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Browning of boreal lakes: Do public perceptions and governance align with the biological foundations?

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Abstract

Browning of surface waters, also known as brownification, is a process of decreasing water transparency, particularly in boreal lakes surrounded by intensively managed forests and wetlands. In this paper, we review the ecological consequences and ecosystem-based management (EBM) of browning through a systematic review approach and adopt an interdisciplinary approach to formulating new governance of this complex phenomenon. To understand the effects of browning on the recreational value of freshwaters, we present primary survey data on public perceptions of recreational fishing tourists on water quality in Finland. We identify a need to develop EBM beyond the EU's Water Framework Directive (WFD) to fully account for the extensive implications of browning. We also highlight the need for a better understanding of the within-lake microbial processes to estimate the browning-associated changes in the greenhouse gas balance of lakes. Tourist perceptions of the quality of waterbodies in Finland were largely in agreement with the general proportion of waterbodies classified in a good or excellent ecological status class, but these perceptions may be detached from biological quality assessment criteria. Consequently, we suggest that the EBM of inland waters should improve the utilization of information on not only biogeochemical processes but also users' perspectives on aquatic ecosystems beyond the EU WFD.

KEYWORDS
brownification, ecosystem-based management, recreation, regulation, tourism, water quality

INTRODUCTION

Water browning, or brownification, refers to a process of decreasing water transparency and increasing water color without direct increase in the number of suspended materials or plankton (Graneli, 2012; Weyhenmeyer et al., 2014). The concentrations of dissolved organic matter (DOM, including dissolved organic carbon [DOC]) and iron (Fe), which are the main coloring substances, have, on average, increased in recent decades in temperate and boreal inland waters across the Northern Hemisphere (e.g., Klavins et al., 2012; Kritzberg & Ekström, 2012; Monteith et al., 2007). Yet significant local and temporal variation exists (Arvola et al., 2017; Eklöf et al., 2021). Local and regional land-use patterns largely explain brownification trends in boreal environments (Blanchet et al., 2022; Kritzberg et al., 2020), but global processes such as climate change and decreased sulfur deposition have contributed to browning and the chemical composition of DOM in a nearly universal manner (Xenopoulos et al., 2021). Climate change also alters the hydrological regimes of catchments due to increased rainfall and warmer winters (de Wit et al., 2016; Finstad et al., 2016; Weyhenmeyer et al., 2016) and can thus interact with local processes. Without novel adaptation measures, increased exports of DOC from terrestrial systems to waters are expected (Estlander et al., 2021; Kritzberg et al., 2020). The relative importance of global changes and other anthropogenic stressors, including peat mining and forestry practises, varies locally, and there are no global mechanisms explaining local brownification trends (Kritzberg et al., 2020; Xenopoulos et al., 2021).

The susceptibility of individual lakes to browning is dependent on catchment properties such as the proportional cover of peatlands and coniferous forests (Arvola et al., 2016; Houle et al., 2020). Human land use generally accelerates runoff, with a subsequent increase in the loading of terrestrial matter to waters (Estlander et al., 2021; Kritzberg, 2017; Lepistö et al., 2021). Intensive forestry and the associated mechanical modification of soil surface layers and ditching are major sources of terrestrial organic carbon and Fe loading to many boreal aquatic ecosystems (Bathurst et al., 2018; Finér et al., 2021; Nieminen et al., 2021; Škerlep et al., 2020, 2022). Periods with heavy rainfall can result in significantly increased loading of organic matter and ferrous compounds from exposed terrains (Hongve et al., 2004; Kothawala et al., 2014; Tuvendal & Elmqvist, 2011). These impacts are magnified with anthropogenic impacts such as climate change, intensive forestry, and peatland drainage (Björnerås et al., 2021; Klante et al., 2021; Miettinen et al., 2020; Peltomaa & Ojala, 2016; Sarkkola et al., 2013; Strock et al., 2017).

Browning of freshwaters has recently attracted attention from scientists, policymakers, and the public. Browning alters regulating and supporting ecosystem services in inland waters, with accompanying consequences for aquatic biodiversity (Ask et al., 2009; Blanchet et al., 2022; Kritzberg et al., 2020). Browning affects provisional ecosystem services by impacting fisheries and recreational uses of waters and by imposing increased costs for drinking water treatment (Blanchet et al., 2022; Forsius et al., 2017; Kritzberg et al., 2020; Langhans et al., 2019). Browning also affects cultural ecosystem services, for example by altering the aesthetic value of waters and by inducing loss of personally valued landscapes. Our paper focuses on the browning of lakes and other inland waters, which are used for many recreational activities, including recreational fishing, and are of considerable socioeconomic importance in the Nordic countries.

Understanding of public perceptions of water quality is necessary for defining waterbodies' uses (e.g., as suitable or unsuitable for recreation), estimating the potential recreational value of waterbodies, possible impacts, and managerial implications. It is important to align biological reality with social demands and to form a holistic perspective for public programs and policies (Artell et al., 2013; Barnett et al., 2018; Ceccaroni et al., 2020; Flotemersch & Aho, 2021). Despite the far-reaching implications of browning for recreational users of aquatic environments, studies on the public perceptions of browning are surprisingly rare (e.g., Kritzberg et al., 2020; Tuvendal & Elmqvist, 2011). Previous studies demonstrated that laypersons prefer aquatic environments that are aesthetically pleasing and perceived to be of good quality (Flotemersch & Aho, 2021; Keeler et al., 2015). A brown color is seen as a negative attribute of water (Kritzberg et al., 2020), while clear water increases the perceived recreational value of waterbodies (Curtis & Stanley, 2016; Keeler et al., 2015). Greater water clarity is associated with a higher number of visits to a particular waterbody, and recreational users are willing to travel longer distances for clearer water (Keeler et al., 2015). However, different types of water-related activities and how laypersons relate to waterbodies may also lead to varied perceptions (Barnett et al., 2018; Curtis & Stanley, 2016). Moreover, water quality predefines the use of waterbodies and the types of activities they support, which is important in spatial planning and zoning of land uses (Vesistön virkistysarvo, 2021).

It could be claimed that browning is not an independent environmental issue but a consequence of global changes and intensive land use at a local scale. However, some of the mechanisms and subsequent implications of browning call for novel management and associated new research (Blanchet et al., 2022). Ecosystem-based management (EBM) takes a comprehensive approach to promoting aquatic biodiversity within water ecosystems (Rouillard et al., 2018). It was introduced through the Water Framework Directive (WFD, 2000/60/EC), which seeks to prevent the ecological deterioration of waters and ensure that good water status is reached by 2027 at the latest. WFD is the main European Union (EU) policy instrument to address issues of environmental management as related to the quality and quantity of water and aquatic biodiversity. While the EU Biodiversity Strategy 2030 (COM[2020] 380 final) and the proposed EU Nature

Restoration Law (COM[2022] 304 final) have significant potential for tackling brownification through restoration measures in the future, most current legal requirements regulating brownification stem from the WFD. For this reason, our focus is on the WFD in this paper.

