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INVITED COMMENTARY

Management perspectives on *Aqua incognita*: Connectivity and cumulative effects of small natural and artificial streams in boreal forests

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1 | *Aqua incognita*—WHAT DO WE KNOW AND WHAT WE DON'T

The original publication of the unknown headwaters—*Aqua Incognita*—by Bishop et al. (2008) ended by posing two compelling questions: (a) Are the headwaters important? and (b) Is it possible to make an assessment of something so vast and changeable? In this commentary, we summarize recent research focused on the original questions, including the ecology, biogeochemistry, and hydrogeomorphology of small streams and their distribution in the landscape. We further include the perspective of artificial drainage ditches dug to increase forest production, with the overall aim to incorporate the *Aqua Incognita* concept into boreal forest management. Finally, we present current knowledge gaps about both natural and artificial forest waterways that likely impede the advancement of best-management practices in boreal forests.

Over the last decade, one major advancement in headwater science is our ability to remotely identify and accurately map the smallest channels in drainage systems (Benstead & Leigh, 2012). This progress reflects the development of computational techniques that leverage increasingly accessible, high-resolution digital elevation models. Together, these tools have revealed the dense distribution and abundance of headwater streams and their temporal dynamics. Meteorological, climatic, and topographic factors determine variation in the source area needed for a waterway to support flow (Hewlett & Hibbert, 1967), and these interacting factors drive temporal fluctuations in the overall size of river networks. For example, in the Krycklan Catchment Study in northern Sweden (Figure 1) the total length of the stream network can be up to 4.5 times longer during wet compared to dry conditions (Ågren, Lidberg, & Ring, 2015). These new techniques have simultaneously revealed the extent of man-made drainage ditches created to promote forest growth, and their connectivity to streams (Figure 1). Indeed, a recent study in the Krycklan Catchment Study found that the ditch network doubled the length of the stream network (Hasselquist, Lidberg, Sponseller, Ågren, & Laudon, In Review) and that many drainage ditches were once headwater streams that have been deepened and straightened to increase their drainage capacity (Figure 1; Ågren et al., 2015).

Recent research has also advanced our understanding of the intimate connection between headwater streams and their surroundings. Riparian forests moderate incoming radiation and thus thermal and light regimes, while also regulating inputs of leaf litter and other subsidies to streams (Richardson & Danehy, 2007). Owing to their small water volume and low discharge, headwater streams are also tightly connected to riparian and upland areas via groundwater. Groundwater inputs to small streams control the thermal, hydrological, and

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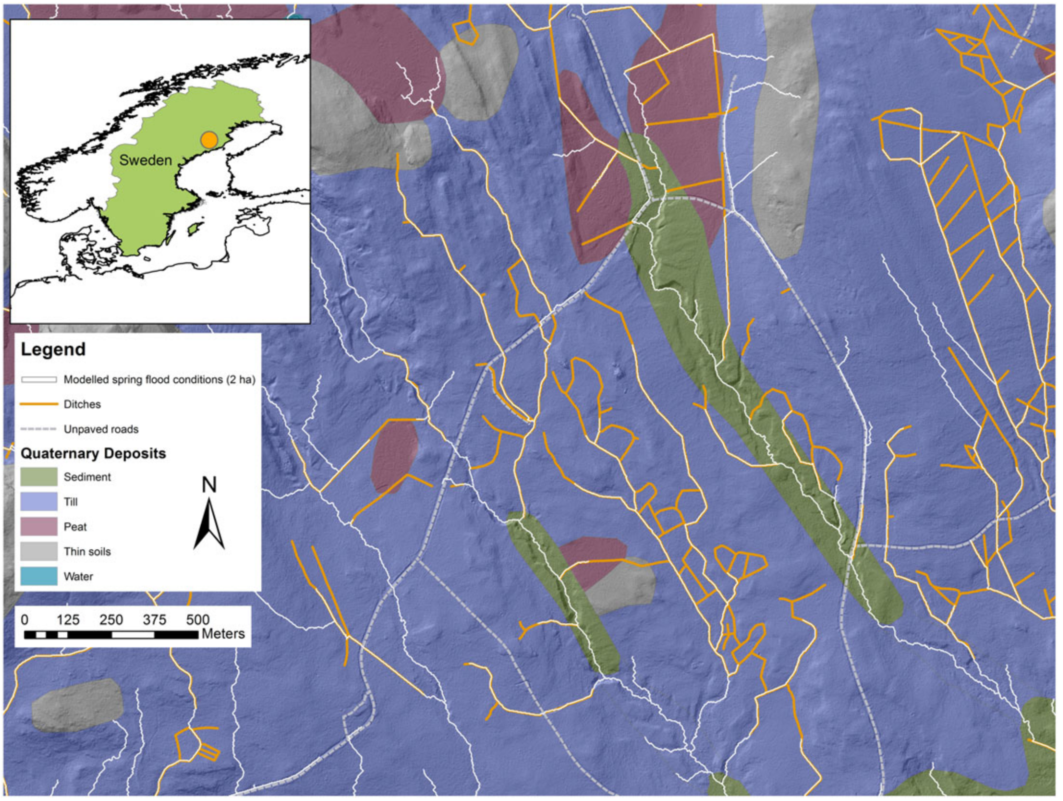

