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Ecology and extent of freshwater browning - What we know and what should be studied next in the context of global change

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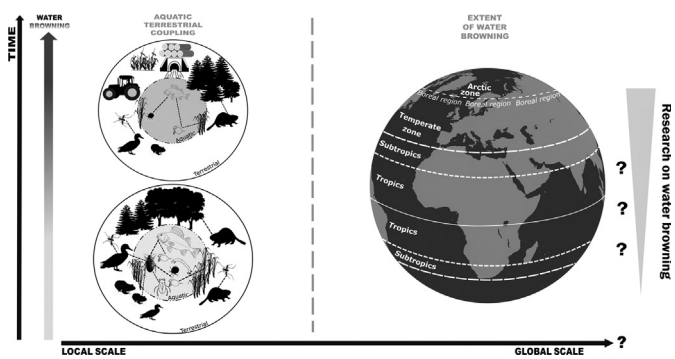
HIGHLIGHTS

- Browning studies overlooked freshwater habitats like small and temporary wetlands.
- Macrophytes, invasive species, and food webs are disregarded in browning studies.
- Browning and the aquatic-terrestrial habitat coupling should be investigated.
- Browning is a more global phenomenon than current focus on boreal zones suggests.
- Remote sensing offers great potential to investigate browning at a global scale.

GRAPHICAL ABSTRACT



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ABSTRACT

Water browning or brownification refers to increasing water color, often related to increasing dissolved organic matter (DOM) and carbon (DOC) content in freshwaters. Browning has been recognized as a significant physicochemical phenomenon altering boreal lakes, but our understanding of its ecological consequences in different freshwater habitats and regions is limited. Here, we review the consequences of browning on different freshwater habitats, food webs and aquatic-terrestrial habitat coupling. We examine global trends of browning and DOM/DOC, and the use of remote sensing as a tool to investigate browning from local to global scales. Studies have focused on lakes and rivers while seldom addressing effects at the catchment scale. Other freshwater habitats such as small and temporary waterbodies have been overlooked, making the study of the entire network of the catchment incomplete. While past research investigated the response of primary producers, aquatic invertebrates and fishes, the effects of browning on macrophytes, invasive species, and food webs have been understudied. Research has focused on freshwater habitats without considering the fluxes between aquatic and terrestrial habitats. We highlight the importance of understanding how the changes in one habitat may cascade to another. Browning is a broader phenomenon than the heretofore concentration on the boreal region. Overall, we propose that future studies improve the ecological understanding of browning

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through the following research actions: 1) increasing our knowledge of ecological processes of browning in other wetland types than lakes and rivers, 2) assessing the impact of browning on aquatic food webs at multiple scales, 3) examining the effects of browning on aquatic-terrestrial habitat coupling, 4) expanding our knowledge of browning from the local to global scale, and 5) using remote sensing to examine browning and its ecological consequences.

Contents

1. Introduction

Over the last three decades, surface waters have become browner throughout the Northern Hemisphere (Monteith et al., 2007) raising concerns about the processes in action, its spatial extent and the consequences for water quality and aquatic trophic webs. The change in water color toward browner hues is known as the "brownification" process or "browning". Since no consensus exists on a preferred term to describe the increase in water color, we refer to it as (water) browning throughout this article.

Browning of surface waters refers to an increase in water color toward yellow-brown hues (Graneli, 2012). Water color is strongly related to dissolved organic matter (DOM) or carbon (DOC) of terrestrial origin (Weyhenmeyer et al., 2014; Kritzberg, 2017). DOM originates from decomposition processes of dead organisms, such as microorganisms, animals, and plants in both aquatic and terrestrial habitats. DOM is a natural component of water and includes any compounds that can pass through a 0.45 μm mesh (Evans et al., 2005). Therefore, the composition of DOM varies between different environments. In general, DOM is composed of a small proportion of low molecular weight compounds, such as amino acids, and a larger proportion of high and medium molecular weight humic and fulvic acids, commonly referred as humic substances. DOM absorbs light in the ultraviolet and in the short wavelengths of visible light, which gives a yellow-brown color to DOM-rich waters (Evans et al., 2005).

DOC is the primary component of DOM. It plays an important role in surface waters' biogeochemistry and ecology, e.g., food web dynamics and structure, carbon budgets and acid-base chemistry (Salonen et al., 1983; Hruška et al., 2003; Cole et al., 2007; Jansson et al., 2007). Browning and lake productivity tend to have a unimodal relationship, where initial increment of DOC tends to boost biological productivity until a concentration of about 5 mg/L is reached, whereafter subsequent browning tends to decrease productivity (e.g., Finstad et al., 2014; Seekell et al., 2015). In lakes, water color is often measured with absorbance coefficients at 254 and 440 nm (e.g., Köhler et al., 2013; Fasching et al., 2014); and is considered brown when DOC concentration exceeds 10 mg/L. However, the browning of waters may be greater than the increase in DOM/DOC content in waters (Hongve et al., 2004; Erlandsson et al., 2008). Concurrent increases in DOM and dissolved iron (Fe) concentrations in surface waters have been observed in the arctic, boreal and temperate zones and associated to changes in water color (e.g., Kritzberg and Ekström, 2012; Sarkkola et al., 2013; Brezonik et al., 2019; Xiao and Riise, 2021). DOM and Fe molecules can form stable complexes that are difficult to process by aquatic organisms, and contribute to the browning process (see in Maranger and Pullin, 2003, Sarkkola et al., 2013, Weyhenmeyer et al., 2014, Lei et al., 2020).

Browning of waters usually refers to the increased amount of terrestrially derived DOM and more recently Fe in surface waters. In contrast, changes in DOM composition have been less studied in regards to browning; but gained more interest in the last ten years (e.g., Jane et al., 2017; Xenopoulos et al., 2021) since it plays an important role in water color changes. Higher proportions of humic substances can partly explain water browning. Humic substances are more aromatic – possessing strong chemical stability – with large size and high molecular weight (Martin-Mousset et al., 1997; Ekström et al., 2011). All these characteristics make DOM less photochemically and biologically degradable, i.e. refractory/recalcitrant DOM (Ågren et al., 2008; Hansell, 2013), as bacteria for instance preferentially use low molecular weight DOM such as carbohydrates and amino acids (Berggren et al., 2010). Moreover, the degradation efficiency of aquatic consumers usually decreases with DOM age (Raymond and Bauer, 2001), whereas fresh DOM from catchment vegetation can significantly boost the system productivity (Lennon and Pfaff, 2005). The seasonal and annual variations of DOM and Fe concentrations have only been

demonstrated in the last 20 years (Laudon et al., 2004; Dawson et al., 2008; Haaland et al., 2010; Finstad et al., 2016). Hence, the understanding of the change in DOM composition and concentration must be improved.

No single mechanism can explain water browning (Temnerud et al., 2014; Škerlep et al., 2020) that is likely to greatly impact both ecological and societal aspects. Water browning affects food webs, e.g., prey-predator interactions or primary production (Karlsson et al., 2009; Ranåker et al., 2012; Kritzberg et al., 2020), and ecosystems services of aquatic ecosystems, e.g., fish production, drinking water quality, and recreation services (Solomon et al., 2015; Kritzberg et al., 2020).

In this review, we focus on the diversity of ecological consequences of water browning on trophic levels of aquatic ecosystems, highlight knowledge gaps regarding the effect of browning on aquatic-terrestrial habitat coupling, and investigate the potential of browning as a more global phenomenon than currently presented. We aim to set research directions to improve our understanding of the browning phenomenon and its impact on ecosystem functioning. Specifically, our objectives are to review the consequences of browning on 1) different freshwater habitats, 2) food webs, 3) aquatic-terrestrial habitat coupling, present 4) browning and the DOM/DOC increase in different regions of the world, and finally 5) examine tools such as remote sensing to investigate the extent of browning from local to global scales.

2. Ecology of water browning

2.1. Browning alters lakes and rivers: what about other freshwater habitats?

Water browning alters directly and indirectly many characteristics of freshwater habitats, such as their optical and thermal conditions, oxygen availability, bioavailability of pollutants in water, and greenhouse gases sequestration and emission (Table 1). However, studies have focused on lakes, rivers, or controlled experiments (e.g., respectively Arzel et al., 2020, Berggren and Al-Kharusi, 2020, and Ekström et al., 2011; Fig. 1). Freshwaters encompass a wide diversity of other habitats, including small and temporary wetlands, which are not defined in regulations globally. There are many different temporary wetland types (e.g., alpine pool, prairie pothole, vernal pool); but they are all small, shallow, and they often dry annually (Calhoun et al., 2017). The unique features of these wetlands make them biodiversity hotspots for many species, such as aquatic invertebrates (Colburn et al., 2007), semi-aquatic amphibians (Snodgrass et al., 2000; Gibbons et al., 2006) or waterbirds (Nummi et al., 2019, 2021), and terrestrial moose (*Alces alces*) or hares (*Lepus* sp.) (Dixneuf et al., 2021).

Browning may have direct and indirect consequences on aquatic and semi-aquatic species (see Sections 2.2 and 2.3) Hence, we may expect that the degradation of small and temporary wetlands due to browning will have drastic consequences on their inhabitants and users. However, no studies have focused on the potential browning of temporary wetlands; although one paper mentioned a concomitant increase of the water color and DOC concentration of temporary ponds in Spain (Fig. 1A and B; Serrano, 1994). Additionally, several papers investigated the DOC/DOM characteristics of temporary wetlands (e.g., Yu et al., 2015; Chow et al., 2016). The importance of small and temporary wetlands is now recognized (Zedler, 2003; Calhoun et al., 2017; Ramsar Convention on Wetlands, 2018). Research on such habitats should thus now investigate how browning may modify them and their communities; it would improve knowledge on the processes of browning and help targeting good integrated watershed management strategies, including networks of all wetland types.

2.2. Browning affects aquatic food webs

The impacts and major role of light, temperature and chemistry on primary production, prey-predator interactions, and food web structure in aquatic environments are well known (Grant, 1986; Wissel et al., 2003; Ask et al., 2009; Ranåker et al., 2012). Hence, most research investigating the ecological consequences of browning focused on the response of primary producers (e.g., Ask et al., 2009; Forsström et al., 2013; Seekell et al., 2015) and planktonic communities (e.g., Estlander et al., 2017; Saebelfeld et al., 2017; Williamson et al., 2020), especially in lakes. Other studies showed the different responses of fishes to browning (Hedström et al., 2017; Hayden et al., 2019; van Dorst et al., 2020) or the direct link between a 20-year decline of aquatic macroinvertebrates and browning of boreal lakes (Arzel et al., 2020). However, there is far less knowledge regarding the effects of browning on macrophytes, invasive species, and food webs.

2.2.1. Macrophytes

Although plants can benefit from browning through the attenuation of UV-B penetration, CO_2 provisioning and binding of harmful metals (Scully et al., 1995; Sobek et al., 2003; Wang et al., 2010), further browning and subsequent change in light regime may cause submerged macrophyte decline (Reitsema et al., 2020) due to a decrease of their maximum growing depth (Bociag, 2003; Reitsema et al., 2018), particularly if associated with climate warming (Choudhury et al., 2019; Reitsema et al., 2020). However, Nagengast and Gąbka (2017) showed that submerged macrophyte

Table 1
Effect of water browning on the characteristics of surface waters (↓ = decrease, ↑ = increase).

Water characteristics affected by browning	Effect of browning	References
Optical conditions	• ↓ Ultraviolet exposure and visible light penetration through the water column • Red colors become the most penetrating wavelengths in high-DOM lakes	Kirk, 1983; Jones, 1992; Kirk, 1994; Thrane et al., 2014; Williamson et al., 2015
Thermal conditions	• Stronger thermal stratification and shallower thermocline in high-DOM lakes • Less likely to happen in shallow lakes that have enough mixing energy to prevent thermal stratification	Houser, 2006; Read and Rose, 2013; Solomon et al., 2015; Williamson et al., 2015; Strock et al., 2017; Pilla et al., 2018
Oxygen (O_2) availability	• Dissolved O_2 depletion due to ↑ microbial respiration and loss of benthic primary producers • Browning-related steeper thermal stratification prevents the mixing of oxygenated water to deeper parts of the waters • Browning-anoxia feedback loop: release and ↑ solubility of DOC, iron (Fe) and phosphorus	Roehm et al., 2009; Foley et al., 2012; Brothers et al., 2014; Knoll et al., 2018; Berggren and Al-Kharusi, 2020
Greenhouse gases sequestration and emission	• DOC concentration positively correlated to CO_2 efflux and total in-lake production • Net contribution of browning to CO_2 emissions from lakes ambiguous: balance between DOC mineralization and burial depends on lake biogeochemistry • ↑ Dissolved methane in lakes	Hanson et al., 2011; Furlanetto et al., 2012; Ferland et al., 2014; Vachon et al., 2017; Zhou et al., 2018; Allesson et al., 2021
Bioavailability of pollutants in water	• ↑ Concentration of arsenic and vanadium linked to ↑ concentration of DOC-Fe complex in surface waters • Concomitant ↑ in water color and mercury burial in lakes, and ↑ in-lake methylation by browning-induced anoxic conditions • ↑ Bioavailability of organic pollutants in water by sorption processes	Wällstedt et al., 2010; Oni et al., 2013; Ripszam et al., 2015; Isidorova et al., 2016; Ahonen et al., 2018; Kozak et al., 2021

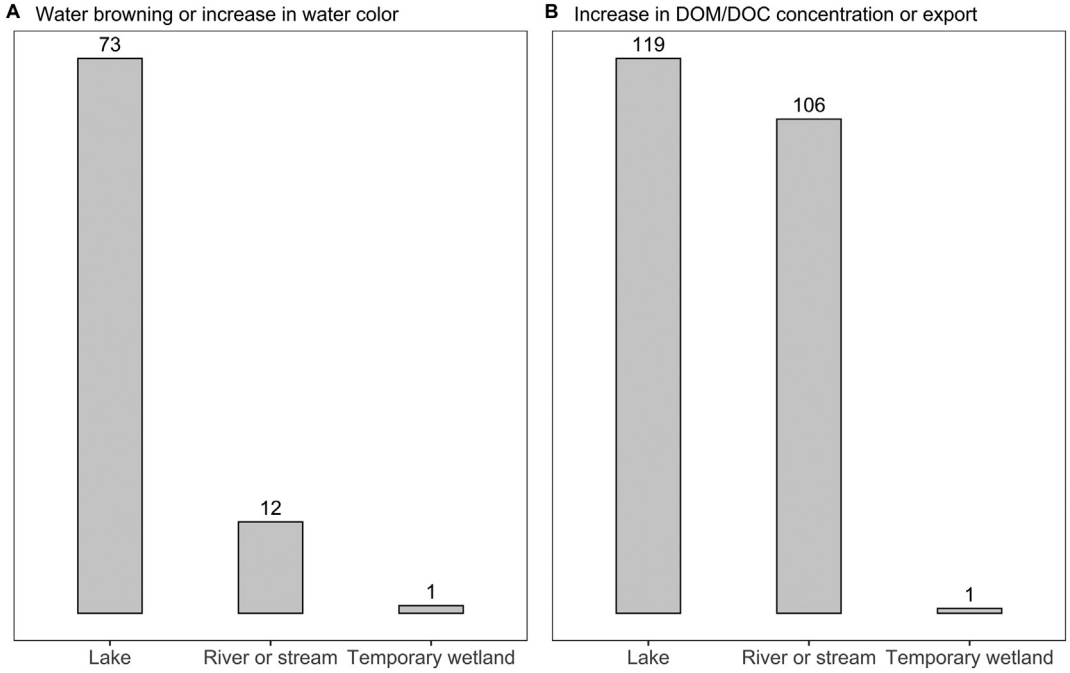

Fig. 1. Number of publications mentioning A) water browning (and synonyms) or an increase in water color in different freshwater habitats, and B) an increase in DOM/DOC concentration or export to waters in different freshwater habitats. Some articles mention both water browning and an increase in DOM/DOC concentration or export, in these cases they are counted in both panels A and B. Advanced search was carried out using Web of Science Core Collection on 12/11/2021; the search terms are provided in the supplementary material (S1).

occurrence depends on water color in Polish lakes. If they might initially benefit from increased temperature and browning, they are expected to collapse after a certain threshold (Choudhury et al., 2019), programming a potential global decline with browning expansion and reinforcement. Macrophyte decline might induce a homogenization effect with a reduction of structurally complex littoral habitats (Hilt et al., 2013), which might in turn disturb higher trophic levels in freshwaters (Scharnweber et al., 2016). In addition, a decline in *Carex* and even stronger in *Equisetum* macrophytes was noted between the 1990s and the 2010s in boreal lakes (Suhonen et al., 2011; Pöysä et al., 2017). Although water browning was not directly linked to the decline of these emergent macrophytes in these studies, it should be further investigated, like the unexplored response of floating macrophytes to browning.

2.2.2. Invasive species

In some cases, water browning may have more influence on lake invasion by non-native macrophytes than climate warming if it negatively affects the growth of the native plants and its capacity to resist invasion or compete (Mormul et al., 2012). Nevertheless Xu et al. (2018) found contrasting results, highlighting the need for further research in different environments. Jellyfish invasions in the Southern Hemisphere are limited by the sensitivity of medusa stage to UV radiation; browning is thus expected to provide favorable conditions for invasion of lakes (e.g., *Craspedacusta sowerbii* in Caputo et al., 2018). Moreover, Gallardo et al. (2016) noted increasing organic matter content in invaded freshwater habitats by invaders of different trophic positions (e.g., primary producers, filter collectors), which may be due to additional loadings such as excretion and changing hydrological conditions. Such increase may lead to water browning, for example via top-down effects by introduced or invasive fish (e.g., Milardi et al., 2019). Severe browning is related to increasing levels of anoxia that may promote the invasion of low oxygen tolerant invasive species. Such could be predatory invertebrates (such as *Chaoborus*), or fishes (such as Crucian and Prussian carps) with a potential for ecosystem-level effect; but we are not aware of such studies directly related to browning. Similarly, there is very little research accounting for the potential effect of invasive species on browning. Invasive species usually have their highest effects far outside of their native range. Different species have been frequently introduced in South America, like the North American beaver (*Castor canadensis*) and African hippopotamus (*Hippopotamus amphibius*). They have caused an enhanced transfer of DOM from terrestrial to aquatic ecosystems, potentially contributing to browning, thus influencing habitats for other species (e.g., Westbrook et al., 2017; Shurin et al., 2020). Introduced ungulates, such as game species (e.g., deer) could indirectly cause browning via their browsing effects; they have potential to alter riparian vegetation, and in turn carbon fluxes to water (Opperman and Merenlender, 2000). All in all, the impact of water browning on invasive species and vice versa has received little attention and requires further research.

