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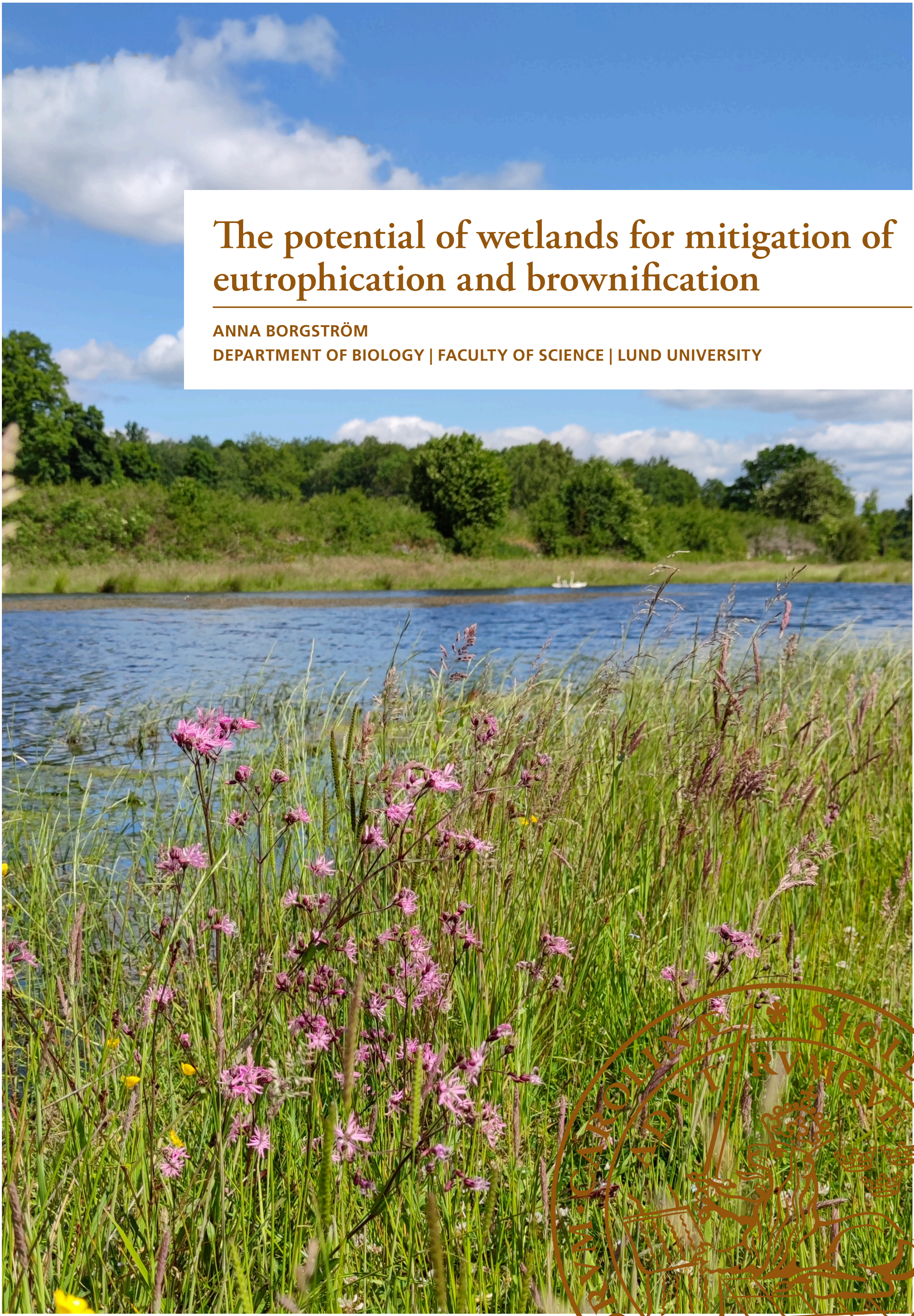

The potential of wetlands for mitigation of eutrophication and brownification

ANNA BORGSTRÖM

DEPARTMENT OF BIOLOGY | FACULTY OF SCIENCE | LUND UNIVERSITY

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List of Papers

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II. Borgström, A., Hansson, L-A. and Sjöstedt, J., 2022. Wetlands as a Local Scale Management Tool to Reduce Algal Growth Potential. *Wetlands*, 42(8), p.123. https://doi.org/10.1007/s13157-022-01640-9.

III. Borgström, A. and Hansson, L-A. Effects of different primary producers on mitigation of eutrophication and brownification. *Manuscript*.

IV. Borgström, A., Persson, A., Sjöstedt, J. and Hansson, L-A. Evaluation of efficiency and future scenarios for constructed wetlands. *Manuscript (submitted)*.

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The potential of wetlands for mitigation of eutrophication and brownification

Anna Borgström

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DOCTORAL DISSERTATION

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Faculty opponent
Professor Peter Hambäck,
Department of Ecology, Environment and Plant Sciences,
Stockholm University

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Abstract: Increasing nutrient concentrations (eutrophication) and water color due to dissolved organic matter (brownification) pose continuous threats to freshwater ecosystems worldwide, threatening ecosystem services like drinking water supply. Changing the increasing trends of eutrophication and brownification on our aquatic ecosystems is challenging. However, constructed wetlands could be a potential local, or regional, scale mitigation measure. Wetlands are highly diverse ecosystems of high importance to humans. They provide several ecosystem services, such as nutrient retention, carbon sequestration and flood protection as well as increased biodiversity. They remove both nitrogen and phosphorus by several in-system processes. However, drought vulnerability can lead to that nutrients and organic matter are released upon rewetting, demanding careful site selection for construction. Additionally, wetlands may have a potential to mitigate eutrophication and brownification simultaneously, since shallow water and longer retention time enable in-system processes such as denitrification, photooxidation and microbial degradation of humic substances, suggesting unexplored multifunctional benefits. My thesis explores the multifunctional potential of wetlands for mitigation of eutrophication and brownification simultaneously. Specifically, I aimed at assessing the capacity of wetlands to reduce total organic carbon (TOC), water color, total nitrogen (TN) and total phosphorus (TP), as well as the potential to reduce algal growth potential (AGP), i.e. the potential for algal blooms. I also aimed at assessing if common primary producers differ in their efficiency to reduce nutrient concentrations, TOC and water color, and AGP. To fulfil the aims of this thesis I performed both fieldwork and laboratory experiments. Additionally, I used future scenarios to estimate the potential of wetlands to mitigate eutrophication and brownification of downstream lakes. Wetlands displayed a high variability in reducing TN, TP, TOC and water color, both temporally and spatially. Some wetlands reduced nutrient concentrations, TOC, and water color simultaneously, whereas others were less efficient. Efficiency peaked in summer and with continuous water flow. Wetlands also reduced the growth potential of phytoplankton in a downstream lake. I also show that there are both temporal within and between wetland variations. Wetlands in catchments dominated by agriculture or pastureland often experiences larger fluctuations in algal growth potential than wetlands in catchments dominated by forests. The common primary producers, Elodea, Myriophyllum, and filamentous algae, varied in their abilities to reduce TN, TP, TOC and water color. Elodea was the most efficient of the three macroflora in reducing all targeted parameters, whereas Myriophyllum and filamentous algae reduced nitrogen, phosphorus, and water color, but increased the concentration of TOC. This highlights the potential benefits of diverse plant communities in constructed wetlands, likely allowing for a higher overall efficiency of the system compared to monocultures. Different phytoplankton groups displayed diverse responses when exposed to water previously inhabited by the macroflora. Cyanobacteria and diatoms generally had a lower growth potential when Elodea and Myriophyllum had previously grown in the water, while green algae generally were not affected by the macroflora. Efficient wetlands might mitigate eutrophication and brownification, but inefficient wetlands may instead exacerbate these environmental problems, harming downstream lake ecosystems by increasing nutrient and water color levels. Efficient wetlands can delay the progress of eutrophication and brownification in aquatic systems, providing a time window which could be of importance for implementing additional restoration efforts or exploring alternative solutions to counteract or even reverse these ongoing environmental problems.