FIGURE 1 Stream network during spring flood conditions for a forested portion of the Krycklan Catchment Study (KCS; stream initiation area of 2 ha; Ågren et al., 2015). Soil types and artificial drainage ditches are shown overlain on a recent digital elevation model. Note that many headwater streams flow within or near forest drainage ditches. Approximate location of the KCS is shown on the inset map of Fennoscandia

biogeochemical regimes of surface water and are regulated by local topography and subsurface geology, which can vary in space and time (Sass, Creed, Riddell, & Bayley, 2014; Valett et al., 1997). For example, it has recently been shown that in the Swedish boreal forest, >60% of stream base flow may originate from discreet groundwater discharge areas which represent only about 10% of the channel length (Leach et al., 2017). This highlights the significance of small-scale heterogeneity in the hydrologic connections between headwater streams and riparian zones that has important implications for how we understand and manage these ecosystems.

It is now well established that headwater streams play multiple important ecological and biogeochemical roles within the landscapes. Small streams represent primary habitat and key dispersal corridors for many species of invertebrates, amphibians, and plants (Clarke, Mac Nally, Bond, & Lake, 2008; Grant, Lowe, & Fagan, 2007; Kuglerová, Dynesius, Laudon, & Jansson, 2016). In addition, numerous fish species may temporarily use headwaters for nurseries and/or to escape predation in downstream reaches (Freeman, Pringle, & Jackson, 2007). Further, emerging aquatic insects from small streams are an important resource for local terrestrial consumers (Marczak & Richardson, 2007) and many subsidies (e.g., dissolved and particulate organic matter, nitrogen, and phosphorus) are supplied from headwaters to downstream ecosystems (Richardson & Danehy, 2007; Rosemond et al. 2015).

Research on the effects of forestry on headwater streams has contributed to insights used to develop new management policies. Harvest operations can cause elevated sediment inputs and transport, negatively altering benthic habitat and associated biota (e.g., Kreutzweiser, Capell, Good, & Holmes, 2009), although this may be less important in till-soil dominated catchments (Jonsson et al., 2017). Some management practices represent higher risks than others; for example, stream crossings, road building, or driving heavy machines in riparian zones and hydrologically sensitive areas (i.e., groundwater discharge areas) can elevate sediment transport and change biogeochemistry but can be mostly avoided by better planning (Ågren et al., 2015; Kreutzweiser, Beall, Webster, Thompson, & Creed, 2013; Laudon et al., 2016). Instream and riparian biota also react to forest harvest; however, many of these temporary changes reflect increased solar radiation, which can be mitigated by various buffer designs (Selonen & Kotiaho, 2013; Warren et al., 2016). Similarly, hydrological and biogeochemical changes following forest harvest may also be transient and moderated by buffer zone processes (e.g., Kreutzweiser, Capell, & Holmes, 2009; Lee, Smyth, & Boutin, 2004; Sweeney & Newbold, 2014).