Since its enactment in 2000, WFD has attracted wide scholarly attention (Boeuf & Fritsch, 2016; Kaika & Page, 2003; Kallis & Butler, 2001; Rouillard et al., 2018; Voulvoulis et al., 2017). In the context of WFD implementation across multiple scales, EBM has been studied, for example, from a multilevel perspective (Newig & Fritsch, 2009; Pahl-Wostl, 2009), from the point of view of policy translation (Ibragimow et al., 2019), and from a legal perspective (e.g., Kymenvaara et al., 2019; Paloniitty, 2018; Söderasp, 2018; Soininen & Platjouw, 2018; Squintani & van Rijswick, 2016). Studies on EBM have covered anthropogenic pollutants, such as chemical pollution and eutrophication, whereas browning has to date attracted little scholarly attention in this context.

In this paper, we review the current literature to understand the EBM aspects of browning and aim to detect development needs with respect to current governance of browning as a phenomenon. We systematically review studies on the impact of browning on freshwaters to explore how browning has been covered in the EBM literature. Second, we present primary data on foreign fishing tourists in Finland to understand how water browning may impact perceptions of water quality. Finally, we analyze whether the EU WFD (2000/60/EC) is suitable for addressing browning-related changes in aquatic ecosystems and how the governance of the issue should be developed to properly account for it. As part of fulfilling these aims, we pose the following questions: (1) What types of disturbance does water browning cause in freshwater ecosystems? (2) Does EBM, as introduced in the WFD, properly account for the biological changes associated with browning? (3) To what extent does browning affect the values and benefits attached to water quality from the perspective of recreational users? We focus on the perceptions of Russian tourists, the most abundant nationality among angling tourists, on water quality, since we expected anglers to have the most experience with and knowledge of the quality of Finnish waters compared to tourists from other countries who might have fewer opportunities to directly experience water quality in Finland.

MATERIALS AND METHODS

Systematic review

We adopt a mixed-method approach (Axinn & Pearce, 2006). Our research material included a literature review, online survey, and legal documents. We aimed to summarize current knowledge and research gaps through a systematic literature review, that is, by searching several databases with two sets of fixed search terms (e.g., Mengist et al., 2020). Scopus, PubMed, EBSCOHost, and Web of Science were searched for studies on lake browning, water quality, and EBM. First, the search terms "browning" or "brownification," "water quality," and "lake" were applied to obtain the papers that explored the browning process. Second, the search terms "ecosystem-based management," "water quality," "public perception AND attitude AND opinion," and "lake" were applied to obtain the studies focused on the management of and public views on browning (Box 1). Although the searches were limited to lakes, other freshwater ecosystems also appeared in the results and were included in the analysis. Our first search resulted in papers related to the biological and hydrological foundations of browning, and the second search extended the pool of literature to EBM studies.

The search results were uploaded to the systematic review analysis software Covidence (2021). This software is dedicated to systematic reviews and automatically checks for duplicates. The search was limited to a period from 2011 to 2021 because in our data set, 2011 was the earliest year with papers on the topic of browning. The search resulted in 589 papers in total, 206 of which were considered irrelevant because they were not related to water browning, water quality or EBM, and aquatic environments. We further applied inclusion and exclusion criteria (Box 2), which yielded 234 papers on water quality, 123 of which were on browning and 111 on EBM (supplementary material in Appendices S1 and S2).

Each of the 234 publications was classified according to the scientific field of the study into the categories of biology (including hydrobiology, microbiology and limnology), physical–chemical studies (including biogeochemistry and hydrology), environmental sciences (e.g., ecotoxicology,

BOX 1 Search terms and databases used in systematic literature review

Search terms

Browning search: "browning" or "brownification," "water quality," and "lake"

Ecosystem-based management search: "Ecosystem-based management," "water quality," "public perception OR attitude OR opinion," and "lake."

Databases

Scopus, PubMed, EBSCOHost, and Web of Science.

anthropogenic degradation of water quality), and social sciences (including EBM, management and governance, public perception, and citizen science studies). We summarized the overall increase in browning and other water quality publication rates according to the scientific field of study (Figure 1). The 123 papers focusing exclusively on browning were categorized by the type of study environment (natural or experimental), the methods applied (e.g., long-term data or experimental setting), and by description of the causes or consequences of browning and the geographical location of the studies.

BOX 2 Inclusion and exclusion criteria applied in systematic literature review

Inclusion

Water browning

Water quality

Aquatic ecosystems, lakes, rivers

Ecosystem-based management

Public perception, opinion, attitude

Exclusion

Food browning

Blue-green algae, chemical pollution, agricultural pollution, eutrophication

Wetlands, sea, groundwater, urban stormwaters, agricultural ponds

Forest management, agricultural land, coastal areas, riparian zones, and urban areas

Online survey

Collecting information on users' past recreational behavior and perceptions is one of the most common methods of investigating the value of water clarity to users (Angradi et al., 2018; Keeler et al., 2015). We collected data on the public perceptions of Russian tourists visiting Finland through a consumer panel survey in May 2021. The survey was targeted at users of aquatic environments. The data were collected by surveying residents of the Leningrad region in Russia. A total of 527 respondents took part in the study, 66% of whom had had experience fishing in Finland.

All the respondents were over 18 years old, and 61% were men and 39% women. Russians had been the largest group of foreign tourists in Finland before the COVID-19 pandemic, accounting for ca. 35% of all foreign trips to Finland (Visit Finland Visitor Survey 2018, 2019). Furthermore, residents of the Leningrad region comprise about 80% of all Russian tourists visiting Finland (Smętkowski et al., 2016). Although the survey data do not allow for distinguishing between specific lakes or areas visited by tourists, earlier studies suggested that eastern Finland, including the Lakeland region, had the largest