Collectively, my thesis shows that constructed wetlands often, even in winter, have the potential to reduce nitrogen, phosphorus, organic carbon, water color as well as reducing the growth potential of different phytoplankton groups. A high biodiversity of plants could also prove beneficial to increase the efficiency of the wetlands. Hence, my thesis highlights the potential of some, but not all, wetlands as multifunctional tools for mitigation of both eutrophication and brownification.

Key words: Brownification, Constructed wetlands, Cyanobacteria, Eutrophication, Filamentous algae, Green algae, Macrophytes, Multifunctionality, Nitrogen, Phosphorus, Total organic carbon, Water color

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Author Contributions

I

LAH, AB, and JS developed the ideas and designed the methodology. AB and JS collected the data. AB performed the lab work with support from JS. AB analysed the data with input from LAH and JS. CK performed catchment analysis of the wetlands. AB led the writing of the manuscript. All authors contributed critically to the draft of the manuscript and gave final approval for publication. All authors contributed to the revision of the manuscript.

II

AB, LAH and JS developed the ideas and designed the methodology. AB and JS performed the fieldwork and experimental set ups. AB and JS performed the lab work. AB analyzed the data with input from LAH and JS. AB led the writing of the manuscript. All authors contributed critically to the draft of the manuscript and gave final approval for publication. All authors contributed to the revision of the manuscript.

III

LAH and AB conceived the ideas and designed the methodology. AB performed the fieldwork and set up the experiments. AB performed the lab work and collected the data. AB analyzed the data and wrote the first draft of the manuscript. All authors read and contributed critically to the manuscript.

IV

AB, LAH, and JS planned the study. AB summarized the background data. AB and AP performed the modelling. AB analyzed the data with input from LAH, AP, and JS. AB led the writing of the manuscript. All authors contributed critically to the draft of the manuscript and gave final approval for publication.

All authors in the list of papers have given their consent for the use of their work in the thesis.

List of all authors: Anna Borgström (AB), Anders Persson (AP), Clemens Klante (CK), Johanna Sjöstedt (JS), Lars-Anders Hansson (LAH)

Abbreviations and definitions

AGP	Algal growth potential, here defined as "the phytoplankton growth over a set amount of time at standardized conditions (temperature/light) and without grazing pressure from zooplankton" (see Raschke and Schultz (1987) for further insight in AGP).
Allelopathy	Influence/effects of a living plant on other nearby organisms. The influence/effect can sometimes be harmful or inhibitory.
Allochthonous carbon	Carbon originating from the terrestrial environment.
Autochthonous carbon	Carbon originating within the system by autotrophs, e.g. photosynthesis by algae.
CDOM	Colored dissolved organic matter.
DOC	Dissolved organic carbon.
DOM	Dissolved organic matter.
Ecosystem service	A benefit provided by the natural environment and healthy ecosystems that contributes to human wellbeing and quality of life (MEA, 2001).
Generalist wetland	Here defined as "a wetland that has a net reduction in TN, TP, TOC and water color simultaneously".
Macroflora	Plants and algae that are large enough to be seen with the naked eye.
N	Nitrogen.
P	Phosphorus.
Specialist wetland	Here defined as "a wetland that has a net reduction in one or two of the water quality parameters (TN, TP, TOC or water color)".
TN	Total nitrogen.
TOC	Total organic carbon.
TP	Total phosphorus.

Abstract

Increasing nutrient concentrations (eutrophication) and water color due to dissolved organic matter (brownification) pose continuous threats to freshwater ecosystems worldwide, threatening ecosystem services like drinking water supply. Changing the increasing trends of eutrophication and brownification on our aquatic ecosystems is challenging. However, constructed wetlands could be a potential local, or regional, scale mitigation measure. Wetlands are highly diverse ecosystems of high importance to humans. They provide several ecosystem services, such as nutrient retention, carbon sequestration and flood protection as well as increased biodiversity. They remove both nitrogen and phosphorus by several in-system processes. However, drought vulnerability can lead to that nutrients and organic matter are released upon rewetting, demanding careful site selection for construction. Additionally, wetlands may have a potential to mitigate eutrophication and brownification simultaneously, since shallow water and longer retention time enable in-system processes such as denitrification, photooxidation and microbial degradation of humic substances, suggesting unexplored multifunctional benefits.

My thesis explores the multifunctional potential of wetlands for mitigation of eutrophication and brownification simultaneously. Specifically, I aimed at assessing the capacity of wetlands to reduce total organic carbon (TOC), water color, total nitrogen (TN) and total phosphorus (TP), as well as the potential to reduce algal growth potential (AGP), i.e. the potential for algal blooms. I also aimed at assessing if common primary producers differ in their efficiency to reduce nutrient concentrations, TOC and water color, and AGP. To fulfil the aims of this thesis I performed both fieldwork and laboratory experiments. Additionally, I used future scenarios to estimate the potential of wetlands to mitigate eutrophication and brownification of downstream lakes.

Wetlands displayed a high variability in reducing TN, TP, TOC and water color, both temporally and spatially. Some wetlands reduced nutrient concentrations, TOC, and water color simultaneously, whereas others were less efficient. Efficiency peaked in summer and with continuous water flow. Wetlands also reduced the growth potential of phytoplankton in a downstream lake. I also show that there are both temporal within and between wetland variations. Wetlands in catchments dominated by agriculture or pastureland often experiences larger fluctuations in algal growth potential than wetlands in catchments dominated by forests.

The common primary producers, *Elodea*, *Myriophyllum*, and filamentous algae, varied in their abilities to reduce TN, TP, TOC and water color. *Elodea* was the most efficient of the three macroflora in reducing all targeted parameters, whereas *Myriophyllum* and filamentous algae reduced nitrogen, phosphorus, and water color, but increased the concentration of TOC. This highlights the potential benefits of diverse plant communities in constructed wetlands, likely allowing for a higher

overall efficiency of the system compared to monocultures. Different phytoplankton groups displayed diverse responses when exposed to water previously inhabited by the macroflora. Cyanobacteria and diatoms generally had a lower growth potential when *Elodea* and *Myriophyllum* had previously grown in the water, while green algae generally were not affected by the macroflora.

Efficient wetlands might mitigate eutrophication and brownification, but inefficient wetlands may instead exacerbate these environmental problems, harming downstream lake ecosystems by increasing nutrient and water color levels. Efficient wetlands can delay the progress of eutrophication and brownification in aquatic systems, providing a time window which could be of importance for implementing additional restoration efforts or exploring alternative solutions to counteract or even reverse these ongoing environmental problems.