On the other hand, avoiding all modifications to riparian areas and streams through protected no-harvest buffers may also have undesirable consequences in boreal forest landscapes. Historically, boreal forests have been subject to natural disturbance and recovery processes governing vegetation structure, composition, and productivity. Where such processes are prevented, riparian zones and adjacent streams likely benefit from some level of management that emulates natural disturbance. For example, about 12 years after natural stand-replacing fire in boreal headwater catchments, riparian forests were found to be more diverse and dominated by early successional woody vegetation compared to riparian forests protected by no-harvest buffers in the same region. Importantly, the recovering riparian forests in burned catchments delivered higher rates and complexity of leaf litter to streams, and supported richer invertebrate communities than streams in nearby catchments with protected riparian buffers (Musetta-Lambert, Muto, Kreutzweiser, & Sibley, 2017). Similarly, in managed landscapes of northern Sweden, no-harvest buffer zones are eventually dominated by coniferous trees (Norway spruce) and patches of early successional forest generated through harvest serve as critical sources of deciduous litter to headwaters (Lidman, Jonsson, Burrows, Bundschuh, & Sponseller, 2017).

While some level of management that emulates natural disturbances can be beneficial for riparian and stream ecosystems, the potential negative effects of intentional disturbance linked to management of forest drainage ditches is often overlooked and accepted as part of day-to-day forestry practice. Draining new areas for forestry is nowadays avoided in Fennoscandia, but ditch network maintenance (DNM), which includes ditch cleaning and sometimes complementary ditching (digging of new ditches between existing ones) is common and negatively influences water quality by increasing downstream fluxes of suspended solids, metals, and nutrients (Joensuu, Ahti, & Vuollekoski, 1999, 2002; Nieminen et al., 2010; Stenberg et al., 2015). The mobilization of sediment from DNM may further cause shifts in benthic invertebrate diversity and assemblage structure (Hansen et al., 2013; Vuori and Joensuu, 1996). Recently, questions have arisen about how to prioritize DNM (Sikström & Hökkä, 2016; Hasselquist et al., in review), and how it can be aligned with sustainable forest management (Lõhmus, Remm, & Rannap, 2015).

Although we know that the *Aqua Incognita* have important ecological and biogeochemical roles, there are still some knowledge gaps in our understanding of biological communities and ecosystem functions within the headwaters. The distribution and diversity of many headwater-dependent organisms is still poorly described as well as the spatial and temporal function of headwaters as population sources for downstream ecosystems (Freeman et al., 2007). There is also continued debate regarding the significance of ecosystem processes in headwaters with respect to, for example, nutrient retention (Brookshire, Valett, & Gerber, 2009), organic matter processing (Raymond, Saiers, & Sobczak, 2016), and primary and secondary production (Freeman et al., 2007). How these various functions apply to ditches is even less understood. For example, ditches may serve to expedite the flux of water, solutes, and sediments from landscapes by concentrating flow and increasing drainage density (Doyle & Bernhardt, 2011); yet, they could also play a role in the removal and transformation of these same materials. Furthermore, it is still unknown if forest ditches provide habitat similar to small, intermittent streams or if they support unique sets of organisms and ecosystem processes (Lõhmus et al., 2015).

Another largely unexplored aspect of headwater science is the cumulative contribution of small streams to downstream lotic systems (Kreutzweiser et al., 2013). Headwater streams are sources of water, biogeochemical substances, and biological communities that support and sustain downstream reaches (Freeman et al., 2007; Wipfli, Richardson, & Naiman, 2007); nevertheless, the cumulative consequences of headwater disturbance have just emerged as a crucial topic (Seitz, Westbrook, & Noble, 2011). Headwaters are numerous, usually representing >80% of the total river network length (Bishop et al., 2008; Gomi, Sidle, & Richardson, 2002). However, whether the effects of headwater impairments on different downstream variables are additive, synergistic, or simply dissipate is poorly known, particularly when those disturbances are spatially scattered. In a similar manner, headwater conditions are likely affected by the density and configuration (e.g., dendritic, comb, and grid) of the upstream ditch network and whether ditches connect to streams directly or through various mitigation structures (e.g., sediment traps, overland flow fields, and breaks in ditches); yet this has not been explicitly shown.