2.2.3. Food webs

Browning influences the productivity of food webs nonlinearly: it initially increases the overall biomass, but subsequently starts to reduce it (Karlsson et al., 2009, 2015; Seekell et al., 2015). While such changes are documented, especially in algal communities and fish biomass (Karlsson et al., 2009; Finstad et al., 2014; van Dorst et al., 2020), very few studies included most or all different trophic levels to measure how a browning gradient in nature influences overall biomass, energy flows and transfer. When considering browning gradients and food webs together, one issue is the multiplicity of simultaneous processes, since browning is associated with increasing levels of nitrogen and phosphorus that give a net boost to food webs (e.g., Hayden et al., 2019; Keva et al., 2021). However, semi-natural experiments have used terrestrial carbon additions in small ponds or lakes, using various tracers (e.g., sugar) or isotopically different terrestrial plants (e.g., maize), to track how additional carbon is transferred upwards in food webs (e.g., Pace et al., 2004; Carpenter et al., 2005; Taipale et al., 2008; Scharnweber et al., 2014; Jones et al., 2018). They mainly suggest a relatively high carbon transfer up to fish, but there is often a very clear contrast to natural conditions where terrestrial-derived dissolved organic carbon is often of residual quality, meaning not available or not preferred by upper trophic level consumers (e.g., Brett et al., 2017). Studies about lake food webs along browning gradients are scarce and even less is known about small and temporary wetlands. Their hydroperiodicity and

varying food web structure, usually without fish predators, strongly deviate from lakes. Browning may therefore impact food webs differently pending on freshwater habitat types. Moreover, their small size makes them more influenced by the surrounding terrestrial habitats, with which they are likely linked through bidirectional fluxes of elements and organisms.

2.3. Browning calls for an aquatic-terrestrial habitat coupling approach

Terrestrial and aquatic habitats are inherently connected via fluxes of elements and organisms, but most studies focus on habitats separately (e.g., Polis et al., 1997; Soininen et al., 2015). Many animals are living at the interface of terrestrial and aquatic habitats, providing important insights to understand how changes in one habitat may cascade to another. Furthermore, aquatic-terrestrial coupling is likely bidirectional and should be viewed as feedback loops since many organisms use both habitats during their lifecycle.

2.3.1. Amphibians

To our knowledge, no research has been carried out to investigate the potential impact of browning on amphibian populations. Amphibians provide ecosystem services (Hocking and Babbitt, 2014) from cultural services to structural and functional supporting services (i.e., influence ecosystem structure through bioturbation, and ecosystem functions such as nutrient cycling through waste excretion, respectively). They also have an unfavorable conservation status worldwide (Stuart et al., 2004). Water browning is expected to extend and intensify in ponds and small lakes which are the breeding habitats of most Palearctic amphibians (Bolochio et al., 2020). It is therefore important to assess the potential effects of this phenomenon on this group. The reduction in light intensity may be detrimental to species or stages using vision to forage underwater. The predictions are not obvious for tadpoles that feed on phytoplankton but also on biofilm (Altig et al., 2007) if the proportion of autotroph bacteria increases in lentic ecosystems. Less ambiguous is the fact that humic acids can, on one hand, interfere with olfaction in fish (Fisher et al., 2006), thus potentially decreasing their predation pressure on tadpoles; but on the other hand, impair the tadpole's ability to recognise dragonfly predators (Polo-Cavia et al., 2016).

The larval stages of amphibians may benefit from the attenuation of UV-B radiation due to browning. UV radiation is harmful to amphibians especially during their development (Bancroft et al., 2008; Londero et al., 2019). For instance, in the boreal species *Rana temporaria*, embryos exposed to UV-B displayed a higher frequency of developmental anomalies, late metamorphosis and smaller size than controls (Pahkala et al., 2001). In addition to the effects on foraging and development, the changes in the photic environment induced by browning (Scully et al., 2003; Nydahl et al., 2019) are expected to affect social interactions of species that mate in water and partly rely on visual communication with bright UV-reflecting color patches and exaggerated morphological traits like European newts. A reduction of light transmission in turbid water seems to limit the expression of sexual traits of *Lissotriton helveticus* males even if the underlying mechanism is not identified (Secondi et al., 2007) but a reduction of the food acquisition rate is a possible cause (Baker, 1992). Newts display a complex courtship usually on the pond bottom that includes visual and olfactory components (Halliday, 1977). *Lissotriton vulgaris* females assess the UV component of the ventral coloration of males and spend more time close to a male when UV radiation is available (Secondi et al., 2012). The lack of UV in brown waters was shown to affect species recognition between *L. vulgaris* and *L. helveticus* in the lab (Secondi and Théry, 2014). When visual cues are not available females may give more weight to olfactory information as observed in the Alpine newt though (Denoël and Doellen, 2010). However, humic acids may interfere with olfactory communication in water breeding amphibians like newts, as demonstrated in fish (Mesquita et al., 2003; Fisher et al., 2006). Finally, humic acids have been shown experimentally to have a hormone-like effect in fish and amphibians causing a slight feminization (Steinberg et al., 2004). Thus, a change in water color may reduce the ability for individuals to acquire food, detect predators, express sexual traits involved in mate selection, assess potential mates, and affect the expression of sexual hormones. These issues have not been investigated in amphibians yet. Nevertheless, negative consequences on individual fitness and population growth may be expected. It is noteworthy that many amphibian species breed in naturally stained water and seem to sustain viable populations, even *Lissotriton* newts where sexual selection for visual traits is strong. Particular attention should be given to areas where clear waters were dominant and are now browning. There, locally adapted populations may be more at risk than populations that have been living in heterogeneous environments where water bodies with different levels of browning have been co-occurring for a long time, for instance in mixed landscapes with forest and open areas. This concern should be rapidly addressed as clear lakes are more sensitive to browning than brown lakes (Knoll et al., 2018; Williamson et al., 2020).

2.3.2. Waterbirds

In the boreal environment, the abundance of waterbirds feeding on fishes, plants and invertebrates showed a positive relation with clear water and macrophyte percentage cover (Hansson et al., 2010). The impact of browning on waterbirds has not been demonstrated yet, but water browning causes macrophyte decline (Reitsema et al., 2018). The decline (richness and abundance) of ducks with an insectivorous diet over the past 25 years (Pöysä et al., 2019; Elmberg et al., 2020) could also be linked to the concomitant decline of aquatic invertebrates associated with water browning (Arzel et al., 2020). The different compartments of lake food webs are interrelated, so disturbances on one level can greatly impact others, potentially leading to changes from local to large scale. Fennoscandian lakes are the main breeding area of migratory ducks in Europe (European Commission, 2001). A decline in duck breeding success over the boreal environment, as a direct or indirect result of browning, could lead to strong consequences on their population dynamics. Insectivores are one of the largest guilds of predators (Nyffeler et al., 2018). A decline in insects will surely negatively impact their predators through trophic cascades. For instance, the Diptera family, in which many species have an aquatic larval stage, represents at least 20% of the diet of predators of distinct taxa, e.g., birds, bats and invertebrate predators such as Odonates (Vesterinen et al., 2020). A general decline of biomass or abundance in this taxon may thus have profound and global consequences in the tree of life as the insect resource is shared by so many predator groups.

2.3.3. Pathogens

At the global scale, browning may also affect drinking water quality, and increase the risk of pathogen persistence by reducing the potential for solar UV inactivation of pathogens (Williamson et al., 2017). Waterborne pathogens are one of the most frequent sources of infectious diseases. For example, the United States counts between 12 and 19 million people infected annually (Trtanj et al., 2016; Williamson et al., 2017). Waterborne pathogens of humans and wildlife include bacteria, fungi, protozoans and viruses. Among them, slow and high pathogenic avian influenza persistence in the aquatic environment is expected to be promoted by climate change with an increase in temperatures (see in Dalziel et al., 2016); but studies overlooked browning processes also linked to climate change. Many studies demonstrated the importance of solar radiation in the inactivation of the four types of pathogens in surface waters (King et al., 2008; Overholt et al., 2012; Mattle et al., 2015; Nguyen et al., 2015). Pathogen vectors, e.g., mosquitoes, are also sensitive to natural solar UV radiation (Berry et al., 2020), through a decrease in larval survivorship. Browning decreases UV-B penetration (Williamson et al., 2016), hence its solar inactivation potential (SIP) in the water column, which can favor the survival of pathogens. For example, Williamson et al. (2015) showed that the long-term increase of DOM in lake Giles in North America and the concurrent increased UV absorption led to a two-fold diminution of SIP. Similarly, DOM provides a refuge for mosquito larvae to UV radiation, which increases habitat suitability (Berry et al., 2020).

Climate change projections predict increased heavy precipitation events, which will translate into an enhanced release of DOM into surface waters, especially in highly disturbed catchments (Ren et al., 2016). Further research is

needed to efficiently target relevant management and treatment efforts against pathogens; focus should be on high-DOM waters and future increased precipitation zones where pathogens are highly expected to thrive.

2.3.4. Flows of energy and organisms between terrestrial and aquatic environments

Browning may impact strongly and in multiple ways energy sources and flows in aquatic environments, but may also alter the fluxes from aquatic to terrestrial environments. Terrestrial leaves may be an alternative carbohydrate source for herbivorous zooplankton, which can use terrestrial carbohydrates for their fatty acid synthesis under phytoplankton deficiency (Taipale et al., 2016a). However, the fate of other terrestrial origin biomolecules (e.g., amino acids) in the aquatic food webs is not known, and most of current knowledge is related to indirect consequences. For example, browning has a great impact on the phytoplankton composition, and the synthesis and transfer of physiologically essential long-chain polyunsaturated fatty acids (PUFA), such as eicosapentaenoic acid (EPA, 20:5ω3) and docosahexaenoic acid (DHA, 22:6ω3) (Taipale et al., 2016b; Strandberg et al., 2016); PUFA are required for optimal growth and reproduction of zooplankton, fish and mammals (Arts et al., 2009). Since EPA and DHA are synthesized only by certain phytoplankton taxa (Taipale et al., 2016b), changes in the phytoplankton community influence EPA and DHA availability for herbivorous zooplankton, and their transfer in the food web. Browning might have opposite impacts on the phytoplankton composition in different climatic zones and biomes. Consequences in nutritional quality of seston might thus differ markedly between these zones. For example, Senar et al. (2019) found that browning favored cyanobacteria and decreased sestonic EPA and DHA content in temperate lakes. However, in boreal lakes, strong browning is known to inhibit cyanobacteria (Taipale et al., 2016b; Senar et al., 2021), but favor the raphidophyte *Gonyostomum semen* (Lepistö et al., 1994; Lebret et al., 2018) which might result in an apparent increase on EPA even though *G. semen* is too large to be consumed by most zooplankton (Gutseit et al., 2007; Strandberg et al., 2020).

Zooplankton studies are scarce, but current results suggest that herbivorous cladocerans and calanoids are able to detect high quality alternative diets, and thus mitigate browning-induced lower nutritional quality of seston (Taipale et al., 2016a; Senar et al., 2019). However, the low availability of high-quality algae may limit zooplankton biomass production (Taipale et al., 2019). Moreover, the negative impact of browning on the nutritional quality of seston and zooplankton was recently identified in the productivity gradient of subarctic lakes (Keva et al., 2021), and was mostly explained by the structural changes in the zooplankton community. Altogether, two separate studies have shown that browning decreases nutritional quality of perch for human consumption by leading to lower EPA and DHA and higher mercury content (Taipale et al., 2016b; Strandberg et al., 2017).

Recent studies have also shown the impact of PUFA on the survival of insectivore bird chicks (Twining et al., 2016), which makes aquatic ecosystem insect fluxes important PUFA sources also for insectivorous birds. While the hatching of aquatic insects will have direct important effects on birds and riparian insects, there might be a feedback loop via terrestrial insects and bird faeces back to the aquatic environment (Scharnweber et al., 2014). Aquatic invertebrate communities are strongly structured by selective fish predation that may change the insect fluxes to terrestrial habitats (Gratton et al., 2008; Milardi et al., 2019), and may even cause trophic cascades in riparian terrestrial habitats (Knight et al., 2005). Insect flux also contains both harmful and beneficial substances (Chaves-Ulloa et al., 2016; Popova et al., 2017), differing between ecosystems. Moreover, very little is known on how potential changes in the synthesis and transfer of essential biomolecules in freshwater food webs influence consumers in the interface of aquatic and terrestrial ecosystems (but see Taipale et al., 2016b); for instance, the consequences on animals feeding on aquatic resources such as waterbirds or semi-aquatic mammals is not known and calls for future research.

2.3.5. Beavers as promoters of browning

While the causes of browning are mainly attributed to human activities (see Section 3.1), natural disturbances such as beaver-induced floods may also substantially contribute to the process. Beavers (*Castor* sp.) are known as ecosystem engineers to cause significant patch disturbance in boreal riparian ecosystems (Remillard et al., 1987; Nummi and Kuuluvainen, 2013; Kivinen et al., 2020). By damming, and the ensuing flooding, beavers cause the death of herbaceous vegetation and trees because of the anaerobic conditions of roots caused by the flood (Thompson et al., 2016; Johnston, 2017). Organic matter and nutrients coming from the dead plants and soil are then flushed from the flood zone to the dammed water body, hence affecting the biogeochemical conditions of the water (Vehkaoja et al., 2015; Nummi et al., 2018). Vehkaoja et al. (2015) showed that beaver lakes had higher DOC concentrations than non-beaver lakes in small boreal lakes, with an increase in DOC concentration within the three first years of beaver impoundment. DOC concentrations returned to their pre-flooding level after 4–6 years. Blanchet (2020) observed the same pattern with higher water color measured in lakes recently flooded, i.e. three years, compared to lakes without beaver activity or with older flood events. In the first impoundment years, DOC arriving in water bodies comes from the decaying plants (Hodkinson, 1975; Nummi, 1989) and is mainly composed of low molecular weight molecules that could be easily processed microbially. The following impoundment years, however, bring DOC with terrestrial characteristics to the waterbody (Rasilo et al., 2015), i.e. refractory and aromatic molecules with high molecular weight which are less efficiently used by organisms and mainly removed by photochemical reactions. Although DOC concentrations usually return to their pre-flood level (Vehkaoja et al., 2015), the remaining DOC may be composed of more colored molecules, hence contributing to the browning phenomenon. Newly established beaver ponds, in particular, may contribute more to browning in comparison to old beaver ponds as they have more humic-like DOM (Catalán et al., 2017).

While the immediate effects of beavers on water chemistry and aquatic animals are known, there is far more limited understanding of riparian changes and potential feedback loops back to aquatic habitats. These aspects are important to consider, as beavers were hunted to the brink of extinction between the 16th and 19th centuries in Eurasia, leaving only eight isolated populations from France to Mongolia by the end of the 19th century (Nolet and Rosell, 1998). They were reintroduced in the 20th century which led to a successful recovery of some beaver populations and their gradual return to their previous distribution area (Whitfield et al., 2015; Halley et al., 2021). Their increasing population, for instance, resulted in increased DOC concentrations in streams in a 30-year study in Germany (Smith et al., 2020). Therefore, the recent and current population increase of beavers and their substantial role in the biogeochemistry of headwater bodies and the riparian zone are strong arguments to include them in research on water quality, especially in the boreal landscape where beavers are largely distributed, and in areas where they are non-indigenous.

3. Drivers and subsequent spatial extent of water browning

3.1. Main drivers of water browning

Over the past two decades of studies, no single mechanism but rather a combination of several drivers can explain water browning (Temnerud et al., 2014; Škerlep et al., 2020; Xiao et al., 2020), such as acid recovery, weather patterns and land-use (Hongve et al., 2004; Monteith et al., 2007; Björnerås et al., 2017; Kritzberg, 2017), which evolve at different timescales. Most of the research investigating the causes of browning was carried out on lakes and rivers (e.g., de Wit et al., 2016; see Fig. 1A and B). As mentioned in Section 2.1, browning processes in small and temporary wetlands remain unknown, although they are connected to other freshwaters via surface and subsurface hydrologic connections (Ameli and Creed, 2017). Research on browning of surface waters should thus include aquatic networks at the catchment scale at least, to get a more holistic view of the processes.

As several reviews already addressed the potential mechanisms of browning (e.g., Evans et al., 2005; Creed et al., 2018; Kritzberg et al., 2020), we provide a summary of water browning drivers in Table 2 to concentrate

Table 2
Summary of the main past and present factors driving water browning over time (↓ = decrease, ↑ = increase).