Collectively, my thesis shows that constructed wetlands often, even in winter, have the potential to reduce nitrogen, phosphorus, organic carbon, water color as well as reducing the growth potential of different phytoplankton groups. A high biodiversity of plants could also prove beneficial to increase the efficiency of the wetlands. Hence, my thesis highlights the potential of some, but not all, wetlands as multifunctional tools for mitigation of both eutrophication and brownification.

Popular science summary

Water is of utmost importance for all living organisms and aquatic systems provide several ecosystem services of importance to humans. Wetlands are of especially high importance since they often have an unproportionally high biodiversity in proportion to their size and can be viewed as nature´s treatment plants. There are several different types of wetlands in several different environments, such as marshes, mangroves, flood meadows, and provide several important ecosystem functions. Our aquatic systems are under a high pressure from human impacts, increasing nutrients (eutrophication) and brown colored water (brownification). This has consequences for the health of the ecosystem. Brown water and algal blooms, in response to high nutrients, lead to less light in the water which can affect plants and organisms living in the water and it can also lead to oxygen-free zones which is harmful to the organisms living in the water. These changes will also be of concern to the production of drinking water, for example by increasing the cost of production.

So, can constructed wetlands help to reduce the effects of eutrophication and brownification? Wetlands naturally remove nutrients, such as nitrogen and phosphorus, from the water by several processes. Nutrients can bind to particles and fall to the sediment, or be taken up by plants, algae or microorganisms attached to different surfaces in the wetland. Microorganisms consume nutrients and dissolved organic matter. The sunlight will also help by making the dissolved organic matter more available for the microorganisms. Several of these processes are linked to the water flow and depth of the wetland. Their shallow waters and ability to slow down the water in the landscape provides time for several processes in the system to act. This suggests that there may be unexplored benefits for wetlands to counteract the increase of nutrients and water color in our aquatic systems.

My research explored if wetlands could fight both of these threats simultaneously. To study this, fieldwork and experiments were performed. I studied how effective wetlands were at reducing nutrients, organic matter, and water color, and how well they could control algal growth. I also tested different wetland plants and used projections to predict how well wetlands could help a downstream lake in future scenarios.

Some wetlands reduced all four of the water quality parameters and decreased the growth of algae as well. Others were less effective. The wetlands were most efficient during summer, specifically when there was an even water flow through the wetland suggesting that a steady flow is important for the function of the wetland. Aquatic plants also played a role, and the different plants had somewhat different capacities in reducing nutrients and organic matter. This highlights the value of diversity in these ecosystems.

But there is a challenge in constructing wetlands as well. If an inefficient wetland is constructed, it can actually worsen the problem, increasing nutrients and organic matter. On the contrary, efficient wetlands have a high potential to delay eutrophication and brownification, buying us time to find other solutions. Water flow is another important factor, since several of the less efficient wetlands dried out over longer periods of the year, for example during summer drought. So, choosing the right location and managing them well is crucial.

In summary, my thesis shows that wetlands can be powerful tools in protecting our aquatic ecosystems by increasing water quality. Wetlands have a potential to work as a multifunctional tool in the landscape. A high biodiversity of plants may further benefit the effectivity of the wetlands to increase water quality. By understanding their strengths and weaknesses, we can harness their natural powers to protect our precious freshwater ecosystems.

Populärvetenskaplig sammanfattning

Vatten är av stor betydelse för alla levande organismer och akvatiska ekosystem tillhandahåller flera ekosystemtjänster av betydelse för människor. Våtmarker är av speciellt stor betydelse eftersom de ofta har en oproportionerligt hög biologisk mångfald i förhållande till sin storlek och kan ses som naturens egna reningsverk. Det finns flera olika typer av våtmarker i flera olika miljöer, såsom kärr, mangrove, översvämningsängar och tillhandahåller flera viktiga ekosystemfunktioner. Våra akvatiska ekosystem är under högt tryck från mänsklig påverkan, ökande näringsämnen (övergödning/eutrofiering) och organiskt material som leder till brunare vatten (brunifiering). Detta får konsekvenser för ekosystemets hälsa. Algblomning, som svar på höga näringsämnen, och brunt vatten leder till mindre ljus som når ner i vattnet vilket kan påverka växter och andra organismer som lever där, och det kan också leda till syrefria zoner som kommer att minska vattenlevande organismer. Dessa förändringar är också problematiska för dricksvattenproduktionen, till exempel genom att kostnaderna för produktionen ökar.

Så, kan konstruerade våtmarker bidra till att minska effekterna av övergödning och brunifiering? Våtmarker tar naturligt bort näringsämnen, såsom kväve och fosfor, från vattnet genom flera olika processer. Näringsämnen kan binda till partiklar och falla till bottnen, eller tas upp av växter, alger eller mikroorganismer fästa på olika ytor i våtmarken. Mikroorganismerna förbrukar näringsämnen och löst organiskt material. Solljuset hjälper också till att göra det lösta organiska materialet mer tillgängligt för konsumtion av mikroorganismer. Flera av dessa processer är kopplade till våtmarkernas vattenflöde och djup. Deras grunda vatten och förmåga att bromsa vattnet i landskapet ger mer tid för flera processer i systemet att agera. Detta tyder på en outforskad potential för våtmarker att motverka ökningen av näringsämnen och vattenfärg på samma gång.

Min forskning har undersökt om våtmarker kan bekämpa båda dessa hot samtidigt. För att studera detta utförde jag både fältarbete och experiment. Jag studerade hur effektiva våtmarkerna var för att minska näringsämnen, organiskt material och vattenfärg, och hur väl de kunde kontrollera algtillväxt. Jag testade också olika våtmarksväxter och använde även modeller för att se hur våtmarker kan hjälpa en nedströms sjö i framtida scenarior.

Vissa våtmarker ökade vattenkvalitén eftersom de minskade koncentrationen av alla vattenkvalitéparametrarna och även kunde minska tillväxten av alger. Andra våtmarker var mindre effektiva. Effektiviteten var högre på sommaren, speciellt när det fanns ett jämnt vattenflöde igenom våtmarken. Vattenväxter spelade också en roll och de olika växterna hade olika förmåga att reducera näringsämnen och organiskt material. Detta belyser värdet av mångfald i dessa ekosystem.

Men det finns också utmaningar med att bygga våtmarker. Om en ineffektiv våtmark anläggs kan det förvärra problemen och öka näringsämnen och organiskt material. Däremot så har effektiva våtmarker stor potential att fördröja övergödning och brunifiering, vilket ger oss tid att hitta andra lösningar. Här är också vattenflödet av betydelse, eftersom flera av de mindre effektiva våtmarkerna i studien torkade ut under längre perioder av året, till exempel under sommarens torka. Så att välja rätt plats och se till att våtmarkerna har vatten hela året är av stor vikt.

Sammanfattningsvis visar min avhandling att våtmarker kan vara kraftfulla verktyg för att skydda våra akvatiska ekosystem genom att höja vattenkvaliteten. Våtmarker har en potential att fungera som ett multifunktionellt verktyg i landskapet. En hög biologisk mångfald av växter kan ytterligare gynna våtmarkernas effektivitet för att höja vattenkvaliteten. Genom att förstå våtmarkernas styrkor och svagheter kan vi utnyttja deras naturliga förmåga för att skydda våra värdefulla sötvattensekosystem.