2 | CURRENT MANAGEMENT PRACTICES

It is well known that adjacent forests shape multiple facets of stream habitat condition and thus riparian trees are typically left as buffers (Richardson, Naiman, & Bisson, 2012). The guidelines for buffers around mapped or visible headwaters vary among jurisdictions, from no-harvest widths of ≥30 m on each side of the stream (Ontario, Canada) to no treed-buffers required along headwater streams without fish or <1.5 m wide (British Columbia, Canada). In Sweden, 5–30 m of no-harvest buffer is suggested to protect small headwaters (1–2 m width), with the narrowest limit typically seen. Smaller or intermittent streams (<1 m width) in Sweden, Canada, and elsewhere are often left with little or no-treed buffer (but a machine-free zone; Kuglerová, Ågren, Jansson, & Laudon, 2014; Lee et al., 2004; Sweeney and Newbold, 2014; Figure 2a,b). Like small streams, ditches that are *not* cleaned are often left with a machine-free zone (Figure 2c), while

FIGURE 2 (a) A narrow riparian buffer (5–10 m) along a headwater stream in the Balsjö experiment and (b) a small headwater stream left partly with no buffer and partly with a buffer of one-tree-row width. (c) An old drainage ditch within a clear cut with a machine-free zone left on either side. Photo credits: E. Maher Hasselquist and L. Kuglerová

DNM is usually connected to tree removal along ditches to allow for driving machines used for cleaning. This complete lack of (in the case of cleaned ditches) or minimal protection (in the case of the streams) for small waterways has traditionally been motivated by the commercial value of riparian timber. At the same time, this lack of protection was, at least partly, due to insufficient mapping in the past (Bishop et al., 2008), and the lack of legal basis for management at this small scale under current water protection legislation, such as the EU's Water Framework Directive (Futter et al., 2011).

Nevertheless, research on the factors affecting water quantity and quality, biogeochemistry, and ecology of headwaters and their downstream reaches has prompted new thinking about riparian buffer design. The typical fixed-width buffers (i.e., uniform width and stand structure along stream reaches on both sides, Figure 2a) are operationally easy to implement and are somewhat effective in water quality and biodiversity protection; however, these may be inefficient in terms of their cost–benefit analysis (Tiwari et al., 2016) and they may not mimic natural conditions. Fixed-width buffers are based on the assumption that riparian patterns and processes are homogenous along the river continuum. It is well documented that this is not the case, and in reality riparian functions, biodiversity, hydrology, and biogeochemistry vary at small spatial scales (e.g., Kuglerová et al., 2014, 2016; Leach et al., 2017; Sass et al., 2014). Thus, to better protect streams and save on buffer implementation costs (Tiwari et al., 2016), we likely need to design buffers that account for the heterogeneity of riparian processes and functions, along longitudinal, lateral, and temporal dimensions.

Two approaches for designing riparian buffers have been suggested in recent years: hydrologically adapted buffers (HAB; Kuglerová et al., 2014; Figure 3a) and buffers emulating natural disturbance (END; Kreutzweiser, Sibley, Richardson, & Gordon, 2012; Figure 3b). In short, HAB originates from the fact that many ecosystem processes and functions within riparian forests are connected to subsurface hydrology, specifically the flow of shallow groundwater (Kuglerová et al., 2014; Laudon et al., 2016; Sass et al., 2014). Current mapping techniques and hydrological models based on terrain topography are relatively accurate at predicting where in the landscape groundwater discharge or water accumulation occur (Ågren, Lidberg, Strömgren, Ogilvie, & Arp, 2014; Ågren et al., 2015; Creed, Sass, Buttle, & Jones, 2011) and, as such, offer a direct tool for end users to locate these hydrologically active and sensitive areas. Second, END management of riparian forest acknowledges that natural disturbances (e.g., fire, insect outbreak, and windthrow) can remove trees all the way to the water's edge, creating patchy riparian forests with stands of early successional regeneration interspaced with patches of older trees (Kreutzweiser et al., 2012). Keeping riparian forests in conditions that capture a reasonable range of natural variation may therefore require intentional disturbance by careful harvesting in riparian buffers, instead of fixed-width, no-harvest buffers (Naylor, Mackereth, Kreutzweiser, & Sibley, 2012). The HAB and END concepts for riparian management converge in the sense that residual mature riparian forests often remain intact after natural disturbance, fire in particular, in areas of wetted soils or groundwater discharge. Both of these ideas have been discussed for some years now but are only now starting to be individually applied as small-scale experiments (Kreutzweiser, Capell, Good, et al., 2009; Kreutzweiser, Capell, Holmes, 2009; Musetta-Lambert et al., 2017) and in early revisions to forest management guidelines (Naylor et al., 2012; OMNR, 2010; www.skogsstyrelsen.se).