Driver	Effect(s)	References
Acid recovery		
↓ Acid deposition	• ↑ DOM mobility and solubility in soils, and ↑ transport to aquatic systems • Changes in DOM composition toward more colored molecules	Monteith et al., 2007; LoRusso et al., 2020; Meyer-Jacob et al., 2020; Redden et al., 2021
Climate (change)		
↑ Precipitation	• ↑ Water table and ↑ connectivity between organic soils and surface waters: DOM leaching • 10% ↑ in precipitation estimated to ↑ mobilization of organic matter from soils to freshwaters by at least 30%	Hongve et al., 2004; Laudon et al., 2011; de Wit et al., 2016; Mahdiyan et al., 2021
↑ Temperature	• ↑ Export of DOM to freshwaters: stimulation of soil biological activity ↑ organic matter decomposition and DOM solubility • 2 °C ↑ in temperature estimated to ↑ organic matter decay rates up to about 10%, mainly through changes in runoffs	Christ and David, 1996; Moore and Dalva, 2001; Dawson et al., 2008; Catalán et al., 2016
Permafrost thawing (due to ↑ temperatures)	• ↑ DOM concentration in waters • Change in DOM composition: mobilization of ancient DOM from deeper soil layers with lower degradation efficiency	Feng et al., 2013; Ewing et al., 2015; Ward and Cory, 2015; Wauthy et al., 2018; Ma et al., 2019
Land cover		
Forest cover	• Coniferous forests = sources of DOC and Fe in freshwaters	Finstad et al., 2016; Björnerås et al., 2017
Wetland cover	• Wetlands = major contributors of DOM to surface waters • Peatland cover can account for 78% of DOC catchment export to lakes on the long-term	Dillon and Molot, 1997; Mattsson et al., 2005; Arvola et al., 2016
Land use		
Agriculture	• Soil degradation and water flow modification: releases DOM, excess nutrients, and pesticides to freshwaters	Karlen et al., 1997; Ogle et al., 2005; Graeber et al., 2012
Afforestation	• Accumulation of soil organic carbon (due to ↑ in forest cover) and its export to surface waters, especially if coniferous trees • Considered as contributing to long-term browning on the centennial timescale	Meyer-Jacob et al., 2015; Kritzberg, 2017; Škerlep et al., 2020
Clearcutting and site preparation practices	• ↑ DOM leaching through multiple factors: ↑ groundwater level, ↑ loose organic matter due to topsoil disturbance, and ↑ organic matter decomposition rate (due to ↑ soil temperature) • Effect of harvesting and preparation practices potentially of short-term	Piirainen et al., 2007; Laudon et al., 2009; Winkler et al., 2009; Sarkkola et al., 2010; Schelker et al., 2012; Glaz et al., 2015
Peatland drainage	• ↑ Export of DOM to surface waters due to ↑ decomposition of surface peat • Release of old DOM (up to several thousands of years; less efficiently used than modern DOM) by their mobilization from deeper parts of the soil	Hulatt et al., 2014a, 2014b; Marttila et al., 2018; Finér et al., 2021; Nieminen et al., 2021
Interplay between acid deposition, climate change, and land use		
"Greening" phenomenon (i.e., ↑ vegetation productivity due to ↑ growing season, biomass, and cover)	• ↑ DOM concentration in surface waters due to ↑ export of DOM from catchments • DOM export in arctic and boreal waters estimated to ↑ by 65% in the next hundred years, primarily because of greening	Larsen et al., 2011; Finstad et al., 2016; Zhu et al., 2016; Kritzberg, 2017

here below on the actual and potential extent of browning following these drivers.

3.2. Spatial extent of water browning processes

The main factors identified that affect browning processes include acid recovery, climate change (heavier precipitation events and increasing temperatures, melting of permafrost), land cover, land use, and catchment greening. The combination of several of these factors has mainly caught researchers' attention in the Northern Hemisphere (Fig. 2). In the articles cited in this review, evidence of long-term browning has only been demonstrated in the Northern Hemisphere through different processes (Fig. 2A, B, and C), with a clear focus on cold and temperate regions (Fig. 2D). Our work shows that the semantic of water browning remains unclear globally (Fig. 2A, B, C). This is due to the imbrication of diverse processes at its origin. This makes it difficult to get an overview of its extent at the global scale, although evidence of processes linked to browning waters can be found from cold to tropical regions.

3.2.1. Cold regions

Here we focus on the comparatively cold regions of the globe that contain the climate zones (e.g., polar and subpolar) or biomes (e.g., boreal) typical to the region. In the Northern Hemisphere, the increase in water color and DOM concentration in arctic lakes and rivers is mainly due to the greening of tundra (Fraser et al., 2011; Epstein et al., 2012), as well as climate change and its consequences on permafrost (Ma et al., 2019) and peatlands (Dillon and Molot, 1997; Minayeva et al., 2016). Wetlands cover 60% of the Arctic zone, most of which are peatlands (Minayeva and Sirin, 2009). Climate change predictions project a faster warming in the Arctic compared to other climate zones (IPCC, 2014), with increasing precipitation events, which will result in permafrost loss; it will in turn degrade arctic peatlands and facilitate the export of aromatic, high molecular weight, colored DOM (Frey and Smith, 2005; Ewing et al., 2015; Minayeva et al., 2016). In the Southern Hemisphere, no research has investigated a possible browning trend in Antarctic surface waters. Nevertheless, the literature on DOC suggests a generally very low concentration in Antarctic freshwaters, with a low proportion of humic substances (Barker et al., 2013; Foreman et al., 2013). However, ongoing climate change may impact carbon fluxes in Antarctica, including DOC (Quesada and Velázquez, 2013).

The subarctic zone may experience intense browning due to acid recovery, increased temperatures and precipitation, and permafrost thawing, which promote the release of more colored but less efficiently processed DOM from soils (Monteith et al., 2007; Ekström et al., 2011; Finstad et al., 2016; Björnerås et al., 2017; Ma et al., 2019). Mzobe et al. (2018) showed that peatlands and secondarily forest productivity are key contributors of DOC in subarctic streams, but water remains less brown than in boreal zones (Lau et al., 2021). Boreal surface waters are affected by all drivers identified in Table 2, making them particularly susceptible to brownification.

3.2.2. Temperate regions

In the temperate area, DOC/DOM increase and composition change, as well as their drivers have been primarily studied in Europe and North America. In the UK, studies focused more on DOC concentration rather

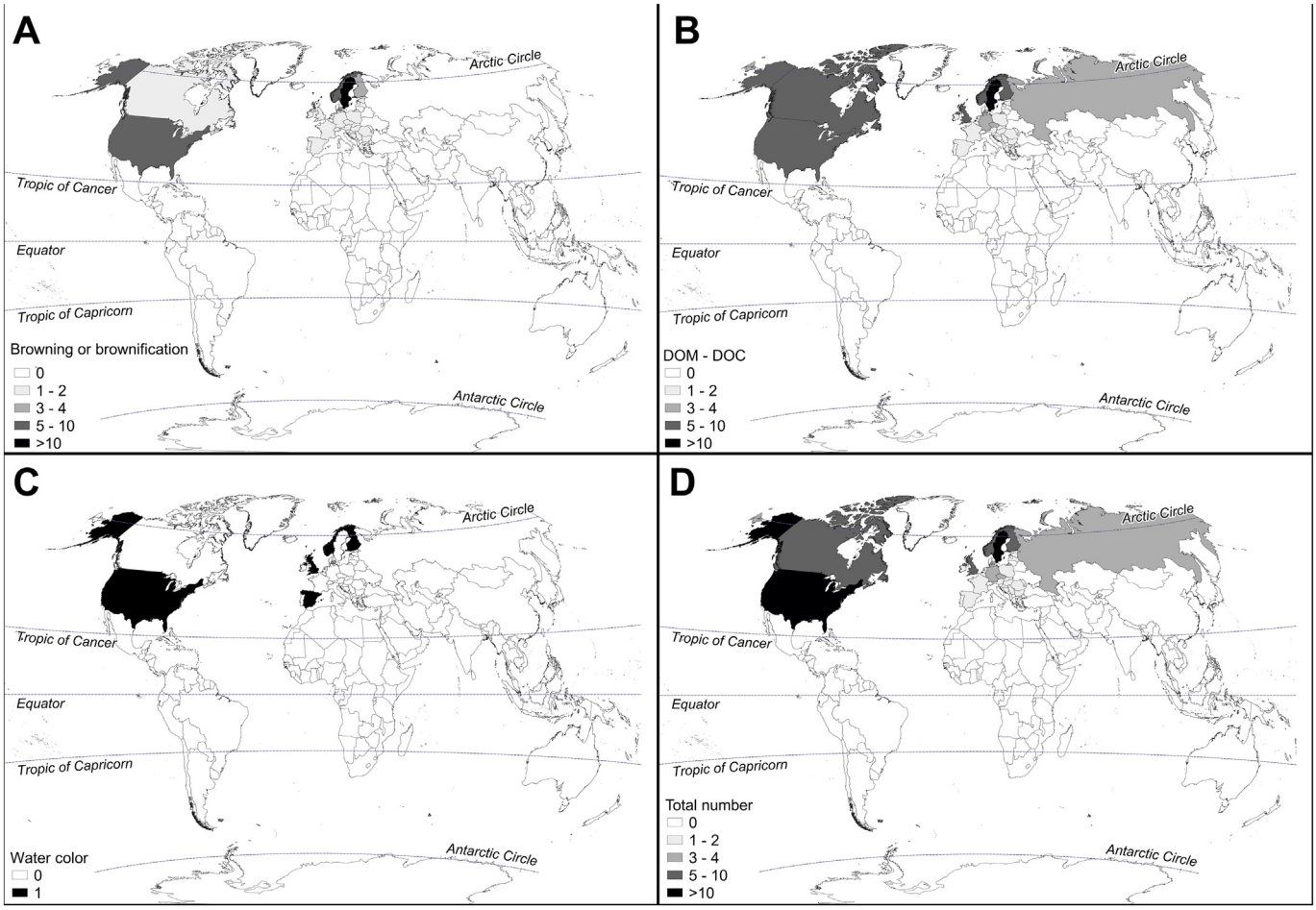

Fig. 2. Spatial extent of in situ studies on water browning processes cited in this review. A: articles demonstrating evidence of water browning or brownification (increase in absorbance, color units, or DOM/DOC content); B: articles highlighting an increase in DOM/DOC concentration with or without mentioning the term water browning (and synonyms); C: articles showing an increase in water color without mentioning the term water browning (and synonyms); D: total number of articles demonstrating browning processes combining A, B, C without duplicated articles. Reviews and controlled experiments were excluded.

than the browning phenomenon in itself (Fig. 2). DOC concentration has doubled in the Acid Waters Monitoring Network since the 1980s (Worrall et al., 2003; Evans et al., 2005), and has been linked to decreasing acid deposition (Davies et al., 2005; Evans et al., 2005). DOC trends were positively correlated to temperature, and negatively correlated to ionic strength (Evans et al., 2005). Rainfall patterns (wet-dry cycles) seem to influence DOC trends, but in a more variable way since rainfall varies intra- and inter-annually, while forestry practices are considered to play a minor role in the increase in DOC levels (Harriman et al., 2003; Evans et al., 2005). However, UK lakes may experience browning differently since the composition of DOM related to water color depends on catchment parameters, i.e. land use/land cover (Yates et al., 2019). It has been demonstrated that DOM originating from agricultural inputs is mainly of a low aromaticity and molecular weight; high aromaticity being associated with high water color (Fasching et al., 2014). As agriculture covers 72% of UK territory (UK Government, 2020), a change in DOM composition is likely to have concurrently happened with increased DOC concentration in waters, potentially leading to slow water browning in some catchment areas.

Czech Republic was exposed to high atmospheric pollution, which peaked in the 1980s and sharply declined in the 2000s. The change in acid deposition strongly influenced DOM concentration in the Malše River since 1969 (Hejzlar et al., 2003) and in 9 water bodies, streams and reservoirs (Oulehle and Hruška, 2009). Concurrently with changes in acid deposition, climatic (increasing temperature) and hydrologic conditions (i.e. proportion of histosols, runoff), may have resulted in large amounts of DOM in surface waters due to an increased solubility, mobility and transport. A change toward more colored DOM may also be expected in response to acid recovery (Ekström et al., 2011).

In France, 30% of the lakes may be affected by organic matter enrichment (Sepp et al., 2018); several studies have investigated DOM parameters in French streams, but no studies focused on browning have been carried out. Humic substances generally dominated DOM composition between 2010 and 2013 in a north-eastern French river, and the highest values of the $SUVA_{254}$ (an index for aromaticity) could not be explained (Assaad et al., 2015). Few studies in France have investigated DOM quality in lakes and reservoirs, although humic substances are present in a higher proportion than in rivers (Martin-Mousset et al., 1997). Birgand and Novince (2004) observed a long-term (15–20 years) increase of DOM concentration in Breton streams (Western France). Climate fluctuations could explain the interannual variation, and the riparian zones appeared as a substantial contributor of DOM export to surface waters. Humic substances, DOC and Fe concentrations were strongly and positively correlated in the Penzé river. As several streams in the Brittany region have already experienced a rise in DOM concentration and exhibited a high proportion of humic substances (Birgand and Novince, 2004; Marie et al., 2015), water browning is likely to impact the local biodiversity and drinking quality since 85% of surface waters in Brittany are used for drinking purposes. Hence, there is a clear necessity to understand the factors governing the transfer of DOM to surface waters in France.

In the US, based on the US Environmental Protection Agency's National Lakes Assessment (NLA) data (1000+ lakes sampled in 2007 and 2012), Leech et al. (2018) showed that the proportion of "murky" lakes (experiencing both eutrophication and browning) increased by almost 12%, with suspected negative consequences for water quality and food web structure. This study called for more research to understand how the combined "greening" and "browning" of lakes affects ecological processes in the US.

In Canada, Meyer-Jacob et al. (2020) assessed whether DOC levels are still influenced by acid deposition in 75 lakes in the Greater Sudbury region that has been heavily affected by sulfur dioxide emissions from local metal smelting during the 20th century. They found that acid deposition has historically had a strong impact on lake-water DOC dynamics in this region, but that other drivers, such as changes in climate or vegetation cover, are becoming the dominant controls on changes in DOC concentration.

At a larger scale, comparisons between European countries have been done. Mattsson et al. (2009) showed that catchments with drained surfaces in France concentrated and exported less DOC compared to Danish and Finnish measurements, explaining that more factors promote the export of DOM into surface waters in boreal environments than in more temperate ones.

3.2.3. Tropical regions

In the tropical and subtropical regions, only one recent article directly mentioned water browning while studying harmful algal blooms (Hu et al., 2021); however, it does not appear in Fig. 2 as the study does not provide evidence of browning. The term "blackwater river" is, nevertheless, often used to describe a type of tropical brown river (Gandois et al., 2020; Zhang et al., 2020; Constantino et al., 2021). With the exception of blackwater rivers, natural tropical rivers have generally low DOC concentration compared to temperate rivers (Lewis et al., 2006).

Land-use and land cover changes (e.g., to pasture, crop production, urbanization) seem to be the main factors influencing DOM export, concentration, and changes in composition, especially in Brazil where agriculture and urbanization contribute the most because of low water treatment (Hudson et al., 2007; Gücker et al., 2016). In Rwanda, agricultural lands are not a substantial contributor of DOC transfer to streams (Rizinjirabake et al., 2019) compared to forest plantations. Many tropical regions have experienced clear-cutting and monoculture plantations. Clear-cutting of tropical riparian areas may have immediate effects on carbon fluxes and water color (Smolders et al., 2018). Indonesian oil palm plantations are often established by draining natural peatlands, with subsequent and potentially long-term effects on DOC leaching (Cook et al., 2018). Tropical peatlands are natural sources of large amounts of DOM: most blackwater rivers drain peatlands (Martin et al., 2018). Peatlands degradation by deforestation and drainage for agricultural exploitation may have resulted in an enhanced export of DOM and Fe to surface waters, especially in the wet season (Moore et al., 2011; Gandois et al., 2013; Zhang et al., 2020). The Siak blackriver in Sumatra, for example, drains heavily degraded peatlands and exhibits one of the highest DOC concentrations in the world (Rixen et al., 2008).

Spencer et al. (2010) showed that DOM concentration with more aromatic and colored molecules, increased in a tropical river with greater runoff, suggesting that hydrological conditions may play a similar role in waters of tropical, temperate and cold regions. In the context of climate change, the predicted increase of temperatures and precipitations could stimulate DOC soil production and export in tropical regions, leading to water browning (Moore and Dalva, 2001; Hawkins and Sutton, 2011).

4. Browning trends with global changes and remote sensing as an approach for global studies

Global changes, e.g., land cover/land-use changes and climate change, are expected to drive further browning, while having major impacts on biodiversity and societies. Land cover and land-use changes are one of the main drivers of changing color of surface waters. Sixty percent of land-use changes are associated with direct human activities and 40% with indirect drivers such as climate change (Song et al., 2018). Waters are likely to become browner in tropical areas with deforestation, and in temperate areas with reforestation or afforestation, since these practices enhance DOM export to surface waters (Schelker et al., 2012; Kritzberg, 2017; Song et al., 2018; Škerlep et al., 2020). Global changes may deeply impact species distribution worldwide (Chen et al., 2011), which in turn will affect ecosystems community composition and functional diversity (Ochoa-Ochoa et al., 2012; Buisson et al., 2013; Pecl et al., 2017), but no studies have assessed the link with browning and potential feedbacks. Browning of waters has not been identified as a global change component yet (but see Freeman et al., 2020), but its strong interrelation with other global environmental changes needs immediate attention and further research to improve conservation and management strategies at all scales.

An array of remote sensing approaches can provide an inclusive view of water quality variability to help understanding the possible causes of variations at large scales (Boggs et al., 2001). Hence, the new availability of spectral and spatial resolutions for remote sensing data time series is opening up opportunities to monitor the impact of land-use and land cover changes on water quality at spatially explicit scales; remote sensing has thus high potential for evaluating control efforts to protect freshwater habitats (e.g., lakes, rivers, ponds, wetlands). Current monitoring data cannot provide a global picture of browning (Sepp et al., 2018). Nevertheless, several remote sensing analyses have focused on color, or DOC and DOM measurement parameters in recent years. The increase in colored DOM (CDOM) concentration can be detected in the blue and green region of the light spectrum (especially below ~500 nm). At high concentrations of CDOM, the absorbance of the red light spectrum can be significant. Hence, passive remote sensing has been investigated through a large number of sensors on various platforms to map this water quality parameter (Gholizadeh et al., 2016). The band ratio has been the most common algorithm used. Landsat 7 and 8 imageries can be reasonably used for the estimation of CDOM levels (R^2 up to 0.82 with Landsat 8 data) (Olmanson et al., 2016; Chen et al., 2020). Using the green to red band ratio (band 3 to band 4, B3/B4 ratio) from Sentinel-2 imagery, Toming et al. (2016) obtained good correlations with lake CDOM ($R^2 = 0.72$) and DOC ($R^2 = 0.92$) concentrations, but weaker ones with lake color ($R^2 = 0.52$). Additionally, lake color in the study did not exceed 30 mg Pt/L, while many lakes in the boreal and arctic regions may display color values twenty times higher (Taipale et al., 2008; Arvola et al., 2010; Vesterinen et al., 2016). Nevertheless, remote sensing of water color is progressing since it is considered as a useful indicator of water quality (Gardner et al., 2021).