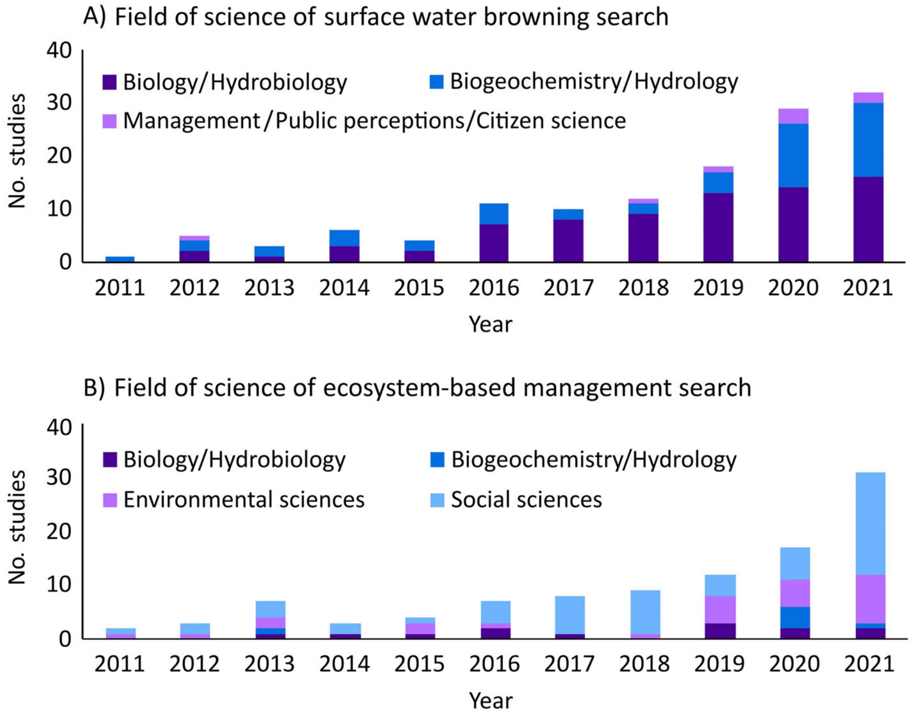

FIGURE 1 Field of science of (A) browning and (B) ecosystem-based management studies.

share (48%) of overnight stays among Russian tourists (Russia Market Report, 2019). The survey included four questions concerning perceptions of aquatic ecosystems for water-related activities. Previous studies indicated that public perceptions of water focus on a limited number of variables, such as color, the presence or absence of aquatic plants and algae, the presence or absence of floating debris, odor, clarity, and movement (Flotemersch & Aho, 2021). It is argued that attributes such as nutrient concentrations or the presence of hazardous substances do not affect public perceptions, because such metrics cannot be observed visually (Angradi et al., 2018; Ceccaroni et al., 2020). Instead, easily observed water clarity can be understood by a nonexpert viewer (Angradi et al., 2018). Thus, the survey questions were designed based on previous research concerning water quality perceptions (Artell et al., 2013; Flotemersch & Aho, 2021). We asked the respondents in an open format (1) what kinds of water they prefer for water-related activities. We also asked them to rate on a 7-point Likert scale (2) how the attributes of transparency, odor, brown color, blue-green algae, slime, and pollution characterize Finnish lakes and rivers in general and (3) whether the absence or presence of these attributes is important for an enjoyable recreational fishing experience. Furthermore, we asked the respondents in an open format (4) whether and how water quality influenced their travel experience in Finland (Figure 3).

RESULTS

Results of systematic literature review

Lack of EBM studies on browning

We assessed 234 studies in the systematic review. A total of 123 studies appeared in the browning search, and 111 papers appeared in the EBM search. The review results revealed that the annual number of publications had increased from four to 60 between 2011 and 2021 (Figure 1). Most of the brownification studies ($N = 72$) focused on biology and hydrobiology, and 44 focused on the hydrological or chemical status and processes of waters. The number of social scientific studies focusing on browning has been marginal, as we could only identify studies on citizen science projects (e.g., Ceccaroni et al., 2020; Seelen et al., 2019).

Methods used in browning studies

Only five studies applied modeling techniques, one study applied remote sensing (Kutser et al., 2015), and two studies applied citizen science, such as citizens observing water color, which can be affected by organic particles (e.g., phytoplankton), inorganic particles (e.g., mineral soils, chalk), and DOC (Ceccaroni et al., 2020), and citizen use of tea bag methods (Seelen et al., 2019). The analysis of long-term data and experiments were the most common methods, with studies combining multiple methods, such as long-term data and in situ sampling (Isles et al., 2020; Leech et al., 2018; Lehtovaara et al., 2014), long-term data and experiments (Kritzberg & Ekström, 2012), or in situ sampling and experiments (Fork & Heffernan, 2014).

Thematically, studies on browning in lake ecosystems focus on the causes or consequences of DOC concentration and color, lake chemistry, and biological or limnological processes (Figure 2; e.g., Kankaala et al., 2019; Nydahl et al., 2019; Williamson et al., 2015). Research on the river basin scale has examined catchment characteristics, such as the impacts of peatland forestry and drainage on downstream waterbodies (e.g., Lepistö et al., 2021; Nieminen et al., 2021; Sarkkola et al., 2013). Experimental ecosystems, such as artificial ponds (Hedström et al., 2017) and aquatic mesocosms, have been studied alongside natural ecosystems from the perspective of impacts of warming (e.g., Nicolle et al., 2012; Urrutia-Cordero et al., 2016; Wilken et al., 2018), DOC (Nydahl et al., 2019), or both (Choudhury et al., 2019; Huss et al., 2021; Wu et al., 2021). Such experiments provide a predictive basis for the response of organisms, for example, charophytes (Choudhury et al., 2019) or fish (Hedström et al., 2017), to ongoing environmental changes.

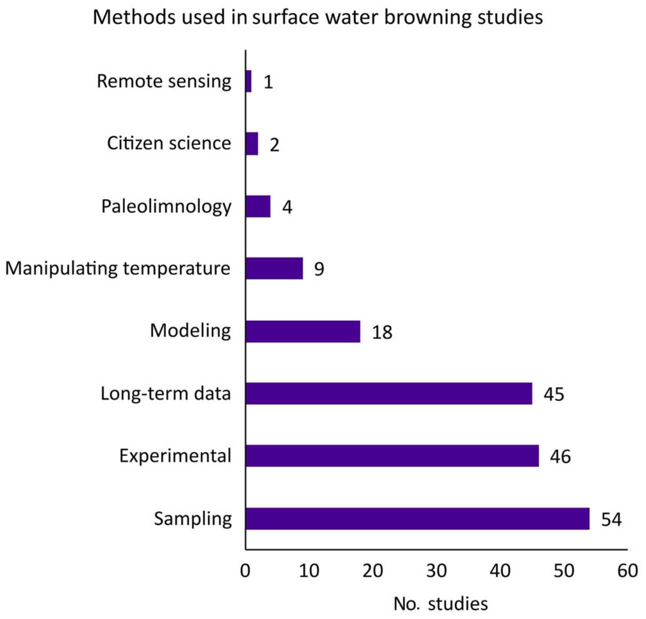

FIGURE 2 Methods used in assessed brownification studies.