Currently, ditches draining valuable wetland environments should be left uncleaned (www.skogsstyrelsen.se), thus being protected in a similar way as HAB intends. In other locations, ditches are not cleaned either because they have permanently altered soil water conditions (i.e., areas with thin peat that has subsided), continue to function, or were poorly planned in the first place and failed their purpose. These ditches could be managed as small streams, and the HAB and END riparian management could apply. Finally, for ditches that are located in unproductive peatlands, wetland restoration by blocking and/or filling in ditches is increasingly performed. In cases

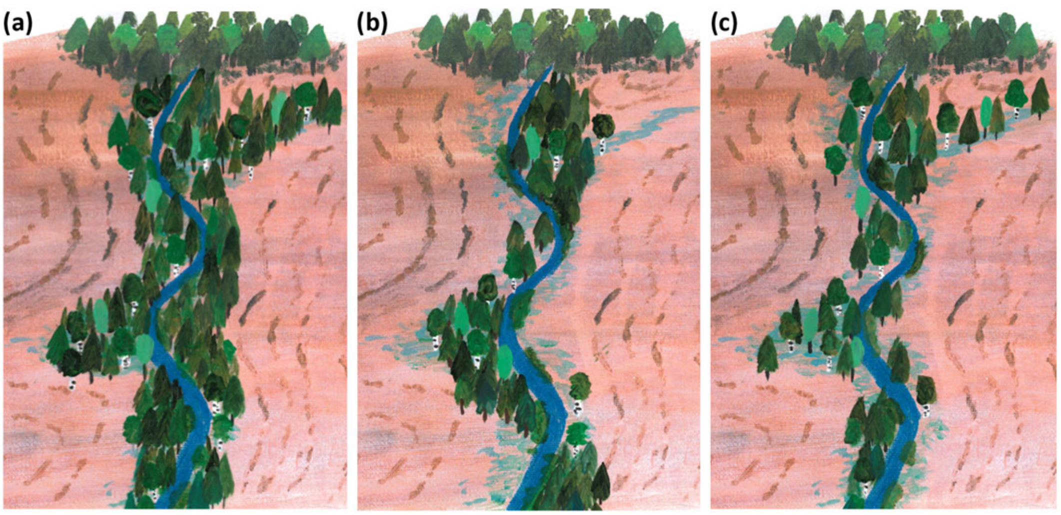

FIGURE 3 Different riparian buffer designs around a headwater stream in a clear-cut catchment. A hydrologically adapted buffer (HAB) is shown in (a) where buffer width is extended at groundwater discharge hotspots. A buffer which emulates natural disturbance (END) is displayed in (b) where the riparian forest was partially removed all the way to the water's edge. The combination of the two approaches (HAB + END) is shown in (c), where wider buffers (with partial tree removal) are maintained on groundwater discharge hotspots, and buffers are narrower, partially harvested or cut to the water's edge on less ecologically sensitive areas. Artwork by L. Kuglerová

where DNM is implemented, mitigation structures, such as sediment pits or ponds and surface runoff areas, are typically used to reduce environmental impacts (Päivänen & Hånell, 2012). Their placement should be at the margin between the cleaned ditch and the stream (www.skogsstyrelsen.se) as an attempt to limit the transport of sediments and nutrients and to prevent downstream effects.

