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Groundwater contamination and land drainage induce divergent responses in boreal spring ecosystems

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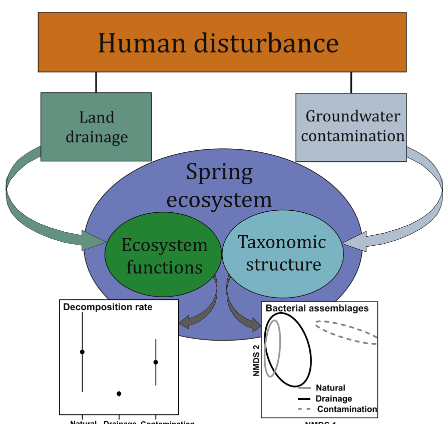
HIGHLIGHTS

- Anthropogenic pressure altered the structure and functioning of boreal springs.
- Groundwater contamination reduced diversity of spring invertebrates and bacteria.
- Primary production exhibited a subsidy-stress response to groundwater contamination.
- Ecosystem processes were inhibited by drainage-induced groundwater brownification.
- Ecosystem functions should be used in bioassessment of groundwater-dependent ecosystems.

GRAPHICAL ABSTRACT



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ABSTRACT

Degradation of freshwater ecosystems has engendered legislative mandates for the protection and management of surface waters while groundwater-dependent ecosystems (GDEs) have received much less attention. This is so despite biodiversity and functioning of GDEs are currently threatened by several anthropogenic stressors, particularly intensified land use and groundwater contamination. We assessed the impacts of land drainage (increased input of dissolved organic carbon, DOC, from peatland drainage) and impaired groundwater chemical quality (NO_3^--N enrichment from agricultural or urban land use) on biodiversity and ecosystem functioning in 20 southern Finnish cold-water springs using several taxonomic and functional measures. Groundwater contamination decreased macroinvertebrate and bacterial diversity and altered their community composition. Changes in macroinvertebrate and bacterial communities along the gradient of water-quality impairment were caused by the replacement of native with new taxa rather than by mere disappearance of some of the original taxa. Also species richness of habitat specialist (but not headwater generalist) bryophytes decreased due to impaired groundwater quality. Periphyton accrual rate showed a subsidy-stress response to elevated nitrate concentrations, with peak values at around 2500 μg L^{-1}, while drainage-induced spring water brownification (increased DOC) reduced both periphyton accrual and leaf decomposition rates already at very low concentrations. Our results highlight the underutilized potential of ecosystem-level functional measures in GDE bioassessment as they seem

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to respond to the first signs of spring ecosystem impairment, at least for the anthropogenic stressors studied by us.

1. Introduction

Freshwaters are globally among the most threatened ecosystems and freshwater biodiversity loss is disproportionately high (Strayer and Dudgeon, 2010). Agricultural intensification and urbanization rank highest among anthropogenic threats to freshwater ecosystems, causing not only nutrient enrichment but also organic pollution (Malaj et al., 2014) and salinization (Cañedo-Argüellus et al., 2013, 2016). The ongoing degradation of freshwater ecosystems has engendered legislative mandates for the protection and management of surface waters (e.g. European Water Framework Directive) while groundwater-dependent ecosystems (GDEs) have received substantially less attention.

Cold-water springs are fed by a continuous flux of thermally stable groundwater, creating unique environmental setting for the development of highly specialized biota (Cantonati et al., 2012). Like most GDEs, also springs are threatened by land use and impaired water quality (Barquín and Scarsbrook, 2008; Lehosmaa et al., 2017). Since the nineteenth century, peatland drainage has greatly modified northern European forest landscapes (Holden et al., 2004), the goal being enhancement of forest growth by channeling surplus water to recipient streams and lakes. In Finland, drainage was practiced until 1997 when the Finnish Forest Act declined further forest drainage, and currently only maintenance of old drainage networks is permitted. Forest drainage has deteriorated fluvial ecosystems by, for example, increasing sediment loads and nutrient concentrations (Jyväsjärvi et al., 2014; Nieminen et al., 2017). Little is known about drainage impacts on GDEs, although some recent studies have documented increased surface water inflow, lower thermal stability and elevated concentrations of dissolved organic carbon (DOC) in drainage-impacted springs (Lehosmaa et al., 2017), with major consequences on spring biodiversity (Lehosmaa et al., 2017).