Biological consequences of water browning

We categorized the biological and ecological impacts of surface water browning by their mechanism, effect, and intensity (Table 1). The most evident effect of browning is the reduction in light penetration, which, combined with higher levels of allochthonous organic matter, changes the net metabolism of lake ecosystems toward heterotrophy (Ask et al., 2009) and may therefore increase the efflux of greenhouse gases from the affected lakes (Kankaala et al., 2019; Nydahl et al., 2019). Increasing DOC alters bacterial abundance and phytoplankton community structure and the nutritional strategies of bacterio- and phytoplankton by favoring mixotrophs and motile algae (e.g., Hagman et al., 2020; Lenard & Ejankowski, 2017; Senar et al., 2021). Browning, when treated as the sole loading of DOC, usually reduces aquatic primary production (Karlsson et al., 2009, 2015; Taipale et al., 2018), while examples with no significant impact also exist (Eie et al., 2021; Erratt et al., 2021). Browning often results in a higher abundance of the nuisance algae *Gonyostomum semen* (Hagman et al., 2019, 2020; Strandberg et al., 2020). The interactive effects of warming and browning and consequent alterations in energy transfer to higher trophic levels are complex, since different responses occur at each trophic level (Hansson et al., 2013). Nevertheless, browning can decrease energy flow through trophic chains by limiting primary production in nutrient-poor lakes (Karlsson et al., 2009; Olin et al., 2017; Taipale et al., 2018). Reduced photosynthesis also affects zooplankton community composition (Lehtovaara et al., 2014; Nicolle et al., 2012; Williamson et al., 2015). Darkening reduces the availability of euphotic benthic habitats for aquatic plants and periphyton (Couture et al., 2015) and often reduces fish biomass, fish production, and fish species diversity (Karlsson et al., 2009; Murdoch et al., 2021; Rahel, 1984; Rask et al., 1999). Decreased visibility weakens the foraging efficiency of visually hunting fish and modifies predator–prey interactions (Hedström et al., 2017; Ranåker et al., 2012; Santonja et al., 2017; Scharnweber et al., 2016). Fish harvested in highly humic lakes may also have a lower nutritional quality compared to clear-water lakes, with implications for the health of human consumers (Taipale et al., 2016). Additionally, fish from humic lakes contain higher mercury levels (Creed et al., 2018; Dittman et al., 2010) due to the increased methylation of inorganic mercury in the anoxic hypolimnion.

Browning affects lakes in their entirety, but along watercourses the impacts of external Fe and DOC are attenuated downstream due to self-purification processes, including dilution, filtering by organisms, chemical transformation, the degradation of substances, and sedimentation (Kalinkina et al., 2020). Photobleaching, degradation of DOM by sunlight, is largely limited to summer (Lorusso et al., 2020; Pace & Cole, 2002) and can have an important priming effect on further microbial degradation of DOM. Humic water results in a strong thermal stratification of water layers during summer due to the increased absorption of solar radiance in humic versus clear lakes (Mazumder & Taylor, 1994; Pilla et al., 2018). Similarly, humic water might prolong ice-free periods by accelerating the melting of ice in spring. Thermal stratification influences the entire aquatic ecosystem functioning by reducing vertical mixing and amplifying vertical gradients of dissolved oxygen and other substances (Couture et al., 2015; Jane et al., 2021). Increased water color and resulting steepened thermal stratification (Mazumder & Taylor, 1994; Pilla et al., 2018) have been found to reduce the availability of euphotic habitats (Couture et al., 2015) and decrease and alter the diversity and growth of multiple species (Blanchet et al., 2022; Karlsson et al., 2009). Because many large lakes are used as drinking water sources, browning also poses an increasing challenge for drinking water treatment (Forsius et al., 2017; Weyhenmeyer et al., 2016).

EBM of lake ecological status in relation to browning

To answer Research question 2, about whether EBM, as introduced in the WFD, properly accounts for the biological changes associated with browning, we reviewed the studies revealed through the EBM search with applications to WFD implementation (Boxes 1 and 2). We classified the EBM publications according to the management type, for example, willingness to pay, user perspectives, and river-basin management (Table 2). In the EBM search, we found no studies focusing specifically on water browning and EBM, either within or outside the WFD context. Instead, we reviewed studies on WFD implementation that focused on the ecological and chemical status of waters and problem areas with chemical and agricultural pollution (Brack et al., 2017; Skoulikidis et al., 2021). A study by Aura et al. (2021) focused on EBM and general water quality in citizen science projects. Water management has been studied in a multilevel context in the EU and from local community perspectives at Lake Erie (Jetoo, 2018). Watershed management has been examined in the context of urban pressures (e.g., Kattel et al., 2021) and agricultural stressors (e.g., Arnillas et al., 2021), and user perspectives on water quality have been investigated (Onyango & Opiyo, 2021; Smith et al., 2018). Traditional knowledge on water flow and other attributes of water have

TABLE 1 Consequences of lake browning.

Consequence	References from systematic review (browning search)
Biogeochemical	
Higher OM/Fe loading	
Higher heterotrophic lake metabolism—greater greenhouse gas emissions	Kankaala et al. (2019), Kazanjian et al. (2021), Nydahl et al. (2019), Peltomaa & Ojala (2016), Vesterinen et al. (2017)
Decreasing bacterial growth per unit of DOM	Berggren & Al-Kharusi (2020), Berggren et al. (2020)
Altered DOM metabolome	Fonvielle et al. (2021)
Altered stoichiometry (high C, low nutrients)—water, seston, macrophytes, *Daphnia*, frogs	Bastidas Navarro et al. (2021), Corman et al. (2018), Isles et al. (2020, 2021), Meyer-Jacob et al. (2020), Minguez et al. (2020), Norlin et al. (2016), Reitsema et al. (2020), Weidman et al. (2014)
Higher C/Fe sequestration through sediment burial	Björnerås et al. (2021)
Higher absorption of radiance: Changes in temperature:	
More stable stratification regime—longer summer stratification—more methane	Couture et al. (2015), Williamson et al. (2015), Pilla et al. (2018), Wauthy & Rautio (2020)
Reduced vertical mixing/light/oxygen—changes in potential habitats—phytoplankton, zooplankton, fish	Couture et al. (2015), Horppila et al. (2018), Lindholm et al. (2018), Pilla et al. (2018), Wauthy & Rautio (2020), Williamson et al. (2015)
Reduced light penetration	
Reduced photodegradation and switch between different photochemical pathways	Calderaro & Vione (2020), Vione & Rosario-Ortiz (2021), Wasswa et al. (2020)
Higher UV protection	Williamson et al. (2017)
Reduced UV priming of microbial DOM degradation	Madsen-Østerbye et al. (2018)
Lower water quality	
Higher OM/Fe loading—carryover pollutants:	
Higher pollutant levels—seston, microplankton, zooplankton, fish, Hg	Anderson et al. (2021), Braaten et al. (2018), Isidorova et al. (2016), Poste et al. (2019), Wu et al. (2021)
OM-bound complexes are less toxic and bioavailable—microalgae, macroinvertebrates, fish, Hg, pollutants	Braaten et al. (2018), Braaten et al. (2020), Rizzuto et al. (2020)
Higher cyanobacterial toxicity	Ekvall et al. (2013), Hu et al. (2021)
Higher DOC—*Gonyostomum semen* blooms—slime, skin irritation, clogging of drinking water filters	Hagman et al. (2019), Hagman et al. (2020), Strandberg et al. (2020), Scharnweber et al. (2021)
Lower denitrification capacity	Fork & Heffernan (2014)
Higher UV protection—decreased sunlight inactivation of waterborne pathogens	Williamson et al. (2017)
Increased cost of water treatment	Weyhenmeyer et al. (2016)
Biological impacts	
Reduced lake productivity through reduced primary production due to less light	
Reduced biomass, growth, fitness, nutritional quality, or diversity—seston, phytoplankton, zooplankton, macroinvertebrates, fish	Arzel et al. (2020), Kankaala et al. (2019), Hedström et al. (2017), Hessen et al. (2017), Huss et al. (2021), Kesti et al. (2022), Murdoch et al. (2021), Nova et al. (2019), Olin et al. (2017), Poste et al. (2019), Saebelfeld et al. (2017), Scharnweber et al. (2016, 2021), Symons et al. (2019), Taipale et al. (2016, 2018, 2019), Van Dorst et al. (2019), Wu et al. (2021)
Higher inversion of pigments, higher biovolume—phytoplankton, macrophytes	Reitsema et al. (2020), Senar et al. (2021), Williamson et al. (2015)
Altered phytoplankton community—increased motile algae and mixotrophs	Freeman et al. (2020), Hagman et al. (2019, 2020), Hu et al. (2021), Lebret et al. (2018), Lenard & Ejankowski (2017), Saulnier-Talbot et al. (2020), Schulhof et al. (2020), Senar et al. (2021)