3 | THE WAY FORWARD

Increasing the land area committed to no-harvest buffers imposes operational constraints and economic trade-offs for landowners and industry and will have to be justified by ecological benefits. Traditional fixed-width buffers along small streams are unlikely the most ecologically beneficial configuration because they do not reflect the heterogeneity in pattern and function of natural riparian forests. The combination of HAB and END management along forested headwaters (Figure 3c) is a potential strategy that can incorporate higher tree retention at hydrologically active and sensitive areas (i.e., groundwater discharge areas) and, at the same time, release some economic pressure by allowing more harvesting at other locations. Groundwater discharge areas along headwater streams are often associated with wider riparian zones (Kuglerová et al., 2016) which require larger buffers compared to current practices to protect their vital ecosystem functions. However, forest productivity (i.e., tree growth) can be lower in these zones, with a higher representation of less commercially valuable tree species (Tiwari et al., 2016). Further, Ågren et al. (2015) showed that wet areas are more susceptible to rutting and costly operational surprises such as trapped machines in wet and less compact soils. Therefore, economic losses from increased spatial protection of wet riparian forests could be minimal.

Allowing harvest within riparian zones as part of END management can be incorporated with HAB at sites with lower ecological, biogeochemical, and hydrological significance (Figure 3c). Some ecosystem changes associated with riparian canopy removal would occur in forest landscapes under natural disturbances (e.g., fires or insect outbreaks; Musetta-Lambert et al., 2017), and we should not be reluctant to incorporate this thinking into streamside management if the goal is long-term sustainability. In fact, in the boreal forest of Fennoscandia where natural fires have largely been eliminated, incorporating END approaches may have positive implications for aquatic diversity and processes (e.g., litter breakdown; Lidman et al., 2017; Musetta-Lambert et al., 2017). Finally, partial harvest or thinning even within groundwater discharge areas could be implemented because sparse canopy gaps can promote diversity and are likely not detrimental for other ecosystem functions in these ecosystem hotspots; however, ground disturbance must be avoided. Fortunately, current hydrological and topographical modelling techniques can determine locations for both higher and lower riparian protection in terms of their hydrological connectivity, steepness, soil depth, and so forth, and they can be easily and reliably generated in boreal landscapes (Ågren et al., 2014, Leach et al. 2017).

How HAB and END management could apply to forest drainage ditch management depends greatly on the landscape context of the ditch. If ditches are undergoing DNM, HAB and END principles are not likely useful, but they can be highly valuable where ditches are not cleaned. Nevertheless, giving ditches the same protection as headwater streams may reduce the financial ability to properly protect natural streams. As such, until we know more about the ecological value of forest ditches (Lõhmus et al., 2015), one approach would be to designate them as low quality or heavily degraded streams. Using this approach, riparian buffers are likely unnecessary for forest ditches and it is likely sufficient that existing ditches have no ground disturbance in or around them to reduce downstream transfer of sediments, nutrients, and pollutants, unless absolutely necessary to maintain a productive forest stand (Figure 2c). Much work is being done to evaluate if and when ditches are functioning for land drainage, if they should be cleaned to facilitate forest productivity (Sikström & Hökkä, 2016), or whether they function as small streams and refugia for displaced wetland species (Lõhmus et al., 2015). With these emerging aspects, ditches could be incorporated into forestry planning after consideration of the cost–benefit analysis of economic and environmental goals.

It is obvious that not all headwaters within the landscape can and will receive sufficient protection to meet every environmental objective, prompting the question of how to prioritize one headwater over other. In boreal systems, the high spatial density of small streams (Figure 1) suggests that headwaters situated close to each other may have similar ecological and ecosystem importance. Still, prioritization is difficult because the extent to which certain headwaters are considered more important than others could be based on multiple criteria, for example, using their flow regimes (e.g., perennial vs. intermittent), ability to support biodiversity, disturbance history, and the landscape patches they drain or flow through (e.g., forests, mires, or lakes). At this point, large-scale experiments to address cumulative effects of headwater disturbance are operationally difficult, and thus models are required to predict what sections of upstream river networks are most important for maintaining the integrity of downstream environments (Wipfli et al., 2007). Once we fully understand the ecological and economic trade-offs between varying riparian buffer retention, we can more confidently prioritize riparian forest protection along headwater streams in an ecologically relevant manner to generate more desirable environmental and economic outcomes.

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