Remote sensing may also be used to monitor drivers of water browning like forestry activities (Xulu et al., 2020) that may contribute to a large export of DOM to surface waters (Schelker et al., 2012). Several approaches could be combined at the catchment scale. For instance, in a study using the Normalized Difference Vegetation Index (NDVI) on forested areas in the western US, vegetation cover and several soil properties were identified as the key variables that explained water quality response across a broad range of conditions (Rust et al., 2019). In Sri Lanka, a study based on remote sensing provided empirical evidence of the contribution of healthy (high NDVI values) forest cover on the improvement of watershed water quality (Kumarasiri et al., 2021). The above ground biomass was the dominant carbon storage among the other carbon pools. The water quality parameters were not correlated with the soil erosion rates, which was possibly attributed to the mitigation effects of the healthy forest cover within the studied catchment. Time series of remote sensing data can also be used to quantify how forest disturbances vary in space and time, then to estimate related factors (e.g., proximity, intensity, and total areal extent of harvest) that influence water quality within a watershed. Regarding active remote sensing, recent technologies of growing interest such as LIDAR sensors offer accurate perspectives to estimate the role of forested wetlands in the carbon cycle, and understand how forest practices impact carbon storage at the landscape scale (Halabisky et al., 2020). Hence, remote sensing can be used to assess the color of surface waters worldwide, as well as the global causes and consequences of water browning.

5. Conclusion and future steps in research on browning

We identified five research actions to make significant steps forward in our knowledge of water browning:

1- *Assess browning ecological processes in other wetland types than lakes and rivers.* No study has addressed processes at the catchment scale, including networks of small and temporary wetlands with lakes and rivers. Their potential degradation due to browning may affect all levels in the landscapes.
2- *Evaluate the impact of browning on aquatic food webs at multiple scales.* The majority of studies overlooked macrophytes, invasive species, and the impact on the whole food web structure in different freshwater habitats. Multiple food web structure markers such as compound specific stable isotopes of amino acids or mercury would likely provide options to study food web processes in full browning gradient.
3- *Investigate the effects of browning on aquatic and terrestrial coupling.* There are many fluxes between the aquatic and terrestrial habitats, such as through beaver activity and pathogen emergence. There is a clear lack of knowledge on the effects of browning on water-dependent amphibians, waterbirds and mammals. The coupling of aquatic and terrestrial habitats will help to understand consequences on the transfer of energy through the food webs.
4- *Understand the water browning processes at the global scale.* Most of the research has focused on the boreal region in the Northern Hemisphere, but we highlighted the occurrence of water browning processes at a larger scale from the polar to the tropical regions. We note a clear lack of knowledge on polar, especially Antarctic, and tropical waters.
5- *Develop remote sensing methods to monitor the ecological consequences of water browning from catchment to global scales.* Passive remote sensing has been mainly used to monitor CDOM in freshwaters, but other promising approaches are emerging; that includes active remote sensing, and focus on landscape parameters and land use determinants related to water quality.

The reinforcement of water browning impacts water bodies through its interrelation with global environmental changes. There is a clear need for global studies to investigate the extent, underlying mechanisms, and ecological consequences of browning. Remote sensing has a crucial role to play in such future research.

CRediT authorship contribution statement

Clarisse C. Blanchet: Conceptualization, Investigation, Writing – Original Draft, Visualization, Project administration, Funding acquisition. **Céline Arzel:** Conceptualization, Resources, Writing – Review & Editing, Visualization, Supervision, Project administration, Funding acquisition. **Aurélie Davranche:** Conceptualization, Resources, Writing – Review & Editing, Visualization, Supervision, Funding acquisition. **Kimmo K. Kahilainen:** Conceptualization, Resources, Writing – Review & Editing, Supervision. **Jean Secondi:** Resources, Writing – Review & Editing. **Sami Taipale:** Resources, Writing – Review & Editing. **Henrik Lindberg:** Resources, Writing – Review & Editing. **John Loehr:** Writing – Review & Editing. **Sanni Manninen-Johansen:** Writing – Review & Editing. **Janne Sundell:** Writing – Review & Editing. **Mohamed Maanan:** Resources, Writing – Review & Editing. **Petri Nummi:** Project Leader, Conceptualization, Resources, Writing – Review & Editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Ågren, A., Berggren, M., Laudon, H., Jansson, M., 2008. Terrestrial export of highly bioavailable carbon from small boreal catchments in spring floods. Freshw. Biol. 53 (5), 964–972. https://doi.org/10.1111/j.1365-2427.2008.01955.x.

Ahonen, S.A., Hayden, B., Leppänen, J.J., Kahilainen, K.K., 2018. Climate and productivity affect total mercury concentration and bioaccumulation rate of fish along a spatial gradient of subarctic lakes. Sci. Total Environ. 637–638, 1586–1596. https://doi.org/10.1016/j.scitotenv.2018.04.436.

Allesson, L., Koehler, B., Thrane, J.-E., Andersen, T., Hessen, D.O., 2021. The role of photomineralization for CO2 emissions in boreal lakes along a gradient of dissolved organic matter. Limnol. Oceanogr. 66 (1), 158–170. https://doi.org/10.1002/lno.11594.

Altig, R., Whiles, M.R., Taylor, C.L., 2007. What do tadpoles really eat? Assessing the trophic status of an understudied and imperiled group of consumers in freshwater habitats. Freshw. Biol. 52 (2), 386–395. https://doi.org/10.1111/j.1365-2427.2006.01694.x.

Ameli, A.A., Creed, I.F., 2017. Quantifying hydrologic connectivity of wetlands to surface water systems. Hydrol. Earth Syst. Sci. 21 (3), 1791–1808. https://doi.org/10.5194/hess-21-1791-2017.

Arts, M.T., Brett, M.T., Kainz, M. (Eds.), 2009. Lipids in Aquatic Ecosystems. Springer-Verlag. https://doi.org/10.1007/978-0-387-89366-2.

Arvola, L., Rask, M., Ruuhijärvi, J., Tulonen, T., Vuorenmaa, J., Ruoho-Airola, T., Tulonen, J., 2010. Long-term patterns in pH and colour in small acidic boreal lakes of varying hydrological and landscape settings. Biogeochemistry 101 (1), 269–279. https://doi.org/10.1007/s10533-010-9473-y.

Arvola, L., Äijälä, C., Leppäranta, M., 2016. CDOM concentrations of large Finnish lakes relative to their landscape properties. Hydrobiologia 780 (1), 37–46. https://doi.org/10.1007/s10750-016-2906-4.

Arzel, C., Nummi, P., Arvola, L., Pöysä, H., Davranche, A., Rask, M., Olin, M., Holopainen, S., Viitala, R., Einola, E., Manninen-Johansen, S., 2020. Invertebrates are declining in boreal aquatic habitat: the effect of brownification? Sci. Total Environ. 724, 138199. https://doi.org/10.1016/j.scitotenv.2020.138199.

Ask, J., Karlsson, J., Persson, L., Ask, P., Byström, P., Jansson, M., 2009. Terrestrial organic matter and light penetration: effects on bacterial and primary production in lakes. Limnol. Oceanogr. 54 (6), 2034–2040. https://doi.org/10.4319/lo.2009.54.6.2034.

Assaad, A., Pontvianne, S., Corriou, J.-P., Pons, M.-N., 2015. Spectrophotometric characterization of dissolved organic matter in a rural watershed: the Madon River (N-E France). Environ. Monit. Assess. 187, 188. https://doi.org/10.1007/s10661-015-4422-9.

Baker, J.M.R., 1992. Body condition and tail height in great crested newts,Triturus cristatus. Anim. Behav. 43 (1), 157–159. https://doi.org/10.1016/S0003-3472(05)80081-8.

Bancroft, B.A., Baker, N.J., Blaustein, A.R., 2008. A meta-analysis of the effects of ultraviolet B radiation and its synergistic interactions with pH, contaminants, and disease on amphibian survival. Conserv. Biol. 22 (4), 987–996. https://doi.org/10.1111/j.1523-1739.2008.00966.x.

Barker, J.D., Dubnick, A., Lyons, W.B., Chin, Y.-P., 2013. Changes in dissolved organic matter (DOM) fluorescence in proglacial Antarctic streams. Arct. Antarct. Alp. Res. 45 (3), 305–317. https://doi.org/10.1657/1938-4246-45.3.305.

Berggren, M., Al-Kharusi, E.S., 2020. Decreasing organic carbon bioreactivity in European rivers. Freshw. Biol. 65 (6), 1128–1138. https://doi.org/10.1111/fwb.13498.

Berggren, M., Laudon, H., Haei, M., Ström, L., Jansson, M., 2010. Efficient aquatic bacterial metabolism of dissolved low-molecular-weight compounds from terrestrial sources. ISME J. 4 (3), 408–416. https://doi.org/10.1038/ismej.2009.120.

Berry, N.L., Overholt, E.P., Fisher, T.J., Williamson, C.E., 2020. Dissolved organic matter protects mosquito larvae from damaging solar UV radiation. PLOS ONE 15 (10), e0240261. https://doi.org/10.1371/journal.pone.0240261.

Birgand, F., Novince, E., 2004. Facteurs expliquant la présence de matière organique dans les eaux superficielles en Bretagne: Analyse des données existantes. irstea, p. 84.. https://hal.inrae.fr/hal-02583328.

Björnerås, C., Weyhenmeyer, G.A., Evans, C.D., Gessner, M.O., Grossart, H.-P., Kangur, K., Kokorite, I., Kortelainen, P., Laudon, H., Lehtoranta, J., Lottig, N., Monteith, D.T., Nõges, P., Nõges, T., Oulehle, F., Riise, G., Rusak, J.A., Räike, A., Sire, J., Kritzberg, E.S., 2017. Widespread increases in iron concentration in European and North American freshwaters. Glob. Biogeochem. Cycles 31 (10), 1488–1500. https://doi.org/10.1002/2017GB005749.

Blanchet, C.C., 2020. Assessment of the Impact of Forestry Activities on Water Colour And Identification of Aquatic Invertebrate Communities of Boreal Lakes in the Evo area, Southern Finland. Angers University (Unpublished Master's thesis).

Bociag, K., 2003. The impact of acidic organic matter on the diversity of underwater vegetation in soft water lakes. Acta Soc. Bot. Pol. 72 (3), 221–229.

Boggs, G.S., Delaney, J.L., Conacher, A., 2001. Using digital spatial data and GIS tools to examine water quality variability in the Upper Talbot Brook Catchment, WA. Cartography 30 (2), 15–30. https://doi.org/10.1080/00690805.2001.9714155.

Bolochio, B.E., Lescano, J.N., Cordier, J.M., Loyola, R., Nori, J., 2020. A functional perspective for global amphibian conservation. Biol. Conserv. 245, 108572. https://doi.org/10.1016/j.biocon.2020.108572.

Brett, M.T., Bunn, S.E., Chandra, S., Galloway, A.W.E., Guo, F., Kainz, M.J., Kankaala, P., Lau, D.C.P., Moulton, T.P., Power, M.E., Rasmussen, J.B., Taipale, S.J., Thorp, J.H., Wehr, J.D., 2017. How important are terrestrial organic carbon inputs for secondary production in freshwater ecosystems? Freshw. Biol. 62 (5), 833–853. https://doi.org/10.1111/fwb.12909.

Brezonik, P.L., Finlay, J.C., Griffin, C.G., Arnold, W.A., Boardman, E.H., Germolus, N., Hozalski, R.M., Olmanson, L.G., 2019. Iron influence on dissolved color in lakes of the Upper Great Lakes States. PLOS ONE 14 (2), e0211979. https://doi.org/10.1371/journal.pone.0211979.

Brothers, S., Köhler, J., Attermeyer, K., Grossart, H.P., Mehner, T., Meyer, N., Scharnweber, K., Hilt, S., 2014. A feedback loop links brownification and anoxia in a temperate, shallow lake. Limnol. Oceanogr. 59 (4), 1388–1398. https://doi.org/10.4319/lo.2014.59.4.1388.

Buisson, L., Grenouillet, G., Villéger, S., Canal, J., Laffaille, P., 2013. Toward a loss of functional diversity in stream fish assemblages under climate change. Glob. Chang. Biol. 19 (2), 387–400. https://doi.org/10.1111/gcb.12056.

Calhoun, A.J.K., Mushet, D.M., Bell, K.P., Boix, D., Fitzsimons, J.A., Isselin-Nondedeu, F., 2017. Temporary wetlands: challenges and solutions to conserving a 'disappearing' ecosystem. Biol. Conserv. 211 (B), 3–11. https://doi.org/10.1016/j.biocon.2016.11.024.

Caputo, L., Huovinen, P., Sommaruga, R., Gómez, I., 2018. Water transparency affects the survival of the medusa stage of the invasive freshwater jellyfish Craspedacusta sowerbii. Hydrobiologia 817 (1), 179–191. https://doi.org/10.1007/s10750-018-3520-4.

Carpenter, S.R., Cole, J.J., Pace, M.L., de Bogert, M.V., Bade, D.L., Bastviken, D., Gille, C.M., Hodgson, J.R., Kitchell, J.F., Kritzberg, E.S., 2005. Ecosystem subsidies: terrestrial support of aquatic food webs from 13c addition to contrasting lakes. Ecology 86 (10), 2737–2750. https://doi.org/10.1890/04-1282.

Catalán, N., Marcé, R., Kothawala, D.N., Tranvik, L.J., 2016. Organic carbon decomposition rates controlled by water retention time across inland waters. Nat. Geosci. 9 (7), 501–504. https://doi.org/10.1038/ngeo2720.

Catalán, N., Herrero Ortega, S., Gröntoft, H., Hilmarsson, T., Bertilsson, S., Wu, P., Levanoni, O., Bishop, K., Bravo, A., 2017. Effects of beaver impoundments on dissolved organic matter quality and biodegradability in boreal riverine systems. Hydrobiologia 793 (1), 135–148. https://doi.org/10.1007/s10750-016-2766-y.

Chaves-Ulloa, R., Taylor, B.W., Broadley, H.J., Cottingham, K.L., Baer, N.A., Weathers, K.C., Ewing, H.A., Chen, C.Y., 2016. Dissolved organic carbon modulates mercury concentrations in insect subsidies from streams to terrestrial consumers. Ecol. Appl. 26 (6), 1771–1784. https://doi.org/10.1890/15-0025.1.

Chen, I.-C., Hill, J.K., Ohlemüller, R., Roy, D.B., Thomas, C.D., 2011. Rapid range shifts of species associated with high levels of climate warming. Science 333 (6045), 1024–1026. https://doi.org/10.1126/science.1206432.

Chen, Y., Hozalski, R.M., Olmanson, L.G., Page, B.P., Finlay, J.C., Brezonik, P.L., Arnold, W.A., 2020. Prediction of photochemically produced reactive intermediates in surface waters via satellite remote sensing. Environ. Sci. Technol. 54 (11), 6671–6681. https://doi.org/10.1021/acs.est.0c00344.

Choudhury, M.I., Urrutia-Cordero, P., Zhang, H., Ekvall, M.K., Medeiros, L.R., Hansson, L.-A., 2019. Charophytes collapse beyond a critical warming and brownification threshold in shallow lake systems. Sci. Total Environ. 661, 148–154. https://doi.org/10.1016/j.scitotenv.2019.01.177.

Chow, A.T., Pitt, A.L., Baldwin, R.F., Suhre, D., Wang, J.-J., 2016. Water quality dynamics of ephemeral wetlands in the Piedmont ecoregion, South Carolina, USA. Ecol. Eng. 94, 555–563. https://doi.org/10.1016/j.ecoleng.2016.06.075.

Christ, M.J., David, M.B., 1996. Temperature and moisture effects on the production of dissolved organic carbon in a Spodosol. Soil Biol. Biochem. 28 (9), 1191–1199. https://doi.org/10.1016/0038-0717(96)00120-4.

Colburn, E.A., Weeks, S.C., Reed, S.K., 2007. Diversity and ecology of vernal pool invertebrates. In: Calhoun, A.J.K., DeMaynadier, P.G. (Eds.), Science And Conservation of Vernal Pools in Northeastern North America. CRC Press Inc., pp. 105–126.. https://www.cabdirect.org/cabdirect/abstract/20073216823.

Cole, J.J., Prairie, Y.T., Caraco, N.F., McDowell, W.H., Tranvik, L.J., Striegl, R.G., Duarte, C.M., Kortelainen, P., Downing, J.A., Middelburg, J.J., Melack, J., 2007. Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. Ecosystems 10 (1), 172–185. https://doi.org/10.1007/s10021-006-9013-8.

UK Government: Department for Environment, Food amp, Rural Affairs, 2020. Agriculture in the United Kingdom 2019, p. 157. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/950618/AUK-2019-07jan21.pdf.

Constantino, I., Viana, J., Teixeira, P., Moreira, A., Gama, G., Paschoal, F., Sargentini Jr., É., Bisinoti, M.C., 2021. Interaction of Pb, Ni and Cd with aquatic humic substances of Amazonian blackwater rivers. 32 (2), 260–268. https://doi.org/10.21577/0103-5053.20200176.

Cook, S., Whelan, M.J., Evans, C.D., Gauci, V., Peacock, M., Garnett, M.H., Kho, L.K., Teh, Y.A., Page, S.E., 2018. Fluvial organic carbon fluxes from oil palm plantations on tropical peatland. Biogeosciences 15 (24), 7435–7450. https://doi.org/10.5194/bg-15-7435-2018.

Creed, I.F., Bergström, A.-K., Trick, C.G., Grimm, N.B., Hessen, D.O., Karlsson, J., Kidd, K.A., Kritzberg, E., McKnight, D.M., Freeman, E.C., Senar, O.E., Andersson, A., Ask, J., Berggren, M., Cherif, M., Giesler, R., Hotchkiss, E.R., Kortelainen, P., Palta, M.M., Weyhenmeyer, G.A., 2018. Global change-driven effects on dissolved organic matter composition: implications for food webs of northern lakes. Glob. Chang. Biol. 24 (8), 3692–3714. https://doi.org/10.1111/gcb.14129.