Introduction

Wetlands

Wetlands are ecosystems of high importance, where water is present either at or near the soil surface, either constantly or seasonally. They are a part of our landscape and are neither terrestrial nor aquatic systems, but often transitional zones between the two (Reed, 2005). Wetlands often share features from both terrestrial and aquatic and can have either standing or seasonal water, thus the definition of wetlands as well as defining the boundaries of these systems can be challenging (Reed, 2005). Wetlands can be found worldwide and encompass a range of different environments including, but not limited to, peatland, marshes, flood meadows, mangroves, and tidal marshes. Additionally, the water in the wetlands can be either fresh, brackish, or salt water, either stagnant or flowing (Box 1).

Box 1 – Definition of wetlands by The Ramsar Convention, Iran, 1971

The Ramsar Convention has defined wetlands as:

"*areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres*".

Additional internationally important wetlands taken up on the Ramsar list are:

"*may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands*".

Five different wetland types are generally recognized: marine (e.g., coastal lagoons, coral reefs), estuarine (e.g., deltas, mangrove swamps, tidal marshes), lacustrine (wetlands associated with lakes), riverine (wetlands along rivers and streams) and palustrine (e.g., marshes, swamps, bogs).

Additionally, there are wetlands made by humans (e.g., reservoirs, fish and shrimp ponds, salt pans, irrigated agricultural land).

They are often rich ecosystems, providing habitat for a high diversity of invertebrates, plants as well as birds and other vertebrates. Wetlands are often considered ′hot spots′ for species richness since the high biodiversity contained in these areas often is disproportionate to their area (Gopal, 2009, Hansson et al., 2005, Leveque et al., 2005, Mitsch and Gosselink, 2000, Naiman et al., 1993). There has been a considerable decrease in wetland areas globally, and currently only 6% of the surface worldwide is covered by wetlands. The wetlands constitute an essential part in biogeochemical and hydrological cycles and provide several ecosystem services (Junk et al., 2013). Furthermore, wetlands have a high value to humans because of the ecosystem services they provide, e.g. nutrient retention, retaining sediment, improving the recreational potential, reservoirs of water, increased biodiversity, carbon sequestration, flood protection (Land et al., 2016, Verhoeven and Setter, 2010). Wetlands often perform several functions in the landscape simultaneously, however, there is a risk of losing functions if the wetland is being optimised for another (Mitsch and Gosselink, 2000). Our knowledge of the potential multifunctionality of wetlands is currently limited.

Furthermore, the ongoing urbanisation and continuing conversion of wetlands, e.g. to agricultural land, raise the question of how much of a catchment area should remain as wetland areas to benefit from the ecosystem services provided. Thus, the area needed and what ecosystem service is aimed at restoring should be considered during landscape restorations (Mitsch and Gosselink, 2000). Several studies have been conducted to estimate the required area, with suggestions ranging from 5% to 8.8% of the watershed, depending on the wetland’s intended function (Arheimer and Wittgren, 1994, Hey et al., 1994, Hey and Philippi, 1995, Mitsch et al., 1999). For instance, to provide sufficient floodwater storage in the upper Mississippi and Missouri Basins for large-scale flooding events, it was estimated that restoring 7% of the wetland area in the watershed would be adequate (Hey and Philippi, 1995). Furthermore, to reduce the nitrogen load to the Gulf of Mexico or to the Baltic Sea by 20-50%, an estimated 3.4 – 8.8% of the catchment area would have to be converted to wetland and riparian forest (Arheimer and Wittgren, 1994, Mitsch et al., 1999).

Wetlands in Sweden

Sweden has the highest variation in wetland types (e.g. mires, fens, tarns, riverine marshes, swamp forests, wet heaths, flood meadows) in the European Union. However, the majority of the wetlands are impacted by humans with the highest impact in southern Sweden where there is a higher density of the population. Generally, the wetland types most affected by human impact are bogs and limnic wetlands (Gunnarsson and Löfroth, 2014). Wetlands have been utilized in the landscape for centuries, serving various purposes, e.g. as hayfields, agricultural land, and peat mining. The potential use of wetland areas for agriculture and forestry led to large areas being claimed, resulting in the drainage and ditching of vast areas. The majority of the draining occurred during the 19th and 20th centuries, with approximately 3 million hectares of wetland area lost (Naturvårdsverket, 2009).

There are several EU directives (e.g. the nitrate directive, the Water Framework Directive, the Marine Strategy Framework Directive), as well as HELCOM Baltic Sea Action Plan (BSAP), that has emphasized on the need to reduce nutrients to aquatic ecosystems. Construction and restoration of wetlands is one of several measures suggested by the BSAP to reduce nutrient runoff from agricultural land (Land et al., 2016). Furthermore, in sharp contrast to the 19th and 20th centuries when funding was allocated to draining and ditching of wetlands and the lowering of lakes, wetlands have been constructed since the 1990s with the help of various governmental funds in Sweden (Länsstyrelsen, 2011). Thousands of hectares of wetlands have been constructed or restored to meet the BSAP commitments and Sweden's Environmental objectives, including Thriving Wetlands (Myllrande våtmarker), Zero Eutrophication (Ingen övergödning), Flourishing Lakes and Streams (Levande sjöar och vattendrag), A Varied Agricultural Landscape (Ett rikt odlingslandskap), and A Rich Diversity of Plant and Animal Life (Ett rikt växt- och djurliv) (Land et al., 2016, Länsstyrelsen, 2011).

Threats to wetlands and consequences of removal

However, more than 65% of natural wetlands in Sweden have been lost (Figure 1) and approximately 80% of the current wetlands in Sweden are affected by anthropogenic activities, e.g. land-use changes (Gunnarsson and Löfroth, 2014, Silva et al., 2007). Furthermore, anthropogenic impacts and land-use changes have contributed to a major loss of natural wetlands and biodiversity, while the landscape is transformed to urban, arable or forested land globally (Finlayson et al., 1999, Hansson et al., 2005, Kalnay and Cai, 2003, Paludan et al., 2002, Verhoeven and Setter, 2010, Zedler, 2003), resulting in a long-term loss averaging 54-57% worldwide since 1700 (Davidson, 2014).

Figure 1. Skånska rekognisceringskartan was a maping project that took place from 1812 to 1820 (A). The map shows wetlands in Scania, when the region was characterized by large wetland areas showing that approximately 200 years ago Scania was a blue landscape. The map compiled by Länsstyrelsen Skåne (B) shows the current wetland area, including constructed, restored and natural wetlands as well as lakes from 2016.

Consequently, high pressure is placed on terrestrial and aquatic ecosystems alike which has led to an increase in threatened species and deteriorating water quality (Länsstyrelsen, 2011, Søndergaard and Jeppesen, 2007). This has resulted in high amounts of inorganic and organic compounds reaching aquatic systems, which in turn expedites eutrophication and brownification (Beusen et al., 2016, Ekvall et al., 2013, Galloway and Cowling, 2021, Kritzberg et al., 2020, Luimstra et al., 2020, Seitzinger et al., 2010, Taranu et al., 2015).