(Continues)

TABLE 1 (Continued)

Consequence	References from systematic review (browning search)
Reduced potential habitats—increased competition—fish	Couture et al. (2015)
Altered zooplankton community—fewer grazers, more predators	Leech et al. (2018), Lehtovaara et al. (2014), Nicolle et al. (2012), Scharnweber et al. (2021), Williamson et al. (2015)
Weakened foraging efficiency of vision-oriented predatory fish	Hedström et al. (2017), Ranåker et al. (2012, 2014), Scharnweber et al. (2016)
Weakened antipredatory escape efficiency—fish, copepods	Ranåker et al. (2012, 2014), Santonja et al. (2017)
Higher DOC—altered bacterial abundances/community—more heterotrophic bacteria	Lebret et al. (2018), Lennon et al. (2013), Rasconi et al. (2015), Scharnweber et al. (2021), Schulhof et al. (2020)
Depending on intensity of browning	
Intense (DOC > ~11 mg/L): light limitation prevails, lower biomass and nutritional quality	Bergström & Karlsson (2019), Isles et al. (2021), Murdoch et al. (2021), Nicolle et al. (2012)
Mild (DOC < ~11 mg/L): concomitant nutrient loading prevails, biomass increase	Bergström & Karlsson (2019), Feuchtmayr et al. (2019), Isles et al. (2021), Kelly et al. (2016), Senar et al. (2019), Wauthy & Rautio (2020)
Interaction with other stressors	
Interaction with acidification: decoupled trophic responses—phytoplankton, zooplankton	Leach et al. (2019)
Interaction with eutrophication: altered DOM metabolome	Fonvielle et al. (2021)
Interaction with warming	
Reduced energy transfer to higher trophic levels	Leech et al. (2018)
Benefits top trophic level and every other level below, detriment levels within—phytoplankton, zooplankton, fish	Hansson et al. (2013), Nicolle et al. (2012), Urrutia-Cordero et al. (2016)
Increase in biomass, growth, and condition (increasing intensity of warming and browning over a threshold reverse the effect)—several biota	Choudhury et al. (2019), Gall et al. (2017), Hansson et al. (2013), Leech et al. (2018), Nicolle et al. (2012), Norlin et al. (2016), Urrutia-Cordero et al. (2016), Weidman et al. (2014), Wilken et al. (2018)
Reduced nutritional quality, biomass, growth, and size—seston, phytoplankton, zooplankton, fish	Couture et al. (2015), Huss et al. (2021), Lau et al. (2021), Van Dorst et al. (2019), Wu et al. (2021)
Higher pollutant levels—seston, microplankton, MeHg	Wu et al. (2021)
Altered phytoplankton community—increased mixotrophs	Wilken et al. (2018)

Abbreviations: DOC, dissolved organic content; DOM, dissolved organic matter; OM, organic matter; UV, ultraviolet.

been studied in terms of adaptive co-management and co-governance (Harmsworth et al., 2016; Mantyka-Pringle et al., 2017).

In the EU, the WFD is the main policy instrument for water protection. It adopts a river basin perspective on the management of waters, meaning that all pressures affecting aquatic ecosystems are, as a rule, accounted for (Squintani & van Rijswick, 2016). The directive regulates all inland surface waters (lakes, rivers) and groundwater, as well as transitional and coastal waters. The directive aims at achieving a good ecological and chemical status of all surface waters and a good quantitative and chemical status of groundwater. Moreover, the directive requires that human activities not deteriorate the status of waters further from their current status (WFD article 4). Ecological status is evaluated in comparison with a waterbody of a similar type in a natural state that displays no or very little human impact and, thus, by definition represents excellent status. The good water status allows for some human impact on the biota in the waterbody (WFD Annex V). The deadline for achieving the goal of good status was in 2015, but many EU member states have resorted to exemptions provided in article 4 of the directive, allowing them to push the deadline out to 2027. Both the good status and nondeterioration requirements are legally binding on EU member states, as well as when it comes to permitting new projects with a marked impact on waters (CJEU C-461/13; Paloniitty, 2018; Soininen & Platjouw, 2018). The main instruments of the WFD are river basin management plans (RBMPs), which contain the ecological classification of waterbodies, the determination of the most

TABLE 2 List of publications in EBM search by topic.