Dalziel, A.E., Delean, S., Heinrich, S., Cassey, P., 2016. Persistence of low pathogenic influenza A virus in water: a systematic review and quantitative meta-analysis. PLOS ONE 11 (10), e0161929. https://doi.org/10.1371/journal.pone.0161929.

Davies, J.J.L., Jenkins, A., Monteith, D.T., Evans, C.D., Cooper, D.M., 2005. Trends in surface water chemistry of acidified UK Freshwaters, 1988–2002. Environ. Pollut. 137 (1), 27–39. https://doi.org/10.1016/j.envpol.2004.12.029.

Dawson, J.J.C., Soulsby, C., Tetzlaff, D., Hrachowitz, M., Dunn, S.M., Malcolm, I.A., 2008. Influence of hydrology and seasonality on DOC exports from three contrasting upland catchments. Biogeochemistry 90 (1), 93–113. https://doi.org/10.1007/s10533-008-9234-3.

de Wit, H.A., Valinia, S., Weyhenmeyer, G.A., Futter, M.N., Kortelainen, P., Austnes, K., Hessen, D.O., Räike, A., Laudon, H., Vuorenmaa, J., 2016. Current browning of surface waters will be further promoted by wetter climate. Environ. Sci. Technol. Lett. 3 (12), 430–435. https://doi.org/10.1021/acs.estlett.6b00396.

Denoël, M., Doellen, J., 2010. Displaying in the dark: light-dependent alternative mating tactics in the Alpine newt. Behav. Ecol. Sociobiol. 64 (7), 1171–1177. https://doi.org/10.1007/s00265-010-0933-0.

Dillon, P.J., Molot, L.A., 1997. Effect of landscape form on export of dissolved organic carbon, iron, and phosphorus from forested stream catchments. Water Resour. Res. 33 (11), 2591–2600. https://doi.org/10.1029/97WR01921.

Dixneuf, C., Peiris, P., Nummi, P., Sundell, J., 2021. Vernal pools enhance local vertebrate activity and diversity in a boreal landscape. Glob. Ecol. Conserv. 31, e01858. https://doi.org/10.1016/j.gecco.2021.e01858.

Ekström, S.M., Kritzberg, E.S., Kleja, D.B., Larsson, N., Nilsson, P.A., Graneli, W., Bergkvist, B., 2011. Effect of acid deposition on quantity and quality of dissolved organic matter in soil-water. Environ. Sci. Technol. 45 (11), 4733–4739. https://doi.org/10.1021/es104126f.

Elmberg, J., Arzel, C., Gunnarsson, G., Holopainen, S., Nummi, P., Pöysä, H., Sjöberg, K., 2020. Population change in breeding boreal waterbirds in a 25-year perspective: what characterises winners and losers? Freshw. Biol. 65 (2), 167–177. https://doi.org/10.1111/fwb.13411.

Epstein, H.E., Raynolds, M.K., Walker, D.A., Bhatt, U.S., Tucker, C.J., Pinzon, J.E., 2012. Dynamics of aboveground phytomass of the circumpolar Arctic tundra during the past three decades. Environ. Res. Lett. 7 (1), 015506. https://doi.org/10.1088/1748-9326/7/1/015506.

Erlandsson, M., Buffam, I., Fölster, J., Laudon, H., Temnerud, J., Weyhenmeyer, G.A., Bishop, K., 2008. Thirty-five years of synchrony in the organic matter concentrations of swedish rivers explained by variation in flow and sulphate. Glob. Chang. Biol. 14 (5), 1191–1198. https://doi.org/10.1111/j.1365-2486.2008.01551.x.

Estlander, S., Horppila, J., Olin, M., Nurminen, L., 2017. Should I stay or should I go? The diurnal behaviour of plant-attached zooplankton in lakes with different water transparency. J. Limnol. 76 (2), 253–260. https://doi.org/10.4081/jlimnol.2017.1564.

European Commission, 2001. Key Concepts document on Period of Reproduction and prenuptial Migration of huntable bird Species in the EU - Key concepts of Article 7(4) of Directive 2009/147/EC - European Commission. https://ec.europa.eu/environment/nature/conservation/wildbirds/hunting/key_concepts_en.htm.

Evans, C.D., Monteith, D.T., Cooper, D.M., 2005. Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. Environ. Pollut. 137 (1), 55–71. https://doi.org/10.1016/j.envpol.2004.12.031.

Ewing, S.A., O'Donnell, J.A., Aiken, G.R., Butler, K., Butman, D., Windham-Myers, L., Kanevskiy, M.Z., 2015. Long-term anoxia and release of ancient, labile carbon upon thaw of Pleistocene permafrost. Geophys. Res. Lett. 42 (24), 10730–10738. https://doi.org/10.1002/2015GL066296.

Fasching, C., Behounek, B., Singer, G.A., Battin, T.J., 2014. Microbial degradation of terrigenous dissolved organic matter and potential consequences for carbon cycling in brownwater streams. Sci. Rep. 4 (1), 4981. https://doi.org/10.1038/srep04981.

Feng, X., Vonk, J.E., van Dongen, B.E., Gustafsson, Ö., Semiletov, I.P., Dudarev, O.V., Wang, Z., Montluçon, D.B., Wacker, L., Eglinton, T.I., 2013. Differential mobilization of terrestrial carbon pools in Eurasian Arctic river basins. Proc. Natl. Acad. Sci. 110 (35), 14168–14173. https://doi.org/10.1073/pnas.1307031110.

Ferland, M.-E., Prairie, Y.T., Teodoru, C., del Giorgio, P.A., 2014. Linking organic carbon sedimentation, burial efficiency, and long-term accumulation in boreal lakes. J. Geophys. Res. Biogeosci. 119 (5), 836–847. https://doi.org/10.1002/2013JG002345.

Finér, L., Lepistö, A., Karlsson, K., Räike, A., Härkönen, L., Huttunen, M., Joensuu, S., Kortelainen, P., Mattsson, T., Piirainen, S., Sallantaus, T., Sarkkola, S., Tattari, S., Ukonmaanaho, L., 2021. Drainage for forestry increases N, P and TOC export to boreal surface waters. Sci. Total Environ. 762, 144098. https://doi.org/10.1016/j.scitotenv.2020.144098.

Finstad, A.G., Helland, I.P., Ugedal, O., Hesthagen, T., Hessen, D.O., 2014. Unimodal response of fish yield to dissolved organic carbon. Ecol. Lett. 17 (1), 36–43. https://doi.org/10.1111/ele.12201.

Finstad, A.G., Andersen, T., Larsen, S., Tominaga, K., Blumentrath, S., de Wit, H.A., Tømmervik, H., Hessen, D.O., 2016. From greening to browning: catchment vegetation development and reduced S-deposition promote organic carbon load on decadal time scales in nordic lakes. Sci. Rep. 6, 31944. https://doi.org/10.1038/srep31944.

Fisher, H.S., Wong, B.B.M., Rosenthal, G.G., 2006. Alteration of the chemical environment disrupts communication in a freshwater fish. Proc. R. Soc. B Biol. Sci. 273 (1591), 1187–1193. https://doi.org/10.1098/rspb.2005.3406.

Foley, B., Jones, I.D., Maberly, S.C., Rippey, B., 2012. Long-term changes in oxygen depletion in a small temperate lake: effects of climate change and eutrophication. Freshw. Biol. 57 (2), 278–289. https://doi.org/10.1111/j.1365-2427.2011.02662.x.

Foreman, C.M., Cory, R.M., Morris, C.E., SanClements, M.D., Smith, H.J., Lisle, J.T., Miller, P.L., Chin, Y.-P., McKnight, D.M., 2013. Microbial growth under humic-free conditions in a supraglacial stream system on the Cotton Glacier,Antarctica. Environ. Res. Lett. 8 (3), 035022. https://doi.org/10.1088/1748-9326/8/3/035022.

Forsström, L., Roiha, T., Rautio, M., 2013. Responses of microbial food web to increased allochthonous DOM in an oligotrophic subarctic lake. Aquat. Microb. Ecol. 68 (2), 171–184. https://doi.org/10.3354/ame01614.

Fraser, R.H., Olthof, I., Carrière, M., Deschamps, A., Pouliot, D., 2011. Detecting long-term changes to vegetation in northern Canada using the Landsat satellite image archive. Environ. Res. Lett. 6 (4), 045502. https://doi.org/10.1088/1748-9326/6/4/045502.

Freeman, E.C., Creed, I.F., Jones, B., Bergström, A.-K., 2020. Global changes may be promoting a rise in select cyanobacteria in nutrient-poor northern lakes. Glob. Chang. Biol. 26 (9), 4966–4987. https://doi.org/10.1111/gcb.15189.

Frey, K.E., Smith, L.C., 2005. Amplified carbon release from vast West Siberian peatlands by 2100. Geophys. Res. Lett. 32 (9). https://doi.org/10.1029/2004GL022025.

Furlanetto, L.M., Marinho, C.C., Palma-Silva, C., Albertoni, E.F., Figueiredo-Barros, M.P., Esteves, F.de A., 2012. Methane levels in shallow subtropical lake sediments: dependence on the trophic status of the lake and allochthonous input. Limnologica 42 (2), 151–155. https://doi.org/10.1016/j.limno.2011.09.009.

Gallardo, B., Clavero, M., Sánchez, M.I., Vilà, M., 2016. Global ecological impacts of invasive species in aquatic ecosystems. Glob. Chang. Biol. 22 (1), 151–163. https://doi.org/10.1111/gcb.13004.

Gandois, L., Cobb, A.R., Hei, I.C., Lim, L.B.L., Salim, K.A., Harvey, C.F., 2013. Impact of deforestation on solid and dissolved organic matter characteristics of tropical peat forests: implications for carbon release. Biogeochemistry 114, 183–199. https://doi.org/10.1007/s10533-012-9799-8.

Gandois, L., Hoyt, A.M., Mounier, S., Le Roux, G., Harvey, C.F., Claustres, A., Nuriman, M., Anshari, G., 2020. From canals to the coast: dissolved organic matter and trace metal composition in rivers draining degraded tropical peatlands in Indonesia. Biogeosciences 17 (7), 1897–1909. https://doi.org/10.5194/bg-17-1897-2020.

Gardner, J.R., Yang, X., Topp, S.N., Ross, M.R.V., Altenau, E.H., Pavelsky, T.M., 2021. The color of rivers. Geophys. Res. Lett. 48 (1), e2020GL088946. https://doi.org/10.1029/2020GL088946.

Gholizadeh, M.H., Melesse, A.M., Reddi, L., 2016. A comprehensive review on water quality parameters estimation using remote sensing techniques. Sensors 16 (8), 1298. https://doi.org/10.3390/s16081298.

Gibbons, J.W., Winne, C.T., Scott, D.E., Willson, J.D., Glaudas, X., Andrews, K.M., Todd, B.D., Fedewa, L.A., Wilkinson, L., Tsaliagos, R.N., Harper, S.J., Greene, J.L., Tuberville, T.D., Metts, B.S., Dorcas, M.E., Nestor, J.P., Young, C.A., Akre, T., Reed, R.N., Rothermel, B.B., 2006. Remarkable amphibian biomass and abundance in an isolated wetland: implications for wetland conservation. Conserv. Biol. 20 (5), 1457–1465. https://doi.org/10.1111/j.1523-1739.2006.00443.x.

Glaz, P., Gagné, J.-P., Archambault, P., Sirois, P., Nozais, C., 2015. Impact of forest harvesting on water quality and fluorescence characteristics of dissolved organic matter in eastern Canadian Boreal Shield lakes in summer. Biogeosciences 12 (23), 6999–7011. https://doi.org/10.5194/bg-12-6999-2015.

Graeber, D., Gelbrecht, J., Pusch, M.T., Anlanger, C., von Schiller, D., 2012. Agriculture has changed the amount and composition of dissolved organic matter in Central European headwater streams. Sci. Total Environ. 438, 435–446. https://doi.org/10.1016/j.scitotenv.2012.08.087.

Graneli, W., 2012. Brownification of lakes. In: Bengtsson, L., Herschy, R.W., Fairbridge, R.W. (Eds.), Encyclopedia of Lakes And Reservoirs. Springer, Netherlands, pp. 117–119 https://doi.org/10.1007/978-1-4020-4410-6_256.

Grant, J., 1986. Sensitivity of benthic community respiration and primary production to changes in temperature and light. Mar. Biol. 90 (2), 299–306. https://doi.org/10.1007/BF00569142.

Gratton, C., Donaldson, J., Zanden, M.J.V., 2008. Ecosystem linkages between lakes and the surrounding terrestrial landscape in Northeast Iceland. Ecosystems 11 (5), 764–774. https://doi.org/10.1007/s10021-008-9158-8.

Gücker, B., Silva, R.C.S., Graeber, D., Monteiro, J.A.F., Boëchat, I.G., 2016. Urbanization and agriculture increase exports and differentially alter elemental stoichiometry of dissolved organic matter (DOM) from tropical catchments. Sci. Total Environ. 550, 785–792. https://doi.org/10.1016/j.scitotenv.2016.01.158.

Gutseit, K., Berglund, O., Granéli, W., 2007. Essential fatty acids and phosphorus in seston from lakes with contrasting terrestrial dissolved organic carbon content. Freshw. Biol. 52 (1), 28–38. https://doi.org/10.1111/j.1365-2427.2006.01668.x.

Haaland, S., Hongve, D., Laudon, H., Riise, G., Vogt, R.D., 2010. Quantifying the drivers of the increasing colored organic matter in boreal surface waters. Environ. Sci. Technol. 44 (8), 2975–2980. https://doi.org/10.1021/es903179j.

Halabisky, M., Miller, D., Moskal, L.M., 2020. The Wetland Intrinsic Potential Tool: Identifying Forested Wetlands Through Machine Learning of Lidar Derived Datasets. American Geophysical Union Fall Meeting 2020, H027-07. https://ui.adsabs.harvard.edu/abs/2020AGUFMH027...07H.

Halley, D.J., Saveljev, A.P., Rosell, F., 2021. Population and distribution of beavers Castor fiber and Castor canadensis in Eurasia. Mammal Rev. 51 (1), 1–24. https://doi.org/10.1111/mam.12216.

Halliday, T.R., 1977. The courtship of European newts: an evolutionary perspective. In: Taylor, D.H., Guttman, S.I. (Eds.), The Reproductive Biology of Amphibians. Springer, US, pp. 185–232 https://doi.org/10.1007/978-1-4757-6781-0_6.

Hansell, D.A., 2013. Recalcitrant dissolved organic carbon fractions. Annu. Rev. Mar. Sci. 5 (1), 421–445. https://doi.org/10.1146/annurev-marine-120710-100757.

Hanson, P.C., Hamilton, D.P., Stanley, E.H., Preston, N., Langman, O.C., Kara, E.L., 2011. Fate of allochthonous dissolved organic carbon in lakes: a quantitative approach. PLOS ONE 6 (7), e21884. https://doi.org/10.1371/journal.pone.0021884.

Hansson, L.-A., Nicolle, A., Brönmark, C., Hargeby, A., Lindström, Å., Andersson, G., 2010. Waterfowl, macrophytes, and the clear water state of shallow lakes. Hydrobiologia 646 (1), 101–109. https://doi.org/10.1007/s10750-010-0169-z.

Harriman, R., Watt, A.W., Christie, A.E.G., Moore, D.W., McCartney, A.G., Taylor, E.M., 2003. Quantifying the effects of forestry practices on the recovery of upland streams and lochs from acidification. Sci. Total Environ. 310 (1–3), 101–111. https://doi.org/10.1016/S0048-9697(02)00626-5.

Hawkins, E., Sutton, R., 2011. The potential to narrow uncertainty in projections of regional precipitation change. Clim. Dyn. 37 (1), 407–418. https://doi.org/10.1007/s00382-010-0810-6.

Hayden, B., Harrod, C., Thomas, S.M., Eloranta, A.P., Myllykangas, J.-P., Siwertsson, A., Præbel, K., Knudsen, R., Amundsen, P.-A., Kahilainen, K.K., 2019. From clear lakes to murky waters – tracing the functional response of high-latitude lake communities to concurrent 'greening' and 'browning'. Ecol. Lett. 22 (5), 807–816. https://doi.org/10.1111/ele.13238.

Hedström, P., Bystedt, D., Karlsson, J., Bokma, F., Byström, P., 2017. Brownification increases winter mortality in fish. Oecologia 183 (2), 587–595. https://doi.org/10.1007/s00442-016-3779-y.

Hejzlar, J., Dubrovský, M., Buchtele, J., Růžička, M., 2003. The apparent and potential effects of climate change on the inferred concentration of dissolved organic matter in a temperate stream (the Malše River, South Bohemia). Sci. Total Environ. 310 (1), 143–152. https://doi.org/10.1016/S0048-9697(02)00634-4.

Hilt, S., Köhler, J., Adrian, R., Monaghan, M.T., Sayer, C.D., 2013. Clear, crashing, turbid and back – long-term changes in macrophyte assemblages in a shallow lake. Freshw. Biol. 58 (10), 2027–2036. https://doi.org/10.1111/fwb.12188.

Hocking, D., Babbitt, K., 2014. Amphibian contributions to ecosystem services. Herpetol. Conserv. Biol. 9 (1), 1–17. http://www.herpconbio.org/Volume_9/Issue_1/Hocking_Babbitt_2014.pdf.

Hodkinson, I.D., 1975. Energy flow and organic matter decomposition in an abandoned beaver pond ecosystem. Oecologia 21 (2), 131–139. https://doi.org/10.1007/BF00345556.

Hongve, D., Riise, G., Kristiansen, J.F., 2004. Increased colour and organic acid concentrations in Norwegian forest lakes and drinking water—a result of increased precipitation? Aquat. Sci. 66 (2), 231–238. https://doi.org/10.1007/s00027-004-0708-7.

