.C. 2006. A framework for community and ecosystem genetics: from genes
2088 to ecosystems. *Nature Reviews Genetics* 7: 510-523. <https://doi.org/10.1038/nrg1877>

2089

2090 Williams, R.J., Howe, A. & Hofmockel, K.S. 2014. Demonstrating microbial co-occurrence pattern
2091 analyses within and between ecosystems. *Frontiers in Microbiology* 5: 358.

2092 <https://doi.org/10.3389/fmicb.2014.00358>

2093

2094 Willis, K. J., Araújo, M. B., Bennett, K. D., Figueroa-Rangel, B., Froyd, C. A. & Myers, N. 2007. How can a
2095 knowledge of the past help to conserve the future? *Biodiversity conservation and the relevance of long-*
2096 *term ecological studies. Philosophical Transactions B* 362: 175-187.

2097 <https://doi.org/10.1098/rstb.2006.1977>

2098

2099 Wilson, D., Hisdal, H. & Lawrence, D. 2010. Has streamflow changed in the Nordic countries? – Recent
2100 trends and comparisons to hydrological projections. *Journal of Hydrology* 394: 334-346.

2101 <https://doi.org/10.1016/j.jhydrol.2010.09.010>

2102

2103 Winterdahl, M., Wallin, M. B., Karlsen, R. H., Laudon, H., Öquist, M. & Lyon, S. W. 2016. Decoupling of
2104 carbon dioxide and dissolved organic carbon in boreal headwater streams. *Journal of Geophysical*
2105 *Research, Biogeosciences* 121: 2630-2651. <https://doi.org/10.1002/2016JG003420>

2106

2107 Wipfli, M.S. 1997. Terrestrial invertebrates as salmonid prey and nitrogen sources in streams:

2108 contrasting old-growth and young-growth riparian forests in southeastern Alaska, U.S.A. *Canadian*

2109 *Journal of Fisheries and Aquatic Sciences* 54: 1259-1269. <https://doi.org/10.1139/f97-034>

2110

2111 Wipfli, M.S., Gregovich, D.P. 2002. Export of invertebrates and detritus from fishless headwater streams

2112 in southeastern Alaska: implications for downstream salmonid production. *Freshwater Biology* 47: 957–

2113 969. <https://doi.org/10.1046/j.1365-2427.2002.00826.x>

2114

2115 Wipfli, M.S., Richardson, J.S. & Naiman, R.J. 2007. Ecological linkages between headwaters and

2116 downstream ecosystems: transport of organic matter, invertebrates, and wood down headwater

2117 channels. *Journal of the American Water Resources Association* 43: 72-85.

2118 <https://doi.org/10.1111/j.1752-1688.2007.00007.x>

2119

2120 Wohl, E. 2017. The significance of small streams. *Frontiers in Earth Science* 11: 447-456.

2121 <https://doi.org/10.1007/s11707-017-0647-y>

2122

2123 Wolfe, E.R., Younginger, B.S. & LeRoy, C.J. 2019. Fungal endophyte-infected leaf litter alters in-stream

2124 microbial communities and negatively influences aquatic fungal sporulation. *Oikos* 128: 405-415.

2125 <https://doi.org/10.1111/oik.05619>

2126

2127 Wong, W.K. & Beldring, S. 2011. Climate change effects on spatiotemporal patterns of

2128 hydroclimatological summer droughts in Norway. *Journal of Hydrometeorology* 12: 1205-1220.

2129 <https://doi.org/10.1175/2011JHM1357.1>

2130

2131 Wong, G., van Lanen, H.A.J. & Torfs, P.J.J.F. 2013. Probabilistic analysis of hydrological drought
2132 characteristics using meteorological drought. *Hydrological Sciences Journal* 58: 253–270.
2133 <https://doi.org/10.1080/02626667.2012.753147>
2134

2135 Wood, P. J. & Armitage, P. D. 1999. Sediment deposition in a small lowland stream — management
2136 implications. *Regulated Rivers: Research & Management* 15: 199-210.
2137 [https://doi.org/10.1002/\(SICI\)1099-1646\(199901/06\)15:1/3<199::AID-RRR531>3.0.CO;2-0](https://doi.org/10.1002/(SICI)1099-1646(199901/06)15:1/3<199::AID-RRR531>3.0.CO;2-0)
2138

2139 Ylla, I., Canhoto, C. & Romaní, A.M. 2014. Effects of warming on stream biofilm organic matter use
2140 capabilities. *Microbial Ecology* 68: 132-154. <https://doi.org/10.1007/s00248-014-0406-5>
2141

2142 Yuste, J.C., Peñuelas, J., Estiarte, M., Garcia-Mas, J., Mattana, S., Ogaya, R., Pujol, M. & Sardans, J. 2011.
2143 Drought-resistant fungi control soil organic matter decomposition and its response to temperature.
2144 *Global Change Biology* 17: 1475-1486. <https://doi.org/10.1111/j.1365-2486.2010.02300.x>
2145

2146 Zhang, X., Harvey, K.D., Hogg, W.D. & Yuzyk, T.R. 2001. Trends in Canadian streamflow. *Water*
2147 *Resources Research* 37: 987-998. <https://doi.org/10.1029/2000WR900357>
2148

2149 Zinko, U., Seibert, J., Dynesius, M. & Nilsson, C. 2005. Plant species numbers predicted by a topography-
2150 based groundwater flow index. *Ecosystems* 8: 430-441. <https://doi.org/10.1007/PL00021513>
2151

2152 Zogg, G.P., Zak, D.R., Ringelberg, D.B., MacDonald, N.W., Pregitzer, K.S. & White, D.C. 1997.
2153 Compositional and functional shifts in microbial communities due to soil warming. *Soil Science Society*
2154 *of America Journal* 61: 475-481. <https://doi.org/10.2136/sssaj1997.03615995006100020015x>
2155

2156 Zwart, G., Crump, B.C., Kamst-van Agterved, M.P., Hagen, F. & Han, S.-K. 2002. Typical freshwater
2157 bacteria: an analysis of available 16S rRNA gene sequences from plankton of lakes and rivers. *Aquatic*
2158 *Microbial Ecology* 28: 141-155. <https://doi.org/10.3354/ame028141>
2159
2160
2161