Groundwater resources are globally compromised by several harmful agents. Nitrate (NO_3^-) is the most ubiquitous contaminant of groundwater (Spalding and Exner, 1993) and is derived from both diffuse sources (Mahvi et al., 2005) and a mixture of urban and agricultural point sources (Wakida and Lerner, 2005). Nitrate typically covaries with other groundwater contaminants (Katz et al., 2009; Nolan and Weber, 2015) and can thus be considered a proxy of groundwater chemical degradation. Increasing concentrations of dissolved inorganic salts (Cañedo-Argüellus et al., 2016) impose an additional threat to groundwater resources. In northern regions, increased salinity originates mainly from road salt (NaCl) which is easily transported to groundwater (Williams et al., 2000; Thunqvist, 2004).

Despite increasing awareness of the degradation of groundwater and groundwater-dependent ecosystems, comparative studies on the diversity and community composition of GDE biota and ecosystem processes along anthropogenic stressor gradients are largely lacking. We assessed the impacts of two such stressors, land drainage and groundwater contamination, on structural (benthic macroinvertebrates, aquatic bryophytes, leaf-decomposing fungi and groundwater bacteria) and functional (primary productivity and organic matter decomposition) characteristics in 20 boreal springs. Springs unaffected by drainage and with unaltered water chemistry were used as reference sites whereas the impacted sites were characterized by either drainage-induced thermal instability and brownification of the spring water (increased DOC content) or by strongly elevated nitrate concentrations from agricultural or urban land use. We expected that both stressor types should cause communities and ecosystem functions to deviate from those in near-pristine reference conditions. More specifically, we expected (i) land drainage to have the strongest impact on macroinvertebrates (Ilmonen et al., 2009), while autotrophs (Virtanen et al., 2009) and microorganisms (Stein et al., 2010; Korbel et al., 2013) should respond more to changes in groundwater quality. We further expected (ii) ecosystem processes to show a subsidy-stress response (Odum et al., 1979; Wagenhoff et al., 2011) to groundwater contamination. At low-to-moderate doses, nutrient (nitrogen) enrichment should accelerate primary productivity and decomposition rates, while at high concentrations, nutrients (and associated chemicals) cause groundwater contamination, reducing ecosystem process rates (see Woodward et al., 2015). Alternatively, any positive effects of nutrient enrichment could be largely cancelled by other contaminants associated with agriculture or urbanization, resulting in no net change to ecosystem process rates. We also expected (iii) ecosystem processes to show divergent responses to the two stressors, groundwater contamination resulting in the stress-subsidy type of response while land drainage might suppress ecosystem functions already at low stressor levels, due mainly to altered thermal stability and increased brownification caused by humic substances (Lehosmaa et al., 2017).

2. Materials and methods

2.1. Selection of study sites

We collected biological and environmental data from 20 southern Finnish (60.13°–62.16° N; 22.4°–26.9° E) springs. Reference sites and sites disturbed by land drainage or groundwater contamination were spatially interspersed (see Appendix 1). The study sites were comparable in terms of size and habitat structure with a distinct spring pool and an outflowing stream. Spring habitat integrity was assessed using a four-tiered classification by Heino et al. (2005) whereby sites with drainage ditches flowing directly into the spring pool were assigned degraded (hereafter "Drainage"; class 0). Pristine or near-pristine springs with no visible human impact in the vicinity of the spring (within at least 100 m from a spring) were assigned "Natural" (class 3). In situ water quality (pH, electrical conductivity) and water chemistry data of the parent aquifers (obtained from national HERTTA database by Finnish Environment Institute, SYKE) were used to confirm that springs in these two groups showed no major alteration of groundwater quality. To include sites with degraded water quality (WQ), we screened, using SYKE groundwater monitoring database, all southern Finnish aquifers with disproportionately high nitrate (>2000 μg L^{-1} NO_3^--N) concentrations compared to national mean values (see Rossi et al., 2015). Map surveys were used to locate springs connected to contaminated aquifers and these sites were visited to confirm that their habitat structure did not deviate from the reference condition. This site selection procedure resulted in a data set containing 1) 'Natural' springs undisturbed by any anthropogenic stressors (n = 7); 2) 'Drainage' springs, i.e. springs directly impacted by drainage but with negligible changes in groundwater quality (n = 5), and 3) 'WQ' springs with impaired groundwater quality but no drainage impacts (n = 8).

2.2. Environmental data

Area (m^2) of different habitat types (i.e. spring pools, helocrenes, and spring brooks with either minerogenic or organogenic substrate) was measured during sampling visits. Depth of the spring pool and depth and width of the outflowing stream were measured at five