Environmental problems

Environmental threats, such as eutrophication and brownification, are ongoing, affecting aquatic ecosystems globally and in turn affecting ecosystem services provided by these ecosystems, e.g. drinking water supply. Changing the increasing trends of these environmental threats on our aquatic ecosystems is challenging.

Eutrophication

Anthropogenic changes to the landscape are threatening aquatic ecosystems around the world, leading to an accelerated eutrophication of surface waters and increased risk of algal growth (Kosenius, 2010, Nguyen et al., 2019, Sharip et al., 2014, Smith and Schindler, 2009, Withers et al., 2014). Eutrophication is the process by which excess nutrients, primarily nitrogen (N) and phosphorus (P), enter the water and stimulate the growth of phytoplankton and other aquatic plants (Smith, 2003). The main cause is the increased nutrient input from non-point or point sources to aquatic ecosystems, e.g. fertilizer runoff, industrial waste, sewage discharge, atmospheric deposition. This process has negative economic consequences and leads to deteriorating water quality and ecosystem services, for inland as well as marine waters (Le Moal et al., 2019, Pretty et al., 2003, Smith, 2003).

Aquatic ecosystems are sensitive to increased nutrient inputs, leading to an increase in biological activity. In turn, this can cause deterioration in recreational value and changes in the composition and structure of the ecosystem, e.g. shifts in algal community, increased likelihood of algal blooms occurring (Beusen et al., 2016, Jeppesen et al., 2009, Wurtsbaugh et al., 2019). Phytoplankton are an essential part of aquatic ecosystems as they constitute the base of the food web and account for almost half of the global primary production (Behrenfeld et al., 2001, Field et al., 1998). Increased phytoplankton growth (Figure 2) due to excess nutrient input, can reduce water quality and increase the risk of algal blooms as global consequences (Heisler et al., 2008, Li et al., 2011). Furthermore, excess algal biomass can cause harm to aquatic and terrestrial organisms since many bloom-forming phytoplankton taxa, such as cyanobacteria, produce toxins (Carmichael and Boyer, 2016, Ekvall et al., 2013, Hagman et al., 2019, Jonasson et al., 2010, O'Neil et al., 2012). Additionally, they can reduce water clarity and deplete oxygen levels in the water (Le Moal et al., 2019, Schindler, 2012).

Figure 2. Algal bloom in a wetland situated in an agricultural landscape. (Photo: Anna Borgström)

Brownification

Runoff from surrounding catchment areas of aquatic systems can also increase humic substances and dissolved organic carbon (DOC). This can result in a brown water color (Figure 3), a process commonly called brownification. Brownification is an ongoing process in the northern hemisphere, increasing the water color of lakes and running waters, which can lead to changes in water quality and aquatic systems (Haaland et al., 2010, Kritzberg et al., 2020, Monteith et al., 2007). In freshwater systems, brownification has been linked to long-term increases in dissolved organic carbon concentrations and iron (Fe), and several underlying drivers have been suggested, such as increasing temperatures and precipitation, reduced acid deposition, hydrological factors, and land-use changes (Clark et al., 2010, Ekström et al., 2011, Ekström et al., 2016, Hongve et al., 2004, Kritzberg et al., 2020, Monteith et al., 2007). One such land-use change is afforestation which can lead to accumulation of organic carbon in the soil layer which can be transported to surface waters in aquatic systems (Škerlep et al., 2020). There is a variability in DOC concentration and composition in aquatic systems and the organic matter can be separated in two major groups depending on its origin, allochthonous and autochthonous organic carbon (Sachse et al., 2001). Autochthonous carbon originates within the system by autotrophs, e.g. through algal photosynthesis, whereas allochthonous carbon originates from the terrestrial environment, thus outside the system (Holding et al., 2017, Kritzberg et al., 2004, Tranvik, 1993). Allochthonous carbon is affected by land-use such as agriculture and forestry in the watershed (Hagen et al., 2010, Lambert et al., 2017, Lu et al., 2014).

There are several potential problems, both societal and ecological, arising with increased water color in aquatic ecosystems. Increased water color affects the recreational value, trophic web, fish community, light climate, and the potential to use lakes as drinking water resources decreases (Delpla et al., 2009, Ekvall et al., 2013, Estlander et al., 2010, Kritzberg et al., 2020, Lavonen et al., 2013).

Figure 3. Brown water in Lake Bolmen in Småland, southern Sweden. Lake Bolmen was used as study lake in Paper IV. (Photo: Anna Borgström)

Effects on ecosystem services

Ecosystem services provided by lakes are also strongly affected by excess algal biomass, warmer weather, and increased water color. Brownification and eutrophication can have significant impacts on the drinking water production process, increasing costs and treatment of raw water. These factors need to be considered for surface water reservoirs (Boholm and Prutzer, 2017, Delpla et al., 2009). Surface water is of high importance since it is commonly the main source for drinking water production in many countries. In Sweden, approximately 75% of the drinking water supply comes from surface water, directly or through artificial infiltration (Kritzberg et al., 2020).

DOC is reduced by chemical precipitation, hence, increased DOC concentrations in aquatic systems can cause problems in the drinking water-treatment plants since it will lead to an increased use of chemicals to counter the increase, further affecting the cost of drinking water production. Additionally, chemical methods alone cannot remove DOC completely. The residual DOC can disrupt essential water treatment processes like UV disinfection, chlorination, and active carbon filtration (Ritson et al., 2014b). Chemical precipitation lose efficiency with rising DOC concentrations. If concentrations of DOC will continue to increase, water treatment facilities may face the necessity of altering their raw water sources or investing in novel filtration techniques, both of which incur significant costs (Kritzberg et al., 2020).

Furthermore, eutrophication of aquatic systems might lead to excess phytoplankton biomass, expedited by the increased nutrient input, decreasing the quality of the raw water. As a result, drinking water production is affected, e.g. high costs for disinfection, bad taste and odor, or clogging filters (Delpla et al., 2009, Ewerts et al., 2013, Merel et al., 2010, Willen, 2001). Phytoplankton blooms might also reduce the biodiversity within the aquatic system, e.g. reduction in macrophyte and fish species (Boyd, 2019). Eutrophication of aquatic systems can lead to the depletion of dissolved oxygen, since the process of phytoplankton degradation through microbial decomposition uses dissolved oxygen (Rathore et al., 2016). Thus, in aquatic systems, such as lakes and oceans, where there is a high phytoplankton biomass there will be a high decomposition rate which can deplete the dissolved oxygen.

However, high concentrations of DOC can also decrease dissolved oxygen. An increase in DOC might boost the microbial respiration and photooxidation rates, which utilize oxygen and might lead to a depletion of dissolved oxygen in aquatic ecosystems (Brothers et al., 2014). The consequences of reduced dissolved oxygen can be severe, and anoxic conditions typically lead to declines in both the richness and diversity of biological communities, contributing to ecosystem degradation and potential species loss (Diaz, 2001, Levin et al., 2009, Riedel et al., 2012, Zhang et al., 2010). In addition, anoxia strongly influences the release of phosphate, DOC, iron and manganese from the sediments (Skoog and Arias-Esquivel, 2009). Therefore, increasing our understanding and devising strategies to mitigate brownification and eutrophication in aquatic systems is of considerable importance.