Houser, J.N., 2006. Water color affects the stratification, surface temperature, heat content, and mean epilimnetic irradiance of small lakes. Can. J. Fish. Aquat. Sci. 63 (11). https://doi.org/10.1139/f06-131.

Hruška, J., Köhler, S., Laudon, H., Bishop, K., 2003. Is a universal model of organic acidity possible: comparison of the acid/base properties of dissolved organic carbon in the boreal and temperate zones. Environ. Sci. Technol. 37 (9), 1726–1730. https://doi.org/10.1021/es0201552.

Hu, L., Shan, K., Huang, L., Li, Y., Zhao, L., Zhou, Q., Song, L., 2021. Environmental factors associated with cyanobacterial assemblages in a mesotrophic subtropical plateau lake: a focus on bloom toxicity. Sci. Total Environ. 777, 146052. https://doi.org/10.1016/j.scitotenv.2021.146052.

Hudson, N., Baker, A., Reynolds, D., 2007. Fluorescence analysis of dissolved organic matter in natural, waste and polluted waters—a review. River Res. Appl. 23 (6), 631–649. https://doi.org/10.1002/rra.1005.

Hulatt, C.J., Kaartokallio, H., Asmala, E., Autio, R., Stedmon, C.A., Sonninen, E., Oinonen, M., Thomas, D.N., 2014a. Bioavailability and radiocarbon age of fluvial dissolved organic matter (DOM) from a northern peatland-dominated catchment: effect of land-use change. Aquat. Sci. 76 (3), 393–404. https://doi.org/10.1007/s00027-014-0342-y.

Hulatt, C.J., Kaartokallio, H., Oinonen, M., Sonninen, E., Stedmon, C.A., Thomas, D.N., 2014b. Radiocarbon dating of fluvial organic matter reveals land-use impacts in boreal peatlands. Environ. Sci. Technol. 48 (21), 12543–12551. https://doi.org/10.1021/es5030004.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, p. 151. https://archive.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_All_Topics.pdf.

Isidorova, A., Bravo, A.G., Riise, G., Bouchet, S., Björn, E., Sobek, S., 2016. The effect of lake browning and respiration mode on the burial and fate of carbon and mercury in the sediment of two boreal lakes. J. Geophys. Res. Biogeosci. 121 (1), 233–245. https://doi.org/10.1002/2015JG003086.

Jane, S.F., Winslow, L.A., Remucal, C.K., Rose, K.C., 2017. Long-term trends and synchrony in dissolved organic matter characteristics in Wisconsin, USA, lakes: quality, not quantity, is highly sensitive to climate. J. Geophys. Res. Biogeosci. 122 (3), 546–561. https://doi.org/10.1002/2016JG003630.

Jansson, M., Persson, L., De Roos, A.M., Jones, R.I., Tranvik, L.J., 2007. Terrestrial carbon and intraspecific size-variation shape lake ecosystems. Trends Ecol. Evol. 22 (6), 316–322. https://doi.org/10.1016/j.tree.2007.02.015.

Johnston, C.A., 2017. Ecosystem engineers: beaver ponds. In: Johnston, C.A. (Ed.), Beavers: Boreal Ecosystem Engineers. Springer International Publishing, pp. 13–49 https://doi.org/10.1007/978-3-319-61533-2_2.

Jones, R.I., 1992. The influence of humic substances on lacustrine planktonic food chains. Hydrobiologia 229 (1), 73–91. https://doi.org/10.1007/BF00006992.

Jones, R.I., Kankaala, P., Nykänen, H., Peura, S., Rask, M., Vesala, S., 2018. Whole-lake sugar addition demonstrates trophic transfer of dissolved organic carbon to top consumers. Ecosystems 21 (3), 495–506. https://doi.org/10.1007/s10021-017-0164-6.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation (a guest editorial). Soil Sci. Soc. Am. J. 61 (1), 4–10. https://doi.org/10.2136/sssaj1997.03615995006100010001x.

Karlsson, J., Byström, P., Ask, J., Ask, P., Persson, L., Jansson, M., 2009. Light limitation of nutrient-poor lake ecosystems. Nature 460, 506–509. https://doi.org/10.1038/nature08179.

Karlsson, J., Bergström, A.-K., Byström, P., Gudasz, C., Rodríguez, P., Hein, C., 2015. Terrestrial organic matter input suppresses biomass production in lake ecosystems. Ecology 96 (11), 2870–2876. https://doi.org/10.1890/15-0515.1.

Keva, O., Taipale, S.J., Hayden, B., Thomas, S.M., Vesterinen, J., Kankaala, P., Kahilainen, K.K., 2021. Increasing temperature and productivity change biomass, trophic pyramids and community-level omega-3 fatty acid content in subarctic lake food webs. Glob. Chang. Biol. 27 (2), 282–296. https://doi.org/10.1111/gcb.15387.

King, B.J., Hoefel, D., Daminato, D.P., Fanok, S., Monis, P.T., 2008. Solar UV reduces Cryptosporidium parvum oocyst infectivity in environmental waters. J. Appl. Microbiol. 104 (5), 1311–1323. https://doi.org/10.1111/j.1365-2672.2007.03658.x.

Kirk, J.T.O., 1983. Light And Photosynthesis in Aquatic Ecosystems. Cambridge University Press.

Kirk, J.T.O., 1994. Optics of UV-B radiation in natural waters. Arch. Hydrobiol. Beihefte Ergebnisse Limnol. 43, 1–16.

Kivinen, S., Nummi, P., Kumpula, T., 2020. Beaver-induced spatiotemporal patch dynamics affect landscape-level environmental heterogeneity. Environ. Res. Lett. 15 (9), 094065. https://doi.org/10.1088/1748-9326/ab9924.

Knight, T.M., McCoy, M.W., Chase, J.M., McCoy, K.A., Holt, R.D., 2005. Trophic cascades across ecosystems. Nature 437, 880–883. https://doi.org/10.1038/nature03962.

Knoll, L.B., Williamson, C.E., Pilla, R.M., Leach, T.H., Brentrup, J.A., Fisher, T.J., 2018. Browning-related oxygen depletion in an oligotrophic lake. Inland Waters 8 (3), 255–263. https://doi.org/10.1080/20442041.2018.1452355.

Köhler, S.J., Kothawala, D., Futter, M.N., Liungman, O., Tranvik, L., 2013. In-lake processes offset increased terrestrial inputs of dissolved organic carbon and color to lakes. PLOS ONE 8 (8), e70598. https://doi.org/10.1371/journal.pone.0070598.

Kozak, N., Ahonen, S.A., Keva, O., Østbye, K., Taipale, S.J., Hayden, B., Kahilainen, K.K., 2021. Environmental and biological factors are joint drivers of mercury biomagnification in subarctic lake food webs along a climate and productivity gradient. Sci. Total Environ. 779, 146261. https://doi.org/10.1016/j.scitotenv.2021.146261.

Kritzberg, E.S., 2017. Centennial-long trends of lake browning show major effect of afforestation. Limnol. Oceanogr. Lett. 2 (4), 105–112. https://doi.org/10.1002/lol2.10041.

Kritzberg, E.S., Ekström, S.M., 2012. Increasing iron concentrations in surface waters – a factor behind brownification? Biogeosci. Discuss. 8 (6), 12285–12316. https://doi.org/10.5194/bgd-8-12285-2011.

Kritzberg, E.S., Hasselquist, E.M., Škerlep, M., Löfgren, S., Olsson, O., Stadmark, J., Valinia, S., Hansson, L.-A., Laudon, H., 2020. Browning of freshwaters: consequences to ecosystem services, underlying drivers, and potential mitigation measures. Ambio 49 (2), 375–390. https://doi.org/10.1007/s13280-019-01227-5.

Kumarasiri, A.D.T.N., Udayakumara, E.P.N., Jayawardana, J.M.C.K., 2021. Impacts of soil erosion and forest quality on water quality in Samanalawewa watershed, Sri Lanka. Model. Earth Syst. Environ. https://doi.org/10.1007/s40808-021-01082-y.

Larsen, S., Andersen, T., Hessen, D.O., 2011. Climate change predicted to cause severe increase of organic carbon in lakes. Glob. Chang. Biol. 17 (2), 1186–1192. https://doi.org/10.1111/j.1365-2486.2010.02257.x.

Lau, D.C.P., Jonsson, A., Isles, P.D.F., Creed, I.F., Bergström, A., 2021. Lowered nutritional quality of plankton caused by global environmental changes. Glob. Chang. Biol. 27 (23), 6294–6306. https://doi.org/10.1111/gcb.15887.

Laudon, H., Köhler, S., Buffam, I., 2004. Seasonal TOC export from seven boreal catchments in northern Sweden. Aquat. Sci. 66 (2), 223–230. https://doi.org/10.1007/s00027-004-0700-2.

Laudon, H., Hedtjärn, J., Schelker, J., Bishop, K., Sørensen, R., Ågren, A., 2009. Response of dissolved organic carbon following forest harvesting in a boreal forest. Ambio 38 (7), 381–386. https://www.jstor.org/stable/40390255.

Laudon, H., Berggren, M., Ågren, A., Buffam, I., Bishop, K., Grabs, T., Jansson, M., Köhler, S., 2011. Patterns and dynamics of dissolved organic carbon (DOC) in boreal streams: the role of processes, connectivity, and scaling. Ecosystems 14 (6), 880–893. https://doi.org/10.1007/s10021-011-9452-8.

Lebret, K., Östman, Ö., Langenheder, S., Drakare, S., Guillemette, F., Lindström, E.S., 2018. High abundances of the nuisance raphidophyte Gonyostomum semen in brown water lakes are associated with high concentrations of iron. Sci. Rep. 8 (1), 13463. https://doi.org/10.1038/s41598-018-31892-7.

Leech, D.M., Pollard, A.I., Labou, S.G., Hampton, S.E., 2018. Fewer blue lakes and more murky lakes across the continental U.S.: implications for planktonic food webs. Limnol. Oceanogr. 63 (6), 2661–2680. https://doi.org/10.1002/lno.10967.

Lei, L., Thompson, J.A., McDonald, L.M., 2020. Assessment of dissolved organic carbon and iron effects on water color between a forest and pasture-dominated fine-scale catchment in a Central Appalachian region, West Virginia. Environ. Sci. Pollut. Res. 27 (23), 29464–29474. https://doi.org/10.1007/s11356-020-09251-9.

Lennon, J.T., Pfaff, L.E., 2005. Source and supply of terrestrial organic matter affects aquatic microbial metabolism. Aquat. Microb. Ecol. 39 (2), 107–119. https://doi.org/10.3354/ame039107.

Lepistö, L., Antikainen, S., Kivinen, J., 1994. The occurrence of Gonyostomum semen (Ehr.) Diesing in Finnish lakes. Hydrobiologia 273 (1), 1–8. https://doi.org/10.1007/BF00126764.

Lewis, W.M., Hamilton, S.K., Saunders III, J.F., 2006. Rivers of northern South America. In: Cushing, C.E., Cummins, K.W., Minshall, G.W. (Eds.), River And Stream Ecosystems of the World: With a New Introduction. Elsevier Science B.V, pp. 219–256.

Londero, J.E.L., dos Santos, M.B., Schuch, A.P., 2019. Impact of solar UV radiation on amphibians: focus on genotoxic stress. Mutat. Res. Genet. Toxicol. Environ. Mutagen. 842, 14–21. https://doi.org/10.1016/j.mrgentox.2019.03.003.

LoRusso, N.A., McHale, M., McHale, P., Montesdeoca, M., Zeng, T., T. Driscoll, C., 2020. Landscape influence on the browning of a lake watershed in the Adirondack Region of New York, USA. Soil Syst. 4 (3), 50. https://doi.org/10.3390/soilsystems4030050.

Ma, Q., Jin, H., Yu, C., Bense, V.F., 2019. Dissolved organic carbon in permafrost regions: a review. Sci. China Earth Sci. 62 (2), 349–364. https://doi.org/10.1007/s11430-018-9309-6.

Mahdiyan, O., Filazzola, A., Molot, L.A., Gray, D., Sharma, S., 2021. Drivers of water quality changes within the Laurentian Great Lakes region over the past 40 years. Limnol. Oceanogr. 66 (1), 237–254. https://doi.org/10.1002/lno.11600.

Maranger, R., Pullin, M.J., 2003. Elemental complexation by dissolved organic matter in lakes: implications for Fe speciation and the speciation and the bioavailability of Fe and P. In: Findlay, S.E.G., Sinsabaugh, R.L. (Eds.), Aquatic Ecosystems8. Academic Press, pp. 185–214. https://doi.org/10.1016/B978-012256371-3/50009-3.

Marie, L., Pernet-Coudrier, B., Waeles, M., Gabon, M., Riso, R., 2015. Dynamics and sources of reduced sulfur, humic substances and dissolved organic carbon in a temperate river system affected by agricultural practices. Sci. Total Environ. 537, 23–32. https://doi.org/10.1016/j.scitotenv.2015.07.089.

Martin, P., Cherukuru, N., Tan, A.S.Y., Sanwlani, N., Mujahid, A., Müller, M., 2018. Distribution and cycling of terrigenous dissolved organic carbon in peatland-draining rivers and coastal waters of Sarawak,Borneo. Biogeosciences 15 (22), 6847–6865. https://doi.org/10.5194/bg-15-6847-2018.

Martin-Mousset, B., Croue, J.P., Lefebvre, E., Legube, B., 1997. Distribution and characterization of dissolved organic matter of surface waters. Water Res. 3 (31), 541–553.

Marttila, H., Karjalainen, S.-M., Kuoppala, M., Nieminen, M.L., Ronkanen, A.-K., Kløve, B., Hellsten, S., 2018. Elevated nutrient concentrations in headwaters affected by drained peatland. Sci. Total Environ. 643, 1304–1313. https://doi.org/10.1016/j.scitotenv.2018.06.278.

Mattle, M.J., Vione, D., Kohn, T., 2015. Conceptual model and experimental framework to determine the contributions of direct and indirect photoreactions to the solar disinfection of MS2, phiX174, and adenovirus. Environ. Sci. Technol. 49 (1), 334–342. https://doi.org/10.1021/es504764u.

Mattsson, T., Kortelainen, P., Räike, A., 2005. Export of DOM from boreal catchments: impacts of land use cover and climate. Biogeochemistry 76 (2), 373–394. https://doi.org/10.1007/s10533-005-6897-x.

Mattsson, T., Kortelainen, P., Laubel, A., Evans, D., Pujo-Pay, M., Räike, A., Conan, P., 2009. Export of dissolved organic matter in relation to land use along a European climatic gradient. Sci. Total Environ. 407 (6), 1967–1976. https://doi.org/10.1016/j.scitotenv.2008.11.014.

Mesquita, R.M.R.S., Canário, A.V.M., Melo, E., 2003. Partition of fish pheromones between water and aggregates of humic acids. Consequences for sexual signaling. Environ. Sci. Technol. 37 (4), 742–746. https://doi.org/10.1021/es025987e.

Meyer-Jacob, C., Tolu, J., Bigler, C., Yang, H., Bindler, R., 2015. Early land use and centennial scale changes in lake-water organic carbon prior to contemporary monitoring. Proc. Natl. Acad. Sci. 112 (21), 6579–6584. https://doi.org/10.1073/pnas.1501505112.

Meyer-Jacob, C., Labaj, A.L., Paterson, A.M., Edwards, B.A., Keller, W.(Bill), Cumming, B.F., Smol, J.P., 2020. Re-browning of Sudbury (Ontario, Canada) lakes now approaches pre-acid deposition lake-water dissolved organic carbon levels. Sci. Total Environ. 725, 138347. https://doi.org/10.1016/j.scitotenv.2020.138347.

Milardi, M., Petäjä, T., Weckström, J., 2019. Should we further investigate the cascading effects of introduced fish on insectivorous birds? Boreal Environ. Res. 24, 51–62.

Minayeva, T., Sirin, A., 2009. Wetlands - threatened Arctic ecosystems: vulnerability to climate change and adaptation options. In: Bates, P. (Ed.), Climate Change And Arctic Sustainable Development: Scientific, Social, Cultural And Educational Challenges. UNESCO, pp. 76–83.

Minayeva, T., Sirin, A., Kershaw, P., Bragg, O., 2016. Arctic peatlands. In: Finlayson, C.M., Milton, G.R., Prentice, R.C., Davidson, N.C. (Eds.), The Wetland Book. Springer, Netherlands, pp. 1–15 https://doi.org/10.1007/978-94-007-6173-5_109-2.

Monteith, D.T., Stoddard, J.L., Evans, C.D., de Wit, H.A., Forsius, M., Høgåsen, T., Wilander, A., Skjelkvåle, B.L., Jeffries, D.S., Vuorenmaa, J., Keller, B., Kopácek, J., Vesely, J., 2007. Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. Nature 450, 537–540. https://doi.org/10.1038/nature06316.

Moore, T.R., Dalva, M., 2001. Some controls on the release of dissolved organic carbon by plant tissues and soils. Soil Sci. 166 (1), 38–47. https://doi.org/10.1097/00010694-200101000-00007.

Moore, S., Gauci, V., Evans, C.D., Page, S.E., 2011. Fluvial organic carbon losses from a Bornean blackwater river. Biogeosciences 8 (4), 901–909. https://doi.org/10.5194/bg-8-901-2011.

Mormul, R.P., Ahlgren, J., Ekvall, M.K., Hansson, L.-A., Brönmark, C., 2012. Water brownification may increase the invasibility of a submerged non-native macrophyte. Biol. Invasions 14 (10), 2091–2099. https://doi.org/10.1007/s10530-012-0216-y.

Mzobe, P., Berggren, M., Pilesjö, P., Lundin, E., Olefeldt, D., Roulet, N.T., Persson, A., 2018. Dissolved organic carbon in streams within a subarctic catchment analysed using a GIS/remote sensing approach. PLOS ONE 13 (7), e0199608. https://doi.org/10.1371/journal.pone.0199608.

Nagengast, B., Gąbka, M., 2017. Apparent niche partitioning of two congeneric submerged macrophytes in small water bodies: the case of Ceratophyllum demersum L. and C. submersum L. Aquat. Bot. 137, 1–8. https://doi.org/10.1016/j.aquabot.2016.11.001.