Type of EBM study	References from systematic review (ecosystem-based management search)
Ecosystem services studies	Chen et al. (2021), Kaiser et al. (2021), Liang et al. (2021), Seelen et al. (2022; 2021 online), Sikorska et al. (2017), Tseng et al. (2021), Wang et al. (2021)
Willingness to pay	Castro et al. (2016), Girma et al. (2021), Kunwar et al. (2020), Li et al. (2021, 2021), Li & Zhang (2021), L'Ecuyer-Sauvageau et al. (2019), Peng et al. (2021), Pissarra et al. (2021), Shang et al. (2012)
User/community perspectives	de Lira Azevêdo et al. (2020), Hua & Chen (2019), Lorenz & Pusch (2012), Nanayakkara & Wissel (2017), Onyango & Opiyo (2021), Schroeder & Fulton (2013), Smith et al. (2018), Stough-Hunter et al. (2014), Venohr et al. (2018), Zhang et al. (2019)
Citizen science	Aura et al. (2021), Taylor et al. (2021)
River restoration	Becker et al. (2018), Chen et al. (2017), Chou (2016), England et al. (2021), Morandi et al. (2017), Szałkiewicz et al. (2018), Thorel et al. (2018), Wohl et al. (2015)
River basin management/ watershed management	Arnillas et al. (2021), Brack et al. (2017), Jetoo (2018), Kattel et al. (2021), Singh & Singh (2020), Skoulikidis et al. (2021), Syafri et al. (2020)
Lake restoration and management	Alsip et al. (2021), Nygrén et al. (2017)
Socioecological systems	Graziano et al. (2021), Martin et al. (2020), Mooser et al. (2021), Sudha et al. (2013)
Management of water quality	Dunn et al. (2014), Thornton et al. (2013)
Multicriteria decision-making/ deliberative stakeholder processes	Bryan & Kandulu (2011), Langhans & Schallenberg (2021), Lukasiewicz et al. (2016), Veraart et al. (2018)
Indigenous knowledge	Harmsworth et al. (2016), Mantyka-Pringle et al. (2017)
Science–policy interfaces	Cormier et al. (2018)

significant human pressures on waterbodies, and measures to mitigate the pressures and restore waters to a good ecological and chemical status (Soininen et al., 2019; Squintani & van Rijswick, 2016).

As part of the WFD implementation process, EU member states have developed typologies for lakes and rivers based on environmental variables or type descriptors (WFD Annex II). The waterbody types should possess permanent, abiotic characteristics (e.g., altitude, size, basin geology) that largely explain the natural variability of biological quality elements (BQEs) as established in WFD Annex V. Objectives for the ecological status for each waterbody type are set according to their inherent characteristics, with one of them being the water color. Increased browning with increasing evidence of human impacts underlying the phenomenon (Estlander et al., 2021; Finér et al., 2021; Kritzberg et al., 2020; Nieminen et al., 2021), however, suggests that treating water color as a permanent character is highly problematic.

Taking a step further, we argue that the WFD system as it currently stands contains three challenges to the effective regulation of browning. First, while browning can affect some of the BQEs of the WFD, there are no direct ecological criteria focusing on water color or humic substances in Annex V. Second, even if water color and humic substances were directly included in the BQEs, there would be considerable challenges in establishing the natural benchmark against which good status would be evaluated, because the waters vary extensively in their natural water color.

Furthermore, a key challenge in regulating browning is that browning pressures stem not only from land-use sources, such as forestry (Estlander et al., 2021; Finér et al., 2021; Nieminen et al., 2021), but also from climate variables and recovery from atmospheric S deposition (e.g., de Wit et al., 2016; Meyer-Jacob et al., 2019). These are beyond the processes and mitigation measures included in the RBMPs. Third, the WFD needs to be evaluated against other EU goals and legal instruments, for example, the green transition to boost renewable energy production to mitigate climate change and the EU Biodiversity Strategy for 2030 to reverse the degradation of ecosystems. These other EU policy and legal initiatives are driving a land-use change and nature restoration, which might be positive for mitigating water browning if some energy sources and, hence, some forms of land use, such as peat mining, decreased. At the same time, the green transition toward a bioeconomy is spurring new conflicting demands on forest biomass production (Laudon et al., 2011; Marttila et al., 2020). These cross-policy drivers and impacts require further systemic analysis.

Perceptions of users of aquatic environments

When asked to describe what types of water are preferred for water-related activities in general, the majority of the survey respondents (195 responses, corresponding to 37.1% of all answers) indicated that the water should be "clean" (Table 3). Of these answers, the responses included the following categories: clean ($N = 58$), clean and transparent ($N = 35$), clean and warm ($N = 40$), clean water with fish in it ($N = 7$), clean and quiet ($N = 8$), and crystal clear ($N = 4$). In addition to cleanliness, a few individuals mentioned the absence of smell ($N = 6$), pollutants ($N = 3$), and other intervening factors, such as litter, seaweed, green color, and dirt (four mentions). The second most popular water characteristic was water transparency, which was mentioned by 58 respondents. These answers included the already mentioned category of clean and transparent water ($N = 35$), as well as warm and transparent ($N = 13$) and just transparent ($N = 10$) water. Another 57 respondents (10.9%) indicated that water should be warm, either by stating it directly or by indicating the water temperature in degrees.

TABLE 3 Most preferred water characteristics.

Characteristic	No.	Percentage (%)
Clean	195	37.1
Transparent	58	11.0
Warm	57	10.9
Lake or river	50	9.5
Suitable for fishing and swimming	28	5.3

Note: Please note that the numbers include overlaps, and the percentages do not therefore comprise absolute shares.

Fifty respondents stated that they preferred lakes ($N = 33$), forest lakes ($N = 7$), rivers and/or lakes ($N = 8$), and seas or oceans ($N = 7$). In addition, 29 respondents defined the most preferable kind of water through water-related activities, in which fishing and swimming were the dominant types (Table 3). To assess the perceptions of water quality in Finland, the respondents rated six water quality characteristics on a scale from strongly agree to strongly disagree (Figure 3).

Most of the respondents (64%) disagreed (from somewhat disagree to strongly disagree) that Finnish lakes and rivers were polluted. The "polluted" characteristic included industrial pollution, sewage, and, for example, the presence of litter. About 59% expressed disagreement that Finnish lakes and rivers had slimy shores. Another 50% disagreed that lakes and rivers had a bad odor. The options of blooming blue-green algae and the brown(ish) color of Finnish lakes and rivers received divided opinions. While ca. 34% agreed about the presence of blooming blue-green algae, 49% disagreed with this. In a similar way, ca. 46.5% disagreed that Finnish lakes and rivers had a brown(ish) color, but 36% agreed with this. These varying opinions can result from several travel and water experiences in Finland, such as through visiting different areas and waterbodies. Russian tourists mostly visit easily accessible areas in Finland, such as Finnish Lakeland (Visit Finland Visitor Survey 2018, 2019), which includes the largest lake, Lake Saimaa, and belongs to the Vuoksi River Basin Management area, where the largest proportion of lake surface area is typed, according to the WFD,