The potential of wetlands

Brownification and eutrophication pose significant challenges for freshwater ecosystems. However, there are various management practices that can help mitigate and reduce the influx of organic matter and excess nutrients to aquatic systems. Management practices to reduce nutrient influx to aquatic systems include nutrient management practices such as reducing agricultural runoff and fertilizer use and improving wastewater treatment (Khan and Mohammad, 2014). Furthermore, to minimize runoff of organic matter, land use management practices could be of use, e.g. reducing forest clearcuttings, and restoring riparian buffer zones. Additionally, reducing carbon emissions and mitigating climate change could reduce the intensity and frequency of precipitation events, and thus reduce terrestrial runoff to aquatic systems. Implementing these management practices is a challenging task and will take time, it is therefore important to have other measures in the meantime.

Here is where wetlands could play an important role, since constructed wetlands are systems that are purposely built and engineered to achieve ecosystem services provided by natural wetlands (Metcalfe et al., 2018). Wetlands could potentially be useful local-scale (or regional scale) management tools to counteract eutrophication and brownification, with a high potential for reducing nitrogen and phosphorus transport from terrestrial environments, e.g. arable land, to downstream aquatic systems (Cheng et al., 2020, Ge et al., 2019, Hoffmann and Baattrup-Pedersen, 2007, Land et al., 2016, Lu et al., 2009), by removing nutrients from the water column and retaining them in a form that is not readily released (Johnston, 1991). Previous studies suggest that even a modest increase in wetland area can lead to substantial reductions in nitrogen transport (Arheimer and Wittgren, 1994, Cheng et al., 2020). Nutrients in the inflowing water can be reduced by e.g. sedimentation, denitrification, and direct plant uptake. However, the main processes that influence the degradation of carbon complexes in aquatic systems are photooxidation and microbial utilization (Granéli et al., 1996, Lindell et al., 1995).

Nutrient removal

In the reduction of nitrogen and phosphorus, there are a combination of abiotic and biotic processes involved in the removal, with sedimentation, algal uptake, and plant uptake being common processes for both nutrients. However, denitrification is another main process of nitrogen retention, whereas precipitation and sorption are other main processes for phosphorus (Babatunde et al., 2009, Grüneberg and Kern, 2001, Mereta et al., 2020, Reddy et al., 1999, Saunders and Kalff, 2001, Vymazal, 2007, Walton et al., 2020). However, in wetlands the phosphorus retention is also regulated by physiochemical properties of the soil, plant litter and detrital accumulation, water flow velocity, hydraulic retention time and fluctuations and phosphorous loading. Phosphorus retention can also be affected by wetland size and water depth (Reddy et al., 1999).

Sedimentation and sorption

The inflowing water to wetlands will often slow down and spread out over a larger area, which in turn will lead to particles that are suspended in the water column sinking to the bottom sediment in the wetland, i.e. the process of sedimentation. These particles are often nutrient rich, and sedimentation is a process allowing for nutrient, as well as contaminant, removal (Griffiths and Mitsch, 2020, Nahlik and

Mitsch, 2008). In constructed wetlands, particulate organic nitrogen is mainly removed by sedimentation, by settling on the bottom sediment or attaching to substratum such as plant stems (Lee et al., 2009).

Furthermore, sorption plays a part in the sedimentation process. Since it is the process where a substance is adsorbed in or on another substance, which is common for phosphate (PO_4^{3-}). With its negative ionic charge, it is highly susceptible to bind to positively charged minerals, e.g. calcium (Ca) and iron (Fe), and then sink to the bottom sediment (Nahlik and Mitsch, 2008).

Plant uptake

Since wetlands are shallow it allows for high macrophyte growth which then contributes to nutrient retention by binding nutrients in their tissue, through direct uptake from the water column (Levi et al., 2015). Increased macrophyte cover will also increase the surface area accessible for colonization by denitrifying bacteria (Song et al., 2011). Additionally, macrophytes provide substrate for microbial attachment of microorganisms that might degrade large colored carbon complexes and DOC (Reitsema et al., 2018, Tranvik, 1988).

Denitrification

Denitrification is a microbial process that occurs under low oxygen concentrations. It converts bioavailable nitrogen compounds (nitrite and nitrate), which are accessible for primary production or microbial assimilation, into a gaseous form (N_2). This gaseous nitrogen is then released to the atmosphere, effectively removing it from the aquatic system (Seitzinger et al., 2006). Approximately 75% of nitrogen removal happens through biological processes, with denitrification playing a significant role in wetlands (Howarth et al., 1996). Denitrification and direct plant uptake are season bound processes, which are mainly efficient during warmer periods. As a result, nutrients are stored both short term and long term in wetlands.

Carbon removal

In aquatic ecosystems, DOC represents a large part of the organic carbon reservoirs in the biosphere (Amon and Benner, 1996). DOC in aquatic systems is transformed through the processes, such as microbial degradation, photooxidation and flocculation, that are affected by the composition of the DOC as well as chemical and biological factors (Anderson et al., 2019).

Microbial degradation

Microbial communities act as key drivers in the recycling of terrestrial and aquatic organic carbon back to the atmosphere (Cole et al., 2007). Utilizing organic matter as both food and energy source, these bacteria respire, consuming oxygen and releasing CO_2 (Pollard, 2013). In many aquatic ecosystems the dominant flux of carbon and nutrients is as dissolved organic matter (DOM), and heterotrophic bacteria play an important role in global biogeochemical cycles as the primary consumers (Amon and Benner, 1996, D'Andrilli et al., 2019). DOM serves as essential carbon and energy sources for heterotrophic bacteria, which utilize various metabolic pathways to process DOM, either by consumption or transformation, through biomass production, mineralization, or oxidation (Cole, 1999, Hofmann et al., 2020). Furthermore, microbial utilization of DOM is affected by the biochemical composition, molecular size and inorganic nutrient concentrations of the DOM as well as the bacterial community and environmental parameters, e.g. temperature (Amon and Benner, 1996, D'Andrilli et al., 2019). Although heterotrophic bacteria might degrade large colored carbon complexes (Tranvik, 1988), they prefer the noncolored carbon complexes (Berggren et al., 2018, Hansen et al., 2016) which suggests that the reduction in water color in aquatic systems is not only due to microbial degradation.

Photodegradation

The transfer of DOM from terrestrial sources, such as forests, to aquatic systems exposes it to solar radiation and subsequent photodegradation. This process is induced by sunlight and has a strong influence on the composition and biodegradability of DOC within these aquatic ecosystems (Bowen et al., 2020). Especially ultraviolet (UV) radiation (wavelength <400 nm) plays a significant role in the turnover and dynamics of DOC (Lindell et al., 2000). Photodegradation can fragment carbon complexes, into smaller more bioavailable forms. It can fracture aromatic bonds in large colored carbon complexes, which produces noncolored carbon complexes that are more bioavailable and therefore easier utilized by bacteria (Koehler et al., 2014). Thus, photodegradation often transforms recalcitrant (resistant to microbial breakdown) DOM fractions into more readily utilizable substrates for heterotrophic bacteria, enhancing the overall biodegradability of the DOC pool (Bertilsson and Tranvik, 2000, Cory and Kling, 2018, Ward et al., 2017).