Nguyen, M.T., Jasper, J.T., Boehm, A.B., Nelson, K.L., 2015. Sunlight inactivation of fecal indicator bacteria in open-water unit process treatment wetlands: modeling endogenous and exogenous inactivation rates. Water Res. 83, 282–292. https://doi.org/10.1016/j.watres.2015.06.043.

Nieminen, M., Sarkkola, S., Sallantaus, T., Hasselquist, E.M., Laudon, H., 2021. Peatland drainage—a missing link behind increasing TOC concentrations in waters from high latitude forest catchments? Sci. Total Environ. 774, 145150. https://doi.org/10.1016/j.scitotenv.2021.145150.

Nolet, B.A., Rosell, F., 1998. Comeback of the beaver Castor fiber: an overview of old and new conservation problems. Biol. Conserv. 83 (2), 165–173. https://doi.org/10.1016/S0006-3207(97)00066-9.

Nummi, P., 1989. Simulated effects of the beaver on vegetation, invertebrates and ducks. Ann. Zool. Fenn. 26 (1), 43–52. http://www.jstor.org/stable/23734551.
Nummi, P., Kuuluvainen, T., 2013. Forest disturbance by an ecosystem engineer: beaver in boreal forest landscapes. Boreal Environ. Res. 18 (Suppl. A), 13–24.
Nummi, P., Vehkaoja, M., Pumpanen, J., Ojala, A., 2018. Beavers affect carbon biogeochemistry: both short-term and long-term processes are involved. Mammal Rev. 48 (4), 298–311. https://doi.org/10.1111/mam.12134.
Nummi, P., Suontakanen, E.-M., Holopainen, S., Väänänen, V.-M., 2019. The effect of beaver facilitation on Common Teal: pairs and broods respond differently at the patch and landscape scales. Ibis 161 (2), 301–309. https://doi.org/10.1111/ibi.12626.
Nummi, P., Arzel, C., Sauramo, V., 2021. Populations in stable and variable habitats: green and common sandpiper in a beaver-influenced landscape. Glob. Ecol. Conserv. 28, e01678. https://doi.org/10.1016/j.gecco.2021.e01678.
Nydahl, A.C., Wallin, M.B., Tranvik, L.J., Hiller, C., Attermeyer, K., Garrison, J.A., Chaguaceda, F., Scharnweber, K., Weyhenmeyer, G.A., 2019. Colored organic matter increases CO2 in meso-eutrophic lake water through altered light climate and acidity. Limnol. Oceanogr. 64 (2), 744–756. https://doi.org/10.1002/lno.11072.
Nyffeler, M., Şekercioğlu, Ç.H., Whelan, C.J., 2018. Insectivorous birds consume an estimated 400–500 million tons of prey annually. Sci. Nat. 105, 47. https://doi.org/10.1007/s00114-018-1571-z.
Ochoa-Ochoa, L.M., Rodríguez, P., Mora, F., Flores-Villela, O., Whittaker, R.J., 2012. Climate change and amphibian diversity patterns in Mexico. Biol. Conserv. 150 (1), 94–102. https://doi.org/10.1016/j.biocon.2012.03.010.
Ogle, S.M., Breidt, F.J., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72 (1), 87–121. https://doi.org/10.1007/s10533-004-0360-2.
Olmanson, L.G., Brezonik, P.L., Finlay, J.C., Bauer, M.E., 2016. Comparison of Landsat 8 and Landsat 7 for regional measurements of CDOM and water clarity in lakes. Remote Sens. Environ. 185, 119–128. https://doi.org/10.1016/j.rse.2016.01.007.
Oni, S.K., Futter, M.N., Bishop, K., Köhler, S.J., Ottosson-Löfvenius, M., Laudon, H., 2013. Long-term patterns in dissolved organic carbon, major elements and trace metals in boreal headwater catchments: trends, mechanisms and heterogeneity. Biogeosciences 10 (4), 2315–2330. https://doi.org/10.5194/bg-10-2315-2013.
Opperman, J.J., Merenlender, A.M., 2000. Deer herbivory as an ecological constraint to restoration of degraded riparian corridors. Restor. Ecol. 8 (1), 41–47. https://doi.org/10.1046/j.1526-100x.2000.80006.x.
Oulehle, F., Hruška, J., 2009. Rising trends of dissolved organic matter in drinking-water reservoirs as a result of recovery from acidification in the Ore Mts., Czech Republic. Environ. Pollut. 157 (12), 3433–3439. https://doi.org/10.1016/j.envpol.2009.06.020.
Overholt, E.P., Hall, S.R., Williamson, C.E., Meikle, C.K., Duffy, M.A., Cáceres, C.E., 2012. Solar radiation decreases parasitism in Daphnia. Ecol. Lett. 15 (1), 47–54. https://doi.org/10.1111/j.1461-0248.2011.01707.x.
Pace, M.L., Cole, J.J., Carpenter, S.R., Kitchell, J.F., Hodgson, J.R., Van de Bogert, M.C., Bade, D.L., Kritzberg, E.S., Bastviken, D., 2004. Whole-lake carbon-13 additions reveal terrestrial support of aquatic food webs. Nature 427, 240–243. https://doi.org/10.1038/nature02227.
Pahkala, M., Laurila, A., Merilä, J., 2001. Carry–over effects of ultraviolet–B radiation on larval fitness in Rana temporaria. Proc. R. Soc. B Biol. Sci. 268 (1477), 1699–1706. https://doi.org/10.1098/rspb.2001.1725.
Pecl, G.T., Araújo, M.B., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I.-C., Clark, T.D., Colwell, R.K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R.A., Griffis, R.B., Hobday, A.J., Janion-Scheepers, C., Jarzyna, M.A., Jennings, S., Williams, S.E., 2017. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. Science 355 (6332), aai9214. https://doi.org/10.1126/science.aai9214.
Piirainen, S., Finér, L., Mannerkoski, H., Starr, M., 2007. Carbon, nitrogen and phosphorus leaching after site preparation at a boreal forest clear-cut area. For. Ecol. Manag. 243 (1), 10–18. https://doi.org/10.1016/j.foreco.2007.01.053.
Pilla, R.M., Williamson, C.E., Zhang, J., Smyth, R.L., Lenters, J.D., Brentrup, J.A., Knoll, L.B., Fisher, T.J., 2018. Browning-related decreases in water transparency lead to long-term increases in surface water temperature and thermal stratification in two small lakes. J. Geophys. Res. : Biogeosci. 123 (5), 1651–1665. https://doi.org/10.1029/2017JG004321.
Polis, G.A., Anderson, W.B., Holt, R.D., 1997. Toward an integration of landscape and food web ecology: the dynamics of spatially subsidized food webs. Annu. Rev. Ecol. Syst. 28 (1), 289–316. https://doi.org/10.1146/annurev.ecolsys.28.1.289.
Polo-Cavia, N., Burraco, P., Gomez-Mestre, I., 2016. Low levels of chemical anthropogenic pollution may threaten amphibians by impairing predator recognition. Aquat. Toxicol. 172, 30–35. https://doi.org/10.1016/j.aquatox.2015.12.019.
Popova, O.N., Haritonov, A.Y., Sushchik, N.N., Makhutova, O.N., Kalachova, G.S., Kolmakova, A.A., Gladyshev, M.I., 2017. Export of aquatic productivity, including highly unsaturated fatty acids, to terrestrial ecosystems via odonata. Sci. Total Environ. 581–582, 40–48. https://doi.org/10.1016/j.scitotenv.2017.01.017.
Pöysä, H., Elmberg, J., Gunnarsson, G., Holopainen, S., Nummi, P., Sjöberg, K., 2017. Habitat associations and habitat change: seeking explanation for population decline in breeding Eurasian wigeon Anas penelope. Hydrobiologia 785 (1), 207–217. https://doi.org/10.1007/s10750-016-2922-4.
Pöysä, H., Holopainen, S., Elmberg, J., Gunnarsson, G., Nummi, P., Sjöberg, K., 2019. Changes in species richness and composition of boreal waterbird communities: a comparison between two time periods 25 years apart. Sci. Rep. 9, 1725. https://doi.org/10.1038/s41598-018-38167-1.
Quesada, A., Velázquez, D., 2013. Global change effects on Antarctic freshwater ecosystems: the case of maritime Antarctic lakes. Climatic Change And Global Warming of Inland Waters. John Wiley & Sons, Ltd., pp. 367–382 https://doi.org/10.1002/9781118470596.ch20.
Ramsar Convention on Wetlands, 2018. 54th Meeting of the Standing Committee. Gland, Switzerland. https://www.qa.ramsar.org/sites/default/files/documents/library/sc54-05_sg_report_e.pdf.
Ranåker, L., Jönsson, M., Nilsson, P.A., Brönmark, C., 2012. Effects of brown and turbid water on piscivore–prey fish interactions along a visibility gradient. Freshw. Biol. 57 (9), 1761–1768. https://doi.org/10.1111/j.1365-2427.2012.02836.x.
Rasilo, T., Ojala, A., Huotari, J., Starr, M., Pumpanen, J., 2015. Concentrations and quality of DOC along the terrestrial–aquatic continuum in a boreal forested catchment. Freshw. Sci. 34 (2), 440–455. https://doi.org/10.1086/680682.
Raymond, P.A., Bauer, J.E., 2001. Riverine export of aged terrestrial organic matter to the North Atlantic Ocean. Nature 409, 497–500. https://doi.org/10.1038/35054034.
Read, J.S., Rose, K.C., 2013. Physical responses of small temperate lakes to variation in dissolved organic carbon concentrations. Limnol. Oceanogr. 58 (3), 921–931. https://doi.org/10.4319/lo.2013.58.3.0921.
Redden, D., F. Trueman, B., W. Dunnington, D., E. Anderson, L., A. Gagnon, G., 2021. Chemical recovery and browning of Nova Scotia surface waters in response to declining acid deposition. Environ. Sci. Process. Impacts 23 (3), 446–456. https://doi.org/10.1039/D0EM00425A.
Reitsema, R.E., Meire, P., Schoelynck, J., 2018. The future of freshwater macrophytes in a changing world: dissolved organic carbon quantity and quality and its interactions with macrophytes. Front. Plant Sci. 9 (629). https://doi.org/10.3389/fpls.2018.00629.
Reitsema, R.E., Wolters, J.-W., Preiner, S., Meire, P., Hein, T., De Boeck, G., Blust, R., Schoelynck, J., 2020. Response of submerged macrophyte growth, morphology, chlorophyll content and nutrient stoichiometry to increased flow velocity and elevated CO2 and dissolved organic carbon concentrations. Front. Environ. Sci. 11 (527801), 159. https://doi.org/10.3389/fenvs.2020.527801.
Remillard, M.M., Gruendling, G.K., Bogucki, D.J., 1987. Disturbance by beaver (Castor canadensis Kuhl) and increased landscape heterogeneity. In: Turner, M.G. (Ed.), Landscape Heterogeneity And Disturbance. Springer, pp. 103–122 https://doi.org/10.1007/978-1-4612-4742-5_6.
Ren, W., Tian, H., Cai, W.-J., Lohrenz, S.E., Hopkinson, C.S., Huang, W.-J., Yang, J., Tao, B., Pan, S., He, R., 2016. Century-long increasing trend and variability of dissolved organic carbon export from the Mississippi River basin driven by natural and anthropogenic forcing. Glob. Biogeochem. Cycles 30 (9), 1288–1299. https://doi.org/10.1002/2016GB005395.
Ripszam, M., Paczkowska, J., Figueira, J., Veenaas, C., Haglund, P., 2015. Dissolved organic carbon quality and sorption of organic pollutants in the Baltic Sea in light of future climate change. Environ. Sci. Technol. 49 (3), 1445–1452. https://doi.org/10.1021/es504437s.
Rixen, T., Baum, A., Pohlmann, T., Balzer, W., Samiaji, J., Jose, C., 2008. The siak, a tropical black water river in central Sumatra on the verge of anoxia. Biogeochemistry 90 (2), 129–140. https://doi.org/10.1007/s10533-008-9239-y.
Rizinjirabake, F., Pilesjö, P., Tenenbaum, D.E., 2019. Dissolved organic carbon leaching flux in a mixed agriculture and forest watershed in Rwanda. J. Hydrol. Reg. Stud. 26, 100633. https://doi.org/10.1016/j.ejrh.2019.100633.
Roehm, C.L., Giesler, R., Karlsson, J., 2009. Bioavailability of terrestrial organic carbon to lake bacteria: the case of a degrading subarctic permafrost mire complex. <sb:contribution><sb:title>J. Geophys. Res. </sb:title></sb:contribution><sb:host><sb:issue><sb:series><sb:title>Biogeosci.</sb:title></sb:series></sb:issue></sb:host> 114 (G3). https://doi.org/10.1029/2008JG000863.
Rust, A.J., Saxe, S., McCray, J., Rhoades, C.C., Hogue, T.S., Rust, A.J., Saxe, S., McCray, J., Rhoades, C.C., Hogue, T.S., 2019. Evaluating the factors responsible for post-fire water quality response in forests of the western USA. Int. J. Wildland Fire 28 (10), 769–784. https://doi.org/10.1071/WF18191.
Saebelfeld, M., Minguez, L., Griebel, J., Gessner, M.O., Wolinska, J., 2017. Humic dissolved organic carbon drives oxidative stress and severe fitness impairments in Daphnia. Aquat. Toxicol. 182, 31–38. https://doi.org/10.1016/j.aquatox.2016.11.006.
Salonen, K., Kononen, K., Arvola, L., 1983. Respiration of plankton in two small, polyhumic lakes. In: Forsberg, C., Johansson, J.-Å. (Eds.), Forest Water Ecosystems: Nordic Symposium on Forest Water Ecosystems Held at Färna, Central Sweden, September 28-October 2, 1981. Springer, Netherlands, pp. 65–70 https://doi.org/10.1007/978-94-009-7284-1_8.
Sarkkola, S., Hökkä, H., Koivusalo, H., Nieminen, M., Ahti, E., Päivänen, J., Laine, J., 2010. Role of tree stand evapotranspiration in maintaining satisfactory drainage conditions in drained peatlands. Can. J. For. Res. 40 (8), 1485–1496. https://doi.org/10.1139/X10-084.
Sarkkola, S., Nieminen, M., Koivusalo, H., Laurén, A., Kortelainen, P., Mattsson, T., Palviainen, M., Piirainen, S., Starr, M., Finér, L., 2013. Iron concentrations are increasing in surface waters from forested headwater catchments in eastern Finland. Sci. Total Environ. 463–464, 683–689. https://doi.org/10.1016/j.scitotenv.2013.06.072.
Scharnweber, K., Syväranta, J., Hilt, S., Brauns, M., Vanni, M.J., Brothers, S., Köhler, J., Knežević-Jarić, J., Mehner, T., 2014. Whole-lake experiments reveal the fate of terrestrial particulate organic carbon in benthic food webs of shallow lakes. Ecology 95 (6), 1496–1505. https://doi.org/10.1890/13-0390.1.
Scharnweber, K., Strandberg, U., Karlsson, K., Eklöv, P., 2016. Decrease of population divergence in Eurasian perch (Perca fluviatilis) in browning waters: role of fatty acids and foraging efficiency. PLOS ONE 11 (9), e0162470. https://doi.org/10.1371/journal.pone.0162470.
Schelker, J., Eklöf, K., Bishop, K., Laudon, H., 2012. Effects of forestry operations on dissolved organic carbon concentrations and export in boreal first-order streams. <sb:contribution><sb:title>J. Geophys. Res. </sb:title></sb:contribution><sb:host><sb:issue><sb:series><sb:title>Biogeosci.</sb:title></sb:series></sb:issue></sb:host> 117 (G1). https://doi.org/10.1029/2011JG001827.
Scully, N.M., McQueen, D.J., Lean, D.R.S., Cooper, W.J., 1995. Photochemical formation of hydrogen peroxide in lakes: effects of dissolved organic carbon and ultraviolet radiation. Can. J. Fish. Aquat. Sci. 52 (12), 2675–2681. https://doi.org/10.1139/f95-856.

Scully, N.M., Cooper, W.J., Tranvik, L.J., 2003. Photochemical effects on microbial activity in natural waters: the interaction of reactive oxygen species and dissolved organic matter. FEMS Microbiol. Ecol. 46 (3), 353–357. https://doi.org/10.1016/S0168-6496(03)00198-3.

Secondi, J., Théry, M., 2014. An ultraviolet signal generates a conflict between sexual selection and species recognition in a newt. Behav. Ecol. Sociobiol. 68 (7), 1049–1058. https://doi.org/10.1007/s00265-014-1717-8.

Secondi, J., Aumjaud, A., Pays, O., Boyer, S., Montembault, D., Violleau, D., 2007. Water turbidity affects the development of sexual morphology in the palmate newt. Ethology 113 (7), 711–720. https://doi.org/10.1111/j.1439-0310.2007.01375.x.

Secondi, J., Lepetz, V., Théry, M., 2012. Male attractiveness is influenced by UV wavelengths in a newt species but not in its close relative. PLOS ONE 7 (1), e30391. https://doi.org/10.1371/journal.pone.0030391.

Seekell, D.A., Lapierre, J.-F., Ask, J., Bergström, A.-K., Deininger, A., Rodríguez, P., Karlsson, J., 2015. The influence of dissolved organic carbon on primary production in northern lakes. Limnol. Oceanogr. 60 (4), 1276–1285. https://doi.org/10.1002/lno.10096.

Senar, O.E., Creed, I.F., Strandberg, U., Arts, M.T., 2019. Browning reduces the availability—but not the transfer—of essential fatty acids in temperate lakes. Freshw. Biol. 64 (12), 2107–2119. https://doi.org/10.1111/fwb.13399.

Senar, O.E., Creed, I.F., Trick, C.G., 2021. Lake browning may fuel phytoplankton biomass and trigger shifts in phytoplankton communities in temperate lakes. Aquat. Sci. 83 (2), 21. https://doi.org/10.1007/s00027-021-00780-0.

Sepp, M., Kõiv, T., Nõges, P., Nõges, T., 2018. Do organic matter metrics included in lake surveillance monitoring in Europe provide a broad picture of brownification and enrichment with oxygen consuming substances? Sci. Total Environ. 610–611, 1288–1297. https://doi.org/10.1016/j.scitotenv.2017.08.179.