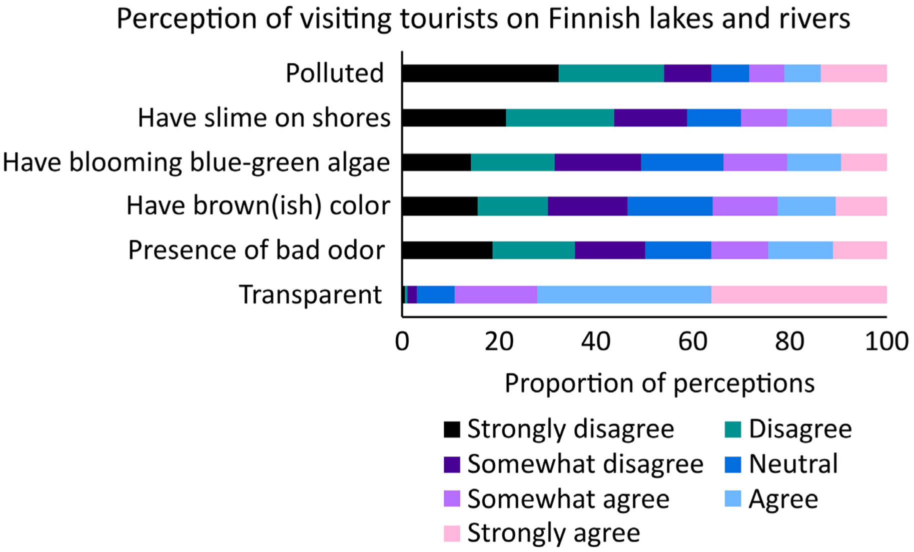

FIGURE 3 Assessment of water characteristics in Finnish lakes and rivers according to Russian tourists visiting Finland.

as nonhumic (57%) or humic (42%) and the rest as other types of lakes (1%). Over 89% of the respondents agreed that water in Finnish lakes and rivers was transparent, while only 3% expressed disagreement with this (Figure 3). It should be noted that public perceptions regarding a brown(ish) color would probably be different if the survey had targeted visitors of, for example, peatland-dominated Finnish Ostrobothnia, where lakes with a total organic carbon content of under 5 mg/L are rare (Kortelainen & Mannio, 1990).

The respondents were asked whether they had experience of fishing in Finland to reveal whether the absence or presence of these water attributes was important for an enjoyable fishing experience. The answers ($N = 347$; 65,7%) with fishing experience were rated on a 7-point Likert scale from strongly important to not important at all. On average, the respondents rated all the given water characteristics as important (from somewhat important to strongly important): absence of pollution (89.4%), absence of smell (83.9%), water transparency (79%), absence of slime (83.8%), absence of a brown(ish) color (71.5%), and absence of blue-green algae (74.1%). The answers were to a large degree consistent with the perceptions of water quality in Finland, specifically in relation to water transparency and the absence of pollution, smell, and slime (Figure 3).

In general, water quality in Finland had either a positive influence (37.1%) or no influence (47.3%) on respondents' visits to Finland in terms of overall experiences holidaying by the water. Another 15% did not pay attention to water quality to assess its possible impact, and only three respondents (0.6%) indicated that the water quality had a negative influence on their travels in Finland.

DISCUSSION

We have identified several ways in which browning affects the structure and function of aquatic ecosystems, but without implications for ecological status assessment. Because water color is used as a criterion for dividing waterbodies into different types rather than being a criterion for classifying waters into quality classes, there are no direct legal implications for addressing changes in water color. Although water browning is partially driven by global climate change and recovery from acidification caused by now decreased sulfur emissions (e.g., Xenopoulos et al., 2021), local anthropogenic factors, such as intensive forestry, exacerbate the large-scale impacts (Estlander et al., 2021; Finér et al., 2021; Nieminen et al., 2021). Thus, the WFD approach fails to account for water browning as an aspect of damage to aquatic ecosystems caused by local and often identifiable land-use pressures.

We revealed a research gap in studies linking EBM and water browning. Despite an increasing trend in the number of publications on both browning and EBM from 2011 to 2021, the limited studies (Kritzberg et al., 2020) focused on the combination of browning and EBM. We also detected a gap in social scientific studies on water browning. This might be because of the varying use of concepts in the natural scientific and social scientific literature. Natural scientific publications referred to increased DOC or DOM and causes and consequences of brownification, whereas social scientific studies focused on management structures and interactions and only made reference to water color or other parameters of water quality. Although the literature contains praise of EBM's capacity to combine multiple disciplines and objectives (Berkes, 2011), our study revealed a research gap in linking surface water browning to EBM. Similarly, a review by Flotemersch and Aho (2021) revealed that the number of studies focusing on users' perceptions of aquatic environments is limited. This can lead to a limited understanding of what is desired by the public or tourists that seek nature experiences.

Browning results from several processes that are partially natural and positive in nature but also detrimental to many ecosystem services enjoyed by humans. Even though climate change and recovery from acidification may exacerbate the impacts of forestry-induced browning, actions to mitigate browning are needed mostly on a local level. Although EBM cannot prevent the browning caused by global emission dynamics, it can account for diminishing negative land-use impacts; hence, RBMPs should also include measures targeted at mitigating the impacts of land-use practices on aquatic ecosystem browning. As for peatland forestry, this would require a transition from the prevailing intensive, even-aged forest management practices to more natural and diverse actions with continuous cover forestry, mixed forest cover, and improved catchment retention (Härkönen et al., 2023; Kritzberg et al., 2020). In river basins located in Northern Europe, leaching of organic carbon, nutrients, and iron from managed terrestrial systems is a major concern, with recent research revealing the scale and intensity of the issue (Aaltonen et al., 2021; Estlander et al., 2021; Finér et al., 2021; Lepistö et al., 2021; Škerlep et al., 2020, 2022). While global and local processes interact to set trends in water color (Lepistö et al., 2021), the green transition and associated intensifying land use should be balanced against the deterioration of aquatic environments (Marttila et al., 2020). Brownification is rarely a single issue in negatively affecting freshwater environments but is often accompanied by leaching of primary nutrients and mercury. Thus, research should be focused on disentangling the most important drivers of change, and EBM should extend to terrestrial environments to manage the pressures that will ultimately affect freshwater ecosystems. Specifically, research could target the specific legal changes needed to the WFD and other regulatory frameworks to better account for browning as an identifiable terrestrial pressure on waters.

Due to intensive engagement in recreational activities on waterbodies, citizens could also make valuable contributions in terms of collecting environmental data, such as measures of water transparency (Ceccaroni et al., 2020). Perceptions, however, are a subjective category, and people differ in their preferences regarding water quality and other characteristics of aquatic ecosystems. In our study, a brown color was noticed by the surveyed tourists but not considered a particularly important feature of water. Overall, the tourist perceptions in our survey did not differ from the general WFD-based classification results, as 87% of the lakes and 68% of the rivers in Finland meet the ecological status of good or excellent (2019). However, public perceptions can often differ from water quality changes indicated by WFD status assessment. Vuori and Kuusipuro-Korjonen (2018) found that, while human observations detected negative changes in lake ecosystem quality during the past 30–50 years, the administrative status remained good or excellent. In their study, the public study participants were locals and had decades of experience living by the waterbodies. Our study, in contrast, revealed positive assessments of water quality in Finland by Russian recreational users, which can be explained by the fact that recreational users of aquatic environments visit clear waterbodies more often than colored ones and, thus, tend to be more positive about water quality (Barnett et al., 2018; Keeler et al., 2015). Whereas foreign visitors' perceptions are limited, local people may be more like to observe indications of water quality changes by noticing, for example, changes in water color and the relative abundances of keystone species in their nearby lakes. Hence, our study faces some limitations since inconsistency in the survey data did not allow us to juxtapose the perceptions of water quality in waterbodies that were visited by the study respondents with their biological status and state of browning.