In addition, exposure to solar radiation can directly transform DOC to inorganic forms (e.g. CO_2), supplementing microbial degradation as a significant pathway for organic matter mineralization in aquatic ecosystems (Granéli et al., 1996, Milstead et al., 2023). This process is often referred to as photooxidation. The majority of photooxidation is attributed to the shorter UV-B radiation (Granéli et al., 1996). By directly converting complex organic matter to CO_2, UV-B radiation might bypass the intricate network of microbial transformations typically associated with organic matter decomposition (Cole, 1999). Thus, DOC may be refractory when transported from e.g. terrestrial soils, but when entering the aquatic system and upon exposure to UV-radiation, it becomes labile due to photochemical transformation.

Flocculation

Flocculation is a process involving aggregation of particles. In the environment flocculation can be initiated by specific compounds, colloids, or particle surfaces, including metal cations, mineral particles, and positively charged polysaccharides or proteins (Berggren et al., 2018). However, natural flocculation tends to occur more favorably at positively charged interaction interfaces under acidic conditions. Additionally, DOC can undergo self-flocculation and aggregation in response to decreasing pH or increasing salinity (Asmala et al., 2014). On mineral surfaces, the sorption potential of DOC is closely tied to particle size (Mayer, 1994). The sorption capacity of DOC with surfaces is also influenced by mineralogical properties, where e.g. iron oxide coatings on mineral surfaces can form stable bonds with DOC (Mayer, 1994). Additionally, flocculation strongly interacts with photoreactivity, since partial photooxidation of DOC generates anionic organic acids which can rapidly flocculate when they encounter positively charged surfaces (von Wachenfeldt et al., 2009).

Trade-offs and potential issues with multifunctionality

Wetlands perform multiple ecosystem services simultaneously, but not all wetlands perform these services equally well. The geographical location of a wetland significantly influences its function. Previous research highlights that wetland size, design, placement, and age play a vital role in their functioning (Greiner and Hershner, 1998, Hansson et al., 2005, Nilsson et al., 2020, Uusi-Kamppa et al., 2000, Zedler, 2003). For instance, larger wetland areas support greater biodiversity and enhance nitrogen retention, although they may reduce phosphorus retention (Hansson et al., 2005, Zedler, 2003). However, wetlands with longer retention times and shallower depths appear more effective at reducing phosphorus levels (Braskerud, 2002, Greiner and Hershner, 1998, Uusi-Kamppa et al., 2000). Also, the placement of a wetland within a watershed matters (Figure 4), as downstream wetlands have a higher potential to trap nutrients compared to those situated higher up in the catchment (Zedler, 2003).

Wetlands that are prone to drought may instead leak phosphorus, nitrogen and organic matter to the water column when rewetted (Lepistö et al., 2008, Macek et al., 2020, McComb and Qiu, 1998, Shumilova et al., 2019, Song et al., 2007, Venterink et al., 2002), although the leaching of dissolved organic carbon has been shown to decrease if there are short rain events happening during the drought (Coulson et al., 2022).

Figure 4. A wetland in the agricultural landscape with water that flows to a lake, then enters the river Helge å and later flows to the Baltic Sea. (Photo: Anna Borgström)

Moreover, the soil composition also matters. For example, Sphagnum mires and peat soil can leach organic carbon and therefore are unlikely to function as humic traps (Ritson et al., 2014a). However, there is potential for many other areas to be suitable for constructing wetlands aimed at reducing both nutrients and humic substances. By doing so, we can potentially mitigate both eutrophication and brownification on a local scale. If wetlands are restored or constructed in our landscape, there is a potential that several negative trends can be mitigated or even reversed (Zedler, 2003). This approach could prove cost-effective in reducing nutrient loads and humic substances in freshwater and coastal waters, including lakes used as drinking water reservoirs.

Current ecological restoration measures

There has been a significant emphasis on the ability of wetlands to reduce nutrients to downstream aquatic systems (e.g. Babatunde et al., 2009, Mereta et al., 2020, Walton et al., 2020) whereas there is a lack of knowledge regarding the ability of wetlands to reduce humic substances as well as the potential multifunctionality in the simultaneous reduction of several water quality parameters. With wetlands in the landscape, water is slowed down which provides more time for the in-system processes to act, e.g. photooxidation, microbial degradation, denitrification, sedimentation (Griffiths and Mitsch, 2020, Kritzberg et al., 2004, Lee et al., 2009, Seitzinger et al., 2006). In shallow waters, where the water is kept in the landscape for some time, carbon compounds, e.g. humic substances, are transformed when exposed to UV-radiation which makes it more accessible for degradation by bacteria (Granéli et al., 1996, Koehler et al., 2014). Hence, wetlands may have an unexplored potential to simultaneously reduce nutrients, TOC, and water color. Therefore, wetlands could be used as a local management tool to counteract the effects of brownification and eutrophication in lakes and reservoirs by facilitating photooxidation and nutrient retention. Given the ongoing problems of eutrophication and brownification in aquatic ecosystems and the services they provide, finding natural ways to mitigate these processes is of considerable importance.

Therefore, in my thesis, I have aimed to fill some of the existing knowledge gaps regarding the potential multifunctionality of wetlands.

Aims and Objectives

Ecosystem services provided by wetlands have been studied for decades (Bolund and Hunhammar, 1999, Costanza et al., 1989, Finlayson et al., 2005, Mitsch et al., 2015, Xu et al., 2020), and wetlands may provide several ecosystem services simultaneously i.e. there is a potential multifunctionality of the wetlands. However, the increased eutrophication and brownification of aquatic systems pose societal challenges in securing water resources for the future. The future health and wellbeing of humans, as well as the future use of ecosystem services provided by aquatic systems, may be significantly impacted due to the increased run-off of humic substances and nutrients, along with the increased likelihood of cyanobacterial blooms. Thus, there are certain ecosystem services provided by wetlands that are of higher importance/interest to be performed simultaneously, which may provide guidance for local- or regional-scale actions by authorities and stakeholders.

In my thesis, I investigate the multifunctional potential of wetlands to mitigate eutrophication and brownification. Furthermore, I aimed at exploring the potential to use wetlands as a tool to mitigate algal blooms as well as investigating the possibility of using specific primary producers in order to raise the efficiency of constructed wetlands.

More specifically, the following aims and objectives were addressed in the chapters of my thesis:

- Assess the multifunctional capacity of wetlands to reduce TOC, water color and nutrients (**Paper I**).
- Evaluate the potential efficiency of wetlands to reduce algal growth potential (AGP) irrespective of temperature constraints (**Paper II**)
- Assess if, and how much, each of the common primary producers reduce nutrients and browning (**Paper III**).
- Assess if the algal growth potential (AGP) differs when exposed to water from different primary producers (**Paper III**).
- Estimate the potential of wetlands to mitigate eutrophication and brownification of a recipient lake through future scenarios (**Paper IV**).

Methodology

In this chapter, I give an overview of the methods used in this thesis. Detailed descriptions of the methods can be found in respective original publication/manuscript (**Paper I-IV**).