Serrano, L., 1994. Sources, abundance and disappearance of polyphenolic compounds in temporary ponds of Donana National Park (south-western Spain). Mar. Freshw. Res. 45 (8), 1555–1564. https://doi.org/10.1071/mf9941555.

Shurin, J.B., Aranguren-Riaño, N., Duque Negro, D., Echeverri Lopez, D., Jones, N.T., Laverde-R, O., Neu, A., Pedroza Ramos, A., 2020. Ecosystem effects of the world's largest invasive animal. Ecology 101 (5), e02991. https://doi.org/10.1002/ecy.2991.

Škerlep, M., Steiner, E., Axelsson, A.-L., Kritzberg, E.S., 2020. Afforestation driving long-term surface water browning. Glob. Chang. Biol. 26 (3), 1390–1399. https://doi.org/10.1111/gcb.14891.

Smith, A., Tetzlaff, D., Gelbrecht, J., Kleine, L., Soulsby, C., 2020. Riparian wetland rehabilitation and beaver re-colonization impacts on hydrological processes and water quality in a lowland agricultural catchment. Sci. Total Environ. 699, 134302. https://doi.org/10.1016/j.scitotenv.2019.134302.

Smolders, K.E., Rolls, R.J., Boulton, A.J., Webb, A.A., Sheldon, F., 2018. Effects of selective forest harvesting best management practices on organic matter and invertebrate detritivores in streams draining subtropical eucalypt forest. Ecol. Eng. 122, 271–285. https://doi.org/10.1016/j.ecoleng.2018.08.010.

Snodgrass, J.W., Komoroski, M.J., Bryan Jr., A.L., Burger Jr., J., 2000. Relationships among isolated wetland size, hydroperiod, and amphibian species richness: implications for wetland regulations. Conserv. Biol. 14 (2), 414–419. https://doi.org/10.1046/j.1523-1739.2000.99161.x.

Sobek, S., Algesten, G., Bergström, A.-K., Jansson, M., Tranvik, L.J., 2003. The catchment and climate regulation of pCO2 in boreal lakes. Glob. Chang. Biol. 9 (4), 630–641. https://doi.org/10.1046/j.1365-2486.2003.00619.x.

Soininen, J., Bartels, P., Heino, J., Luoto, M., Hillebrand, H., 2015. Toward more integrated ecosystem research in aquatic and terrestrial environments. Bioscience 65 (2), 174–182. https://doi.org/10.1093/biosci/biu216.

Solomon, C.T., Jones, S.E., Weidel, B.C., Buffam, I., Fork, M.L., Karlsson, J., Larsen, S., Lennon, J.T., Read, J.S., Sadro, S., Saros, J.E., 2015. Ecosystem consequences of changing inputs of terrestrial dissolved organic matter to lakes: current knowledge and future challenges. Ecosystems 18 (3), 376–389. https://doi.org/10.1007/s10021-015-9848-y.

Song, X.-P., Hansen, M.C., Stehman, S.V., Potapov, P.V., Tyukavina, A., Vermote, E.F., Townshend, J.R., 2018. Global land change from 1982 to 2016. Nature 560, 639–643. https://doi.org/10.1038/s41586-018-0411-9.

Spencer, R.G.M., Hernes, P.J., Ruf, R., Baker, A., Dyda, R.Y., Stubbins, A., Six, J., 2010. Temporal controls on dissolved organic matter and lignin biogeochemistry in a pristine tropical river, Democratic Republic of Congo. J. Geophys. Res.Biogeosci. 115 (G3). https://doi.org/10.1029/2009JG001180.

Steinberg, C.E.W., Höss, S., Kloas, W., Lutz, I., Meinelt, T., Pflugmacher, S., Wiegand, C., 2004. Hormonelike effects of humic substances on fish, amphibians, and invertebrates. Environ. Toxicol. 19 (4), 409–411. https://doi.org/10.1002/tox.20019.

Strandberg, U., Palviainen, M., Eronen, A., Piirainen, S., Laurén, A., Akkanen, J., Kankaala, P., 2016. Spatial variability of mercury and polyunsaturated fatty acids in the European perch (Perca fluviatilis) – implications for risk-benefit analyses of fish consumption. Environ. Pollut. 219, 305–314. https://doi.org/10.1016/j.envpol.2016.10.050.

Strandberg, U., Bhavsar, S.P., Arts, M.T., 2017. Estimation of omega-3 fatty acid (EPA + DHA) intake from Lake Ontario fish based on provincial consumption advisories. J. Great Lakes Res. 43 (6), 1132–1140. https://doi.org/10.1016/j.jglr.2017.08.009.

Strandberg, U., Hiltunen, M., Rissanen, N., Taipale, S., Akkanen, J., Kankaala, P., 2020. Increasing concentration of polyunsaturated fatty acids in browning boreal lakes is driven by nuisance alga Gonyostomum. Ecosphere 11 (7), e03189. https://doi.org/10.1002/ecs2.3189.

Strock, K.E., Theodore, N., Gawley, W.G., Ellsworth, A.C., Saros, J.E., 2017. Increasing dissolved organic carbon concentrations in northern boreal lakes: implications for lake water transparency and thermal structure. J.Geophys. Res. Biogeosci. 122 (5), 1022–1035. https://doi.org/10.1002/2017JG003767.

Stuart, S.N., Chanson, J.S., Cox, N.A., Young, B.E., Rodrigues, A.S.L., Fischman, D.L., Waller, R.W., 2004. Status and trends of amphibian declines and extinctions worldwide. Science 306 (5702), 1783–1786. https://doi.org/10.1126/science.1103538.

Suhonen, S., Nummi, P., Pöysä, H., 2011. Long-term stability of boreal lake habitats and use by breeding ducks. Boreal Environ. Res. 16 (Suppl. B), 71–80.

Taipale, S., Kankaala, P., Tiirola, M., Jones, R.I., 2008. Whole-lake dissolved inorganic 13C additions reveal seasonal shifts in zooplankton diet. Ecology 89 (2), 463–474. https://doi.org/10.1890/07-0702.1.

Taipale, S.J., Galloway, A.W.E., Aalto, S.L., Kahilainen, K.K., Strandberg, U., Kankaala, P., 2016a. Terrestrial carbohydrates support freshwater zooplankton during phytoplankton deficiency. Sci. Rep. 6, 30897. https://doi.org/10.1038/srep30897.

Taipale, S.J., Vuorio, K., Strandberg, U., Kahilainen, K.K., Järvinen, M., Hiltunen, M., Peltomaa, E., Kankaala, P., 2016b. Lake eutrophication and brownification downgrade availability and transfer of essential fatty acids for human consumption. Environ. Int. 96, 156–166. https://doi.org/10.1016/j.envint.2016.08.018.

Taipale, S.J., Vuorio, K., Aalto, S.L., Peltomaa, E., Tiirola, M., 2019. Eutrophication reduces the nutritional value of phytoplankton in boreal lakes. Environ. Res. 179, 108836. https://doi.org/10.1016/j.envres.2019.108836.

Temnerud, J., Hytteborn, J.K., Futter, M.N., Köhler, S.J., 2014. Evaluating common drivers for color, iron and organic carbon in swedish watercourses. Ambio 43, 30–44. https://doi.org/10.1007/s13280-014-0560-5.

Thompson, S., Vehkaoja, M., Nummi, P., 2016. Beaver-created deadwood dynamics in the boreal forest. For. Ecol. Manag. 360, 1–8. https://doi.org/10.1016/j.foreco.2015.10.019.

Thrane, J.-E., Hessen, D.O., Andersen, T., 2014. The absorption of light in lakes: negative impact of dissolved organic carbon on primary productivity. Ecosystems 17 (6), 1040–1052. https://doi.org/10.1007/s10021-014-9776-2.

Toming, K., Kutser, T., Laas, A., Sepp, M., Paavel, B., Nõges, T., 2016. First experiences in mapping lake water quality parameters with Sentinel-2 MSI imagery. Remote Sens. 8 (8), 640. https://doi.org/10.3390/rs8080640.

Trtanj, J., Jantarasami, L., Brunkard, J., Collier, T., Jacobs, J., Lipp, E., McLellan, S., Moore, S., Paerl, H., Ravenscroft, J., Sengco, M., Thurston, J., 2016. Ch. 6: climate impacts on water-related illness. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. U.S. Global Change Research Program, pp. 157–188 https://doi.org/10.7930/J03F4MH4.

Twining, C.W., Brenna, J.T., Lawrence, P., Shipley, J.R., Tollefson, T.N., Winkler, D.W., 2016. Omega-3 long-chain polyunsaturated fatty acids support aerial insectivore performance more than food quantity. Proc. Natl. Acad. Sci. 113 (39), 10920–10925. https://doi.org/10.1073/pnas.1603998113.

Vachon, D., Prairie, Y.T., Guillemette, F., del Giorgio, P.A., 2017. Modeling allochthonous dissolved organic carbon mineralization under variable hydrologic regimes in boreal lakes. Ecosystems 20 (4), 781–795. https://doi.org/10.1007/s10021-016-0057-0.

van Dorst, R.M., Gårdmark, A., Svanbäck, R., Huss, M., 2020. Does browning-induced light limitation reduce fish body growth through shifts in prey composition or reduced foraging rates? Freshw. Biol. 65 (5), 947–959. https://doi.org/10.1111/fwb.13481.

Vehkaoja, M., Nummi, P., Rask, M., Tulonen, T., Arvola, L., 2015. Spatiotemporal dynamics of boreal landscapes with ecosystem engineers: beavers influence the biogeochemistry of small lakes. Biogeochemistry 124 (1), 405–415. https://doi.org/10.1007/s10533-015-0105-4.

Vesterinen, J., Devlin, S.P., Syväranta, J., Jones, R.I., 2016. Accounting for littoral primary production by periphyton shifts a highly humic boreal lake towards net autotrophy. Freshw. Biol. 61 (3), 265–276. https://doi.org/10.1111/fwb.12700.

Vesterinen, E.J., Kaunisto, K.M., Lilley, T.M., 2020. A global class reunion with multiple groups feasting on the declining insect smorgasbord. Sci. Rep. 10, 16595. https://doi.org/10.1038/s41598-020-73609-9.

Wällstedt, T., Björkvald, L., Gustafsson, J.P., 2010. Increasing concentrations of arsenic and vanadium in (southern) Swedish streams. Appl. Geochem. 25 (8), 1162–1175. https://doi.org/10.1016/j.apgeochem.2010.05.002.

Wang, Q., Li, Z., Cheng, S., Wu, Z., 2010. Influence of humic acids on the accumulation of copper and cadmium in Vallisneria spiralis L. from sediment. Environ. Earth Sci. 61 (6), 1207–1213. https://doi.org/10.1007/s12665-009-0444-3.

Ward, C.P., Cory, R.M., 2015. Chemical composition of dissolved organic matter draining permafrost soils. Geochim. Cosmochim. Acta 167, 63–79. https://doi.org/10.1016/j.gca.2015.07.001.

Wauthy, M., Rautio, M., Christoffersen, K.S., Forsström, L., Laurion, I., Mariash, H.L., Peura, S., Vincent, W.F., 2018. Increasing dominance of terrigenous organic matter in circumpolar freshwaters due to permafrost thaw. Limnol. Oceanogr. Lett. 3 (3), 186–198. https://doi.org/10.1002/lol2.10063.

Westbrook, C.J., Cooper, D.J., Anderson, C.B., 2017. Alteration of hydrogeomorphic processes by invasive beavers in southern South America. Sci. Total Environ. 574, 183–190. https://doi.org/10.1016/j.scitotenv.2016.09.045.

Weyhenmeyer, G.A., Prairie, Y.T., Tranvik, L.J., 2014. Browning of boreal freshwaters coupled to carbon-iron interactions along the aquatic continuum. PLOS ONE 9 (2), e88104. https://doi.org/10.1371/journal.pone.0088104.

Whitfield, C.J., Baulch, H.M., Chun, K.P., Westbrook, C.J., 2015. Beaver-mediated methane emission: the effects of population growth in Eurasia and the Americas. Ambio 44, 7–15. https://doi.org/10.1007/s13280-014-0575-y.

Williamson, C.E., Overholt, E.P., Pilla, R.M., Leach, T.H., Brentrup, J.A., Knoll, L.B., Mette, E.M., Moeller, R.E., 2015. Ecological consequences of long-term browning in lakes. Sci. Rep. 5, 18666. https://doi.org/10.1038/srep18666.

Williamson, C.E., Overholt, E.P., Brentrup, J.A., Pilla, R.M., Leach, T.H., Schladow, S.G., Warren, J.D., Urmy, S.S., Sadro, S., Chandra, S., Neale, P.J., 2016. Sentinel responses to droughts, wildfires, and floods: effects of UV radiation on lakes and their ecosystem services. Front. Ecol. Environ. 14 (2), 102–109. https://doi.org/10.1002/fee.1228.

Williamson, C.E., Madronich, S., Lal, A., Zepp, R.G., Lucas, R.M., Overholt, E.P., Rose, K.C., Schladow, S.G., Lee-Taylor, J., 2017. Climate change-induced increases in precipitation are reducing the potential for solar ultraviolet radiation to inactivate pathogens in surface waters. Sci. Rep. 7, 13033. https://doi.org/10.1038/s41598-017-13392-2.

Williamson, C.E., Overholt, E.P., Pilla, R.M., Wilkins, K.W., 2020. Habitat-mediated responses of zooplankton to decreasing light in two Temperate Lakes undergoing long-term

Browning. Frontiers in environmental. Science 8 (73). https://doi.org/10.3389/fenvs.2020.00073.

Winkler, G., Leclerc, V., Sirois, P., Archambault, P., Bérubé, P., 2009. Short-term impact of forest harvesting on water quality and zooplankton communities in oligotrophic headwater lakes of the eastern Canadian boreal shield. Boreal Environ. Res. 14 (2), 323–337. https://helda.helsinki.fi/bitstream/handle/10138/233447/ber14-2-323.pdf?sequence=1.

Wissel, B., Boeing, W.J., Ramcharan, C.W., 2003. Effects of water color on predation regimes and zooplankton assemblages in freshwater lakes. Limnol. Oceanogr. 48 (5), 1965–1976. https://doi.org/10.4319/lo.2003.48.5.1965.

Worrall, F., Burt, T., Shedden, R., 2003. Long term records of riverine dissolved organic matter. Biogeochemistry 64 (2), 165–178. https://doi.org/10.1023/A:1024924216148.

Xenopoulos, M.A., Barnes, R.T., Boodoo, K.S., Butman, D., Catalán, N., D'Amario, S.C., Fasching, C., Kothawala, D.N., Pisani, O., Solomon, C.T., Spencer, R.G.M., Williams, C.J., Wilson, H.F., 2021. How humans alter dissolved organic matter composition in freshwater: relevance for the Earth's biogeochemistry. Biogeochemistry 154 (2), 323–348. https://doi.org/10.1007/s10533-021-00753-3.

Xiao, Y., Riise, G., 2021. Coupling between increased lake color and iron in boreal lakes. Sci. Total Environ. 767, 145104. https://doi.org/10.1016/j.scitotenv.2021.145104.

Xiao, Y., Rohrlack, T., Riise, G., 2020. Unraveling long-term changes in lake color based on optical properties of lake sediment. Sci. Total Environ. 699, 134388. https://doi.org/10.1016/j.scitotenv.2019.134388.

Xu, X., Yang, L., Huang, X., Li, Z., Yu, D., 2018. Water brownification may not promote invasions of submerged non-native macrophytes. Hydrobiologia 817 (1), 215–225. https://doi.org/10.1007/s10750-017-3387-9.

Xulu, S., Mbatha, N., Peerbhay, K., Gebreslasie, M., 2020. Detecting harvest events in plantation forest using Sentinel-1 and -2 data via Google Earth Engine. Forests 11 (12), 1283. https://doi.org/10.3390/f11121283.

Yates, C.A., Johnes, P.J., Owen, A.T., Brailsford, F.L., Glanville, H.C., Evans, C.D., Marshall, M.R., Jones, D.L., Lloyd, C.E.M., Jickells, T., Evershed, R.P., 2019. Variation in dissolved organic matter (DOM) stoichiometry in U.K. freshwaters: assessing the influence of land cover and soil C: N ratio on DOM composition. Limnol. Oceanogr. 64 (6), 2328–2340. https://doi.org/10.1002/lno.11186.

Yu, X., Hawley-Howard, J., Pitt, A.L., Wang, J.-J., Baldwin, R.F., Chow, A.T., 2015. Water quality of small seasonal wetlands in the Piedmont ecoregion, South Carolina, USA: effects of land use and hydrological connectivity. Water Res. 73, 98–108. https://doi.org/10.1016/j.watres.2015.01.007.

Zedler, P.H., 2003. Vernal pools and the concept of "isolated wetlands". Wetlands 23 (3), 597. https://doi.org/10.1672/0277-5212(2003)023[0597:VPATCO]2.0.CO;2.

Zhang, X., Müller, M., Jiang, S., Wu, Y., Zhu, X., Mujahid, A., Zhu, Z., Muhamad, M.F., Sia, E.S.A., Jang, F.H.A., Zhang, J., 2020. Distribution and flux of dissolved iron in the peatland-draining rivers and estuaries of Sarawak,Malaysian Borneo. Biogeosciences 17 (7), 1805–1819. https://doi.org/10.5194/bg-17-1805-2020.

Zhou, Y., Xiao, Q., Yao, X., Zhang, Y., Zhang, M., Shi, K., Lee, X., Podgorski, D.C., Qin, B., Spencer, R.G.M., Jeppesen, E., 2018. Accumulation of terrestrial dissolved organic matter potentially enhances dissolved methane levels in eutrophic Lake Taihu,China. Environ. Sci. Technol. 52 (18), 10297–10306. https://doi.org/10.1021/acs.est.8b02163.

Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Zeng, N., 2016. Greening of the Earth and its drivers. Nat. Clim. Chang. 6 (8), 791–795. https://doi.org/10.1038/nclimate3004.