An increasing humic content (and simultaneously increasing nutrient concentrations) often leads to a higher abundance of the nuisance algae *Gonyostomum semen* that is problematic both to humans and food webs by forming slimy surfaces and by being too large for many zooplankton species to forage on (Hagman et al., 2019, 2020; Strandberg et al., 2020). Such consequences could be reflected in users' perceptions, but most of the implications of water browning are nonetheless measures that cannot be directly, visibly observed and may not be reflected in studies concerning public perceptions. The human eye can only recognize very rough changes in water color, and social scientific research can therefore ask about water color, pollution, and other variables that a layperson can differentiate, as demonstrated by our survey results. Laypersons can also use other experiences with water bodies to base their perceptions on, which are also very dependent on the way laypersons relate to water bodies (e.g., how they utilize the water and how often). Social scientific research can also demonstrate the importance local ecological knowledge, for example, on flora and fauna but also other environmental attributes that are valuable from a local perspective.

Browning of lakes also imposes some risks to humans by altering the toxicity or mobility of certain pollutants, such as mercury, in aquatic environments (Anderson et al., 2021; Braaten et al., 2018, 2020; Isidorova et al., 2016; Poste et al., 2019; Rizzuto et al., 2020; Wu et al., 2021). For human societies, an increased concentration of organic compounds also increases the cost of treating water for household use (Weyhenmeyer et al., 2016). These are implications that highlight future management needs to counteract concomitant surface water browning. Although the causes and consequences of browning in boreal lakes and rivers are relatively well researched from hydrobiological and biogeochemical perspectives, social perceptions have been less frequently considered in research, indicating a future research need. This emphasizes the need for holistic perspectives when studying browning, connecting the chemical and biological status of waters with their use and social perceptions.

The WFD, as a governance instrument targeting water quality challenges, such as chemical pollution and eutrophication, currently lacks indicators for increasing water color and humic substances. The assessment of ecological status largely reflects the state of eutrophication, in relation to which the impacts of water browning may be the converse, for example, the phytoplankton community composition and the share of different cyanobacteria may vary depending on the lake DOC content (e.g., Bergström & Karlsson, 2019; Lenard & Ejankowski, 2017; Senar et al., 2021). Moreover, the impacts of browning on different macrophytic life forms have been insufficiently studied (Blanchet et al., 2022) for the purpose of evaluating the impacts of multiple environmental stressors. Thus, biological data do not yet support conclusions on how certain species respond to correlated or interacting changes in several environmental metrics. Because browning rarely occurs alone without changes in nutrient concentrations or oxygen saturation, there is a clear need for fundamental biological research to improve our understanding of how freshwater ecosystems with different trophic statuses respond to increased browning. For now, the key response to increased light limitation appears to be reduced primary and fish production (Karlsson et al., 2009, 2015). However, a simultaneously increasing nutrient load may compensate for the light limitation, and the overall impacts of browning on the ecosystem level may remain unnoticed. WFD-based classification focuses on the qualitative structure of ecosystems within ranges of certain types, but it largely misses quantitative changes in the function of aquatic ecosystems and their benefits to humans. Another issue in environmental status classification under the WFD arises from the limited extent of biological data often available for status assessments, lowering their confidence in real-life situations. For example, while benthic organisms are sensitive to browning-induced effects such as anoxia and reduced light and photosynthesis (Arzel et al., 2020), data on zoobenthos or submerged macrophytes are not regularly available for ecological assessment. Additionally, zooplankton, as one of the organismal groups vulnerable to the impacts of browning (Lehtovaara et al., 2014; Nicolle et al., 2012; Williamson et al., 2015), is not included in the WFD as a BQE (Jeppesen et al., 2011). It has been demonstrated that multiple organismal groups should be used to support the evaluation of environmental impacts for credible outcomes (Soininen & Könönen, 2004). On the other hand, each aquatic species used as an indicator under WFD-based ecological status assessment has a certain trait-determined, but currently unacknowledged, preferred range of multiple environmental variables (e.g., Culp et al., 2011; Spasojevic et al., 2018; Verberk et al., 2013).

To incorporate browning in EBM and the WFD, there is a need to reach an agreement among EU member states on the browning-related variables to be regularly measured in European water-monitoring programs (Sepp et al., 2018). Whether humic content should be considered in the WFD as a quality measure rather than an inherent character of aquatic ecosystems is a policy issue based on both the biological impacts of water browning and the public perceptions of water quality.

CONCLUSIONS

To the best of our knowledge, this study is the first to combine research on the ecological consequences, public perceptions, and EBM of water browning. In summary, the browning of boreal lakes has mostly detrimental consequences on surface waters because it increases climate impacts by increasing greenhouse gas emissions, reduces aquatic productivity, alters species community composition, and diminishes water quality.

Also, from a human perspective, the consequences of browning can mostly be considered a nuisance. Browning can reduce fish production and lower the nutritional quality of fish, increase the costs of drinking water treatment, and decrease the attractiveness of waters for recreational activities. Our study revealed that public perceptions of surface water browning, and social scientific approaches in general, remain understudied and underutilized. Thus, this paper not only reveals a gap in earlier research but also adds to the literature by presenting primary data on tourist perceptions of water quality. In our study, brown color was noticed by the surveyed tourists but not considered a particularly important attribute of water. Perception is a subjective category, and different people have different perceptions and preferences when it comes to water quality and other characteristics of aquatic ecosystems. Browning leads to a visually obvious decrease in transparency that affects ecosystem functioning, with consequences that extend all the way to fisheries and other human uses of aquatic organisms and waters.

Given the complexity of the phenomenon, future research on browning should incorporate a comprehensive, interdisciplinary perspective to develop EBM that would recognize the biological foundations and user perspectives of water browning. To achieve and maintain the desirable state of waters, indicators of browning should be agreed on and included in biological and chemical monitoring and classification frameworks. Holistic EBM should address the additional sources of organic carbon from terrestrial activities such as forestry to counteract browning on a local level.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data (Albrecht et al., 2022) are available in Zenodo at https://doi.org/10.5281/zenodo.7436158. Metadata of the survey have been permanently archived in the University of Eastern Finland erepository at https://erepo.uef.fi/handle/123456789/28947. The complete lists of peer reviewed publications utilized for this work are provided in Appendices S1 and S2.

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