Data collection

Study systems

Several systems were involved in the studies performed, both wetlands and lakes. In total, eleven wetlands were sampled for 18 months. Nine of the wetlands are located in Scania, southern Sweden (**Paper I-IV**) and two wetlands are located in Småland, southern Sweden (**Paper IV**). The wetlands had different catchment area, land-use (Figure 5), and morphology. All wetlands are constructed wetlands and were originally designed for different purposes, such as biodiversity or nutrient retention.

Water was collected from the eastern basin of Lake Ringsjön (**Paper II-III**) in Scania, southern Sweden (55°51'34.8"N, 13°33'54.3"E). Eastern Ringsjön has an area of 20.5 km^2 with a maximum depth of 16.4 meters, average depth of 6.1 meters, and an approximate turnover time of 0.8 years. The catchment area is 22.1 km^2, consisting of mainly agriculture and forests. Lake Ringsjön is characterized as hypertrophic, and during the last decades the lake has had high amounts of nutrients entering, which has led to a problem with algal blooms. Lake Ringsjön is also a drinking water reservoir but at present the lake is only used as a reserve.

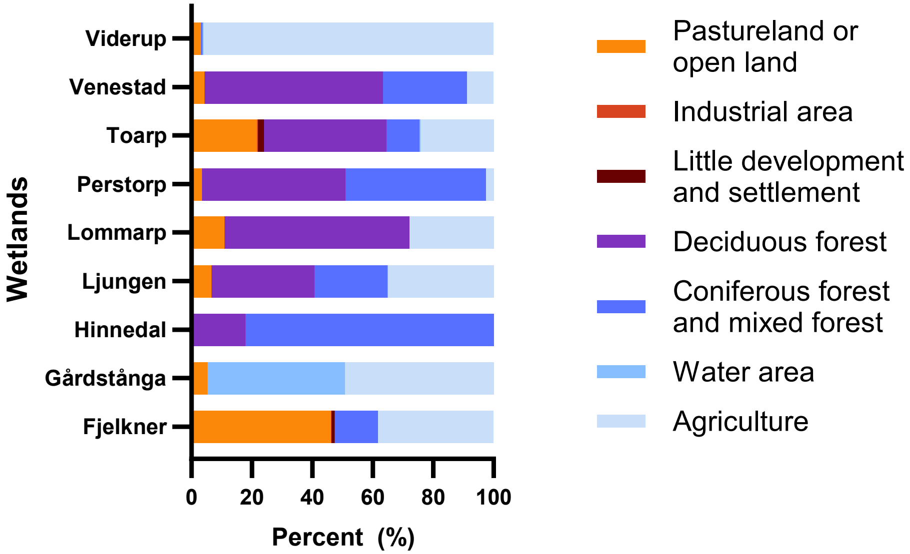

Figure 5. Landuse (%) in the catchment of the nine wetlands in **Paper I**, showing the mixture of landuse in the catchments of the wetlands.

Fieldwork

Here I will give an overview of the field work that has made the projects possible (Figure 6). Constructed wetlands were included in **Paper I, II** and **IV**. Nine constructed wetlands in Scania were sampled monthly from April 2020 until September 2021 (**Paper I-II**) whereas the two wetlands in Småland were sampled monthly from June 2020 until October 2021 together with Sydvatten (**Paper IV**). Water samples were collected from both the in- and outflows of the wetlands to analyze water color, total nitrogen, total phosphorus, and total organic carbon.

Monthly measurements of the water velocity (m/s) were performed using a handheld flowtherm NT (Höntzsch). By combining this with measurements of the area (m^2) of the in- and outflows of the wetlands, the water flow (m^3/s) could be calculated and converted to liters per second (L/s). Water was not collected if there was no flow in the in- and outflows of the wetlands. Thus, data was collected only when there was water running through the wetlands. Additionally, some wetlands could not be sampled during periods of the year due to drought during summer and early fall, or during some winter months if they were frozen to the bottom (**Paper I**).

For the experiments performed in **Paper II-III**, water from Lake Ringsjön was used. Water was also collected monthly over 18 months (April 2020 to September 2021) from seven of the constructed wetlands in Scania, as well as from Lake Ringsjön, to use for incubation of algae cultures (**Paper II**) and for quantification of the algal growth potential (AGP) in the in- and outflows of the wetlands. Water was also collected two times from Lake Ringsjön during the summer of 2023, to use for quantification of the AGP in water where different taxa of primary producers had grown (**Paper III**).

For the experiment performed in **Paper III**, water was collected once from two wetlands in Scania during the summer of 2023. Based on previously measured nutrient concentrations and water color (**Paper I**), two wetlands were selected: the wetland with the highest nutrient concentration and the wetland with the highest water color (**Paper III**). To reduce the algal abundance in the wetland water and minimize phytoplankton during the experiment, the water was filtered through a 10 µm net. For the experimental set-up, macrophytes were also collected (**Paper III**). *Elodea canadensis* and the filamentous algae *Mougeotia* (Zygnemataceae) were collected in Lake Sövdesjön (55°35'04.5"N, 13°40'04.6"E), whereas *Myriophyllum spicatum* was collected from a creek in Lund (55°42'49.6"N, 13°12'28.4"E). *E.canadensis* (further called *Elodea*) and *M.spicatum* (further called *Myriophyllum*) were selected since they are common macrophytes in aquatic freshwater systems in Sweden. Furthermore, different species of filamentous algae commonly grow in wetlands and here the filamentous green algae *Mougeotia* (Zygnemataceae) is used as an example of filamentous algae.

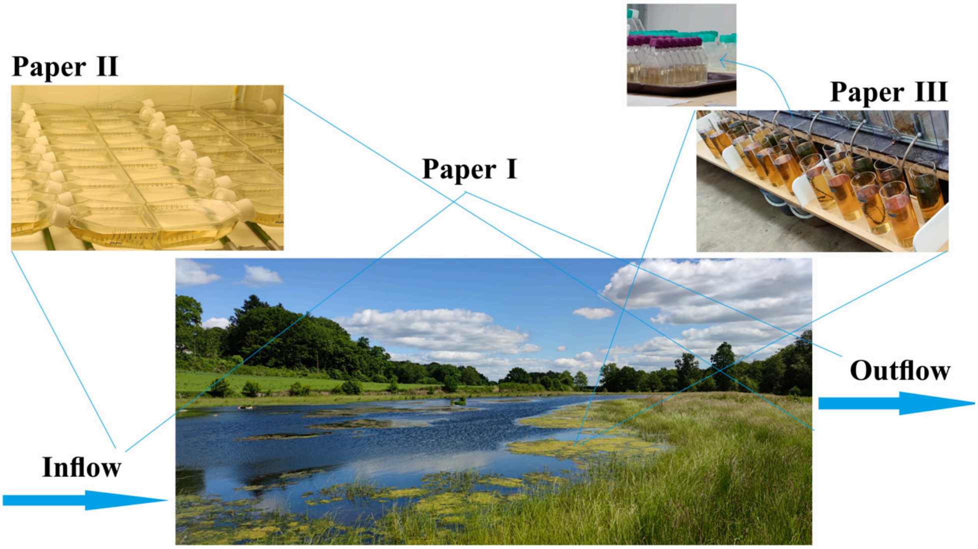

Figure 6. Overview of the fieldwork involved in Paper I – III. Water was collected in the in- and outflow of the constructed wetlands for Paper I – II and additionally for Paper II the water was used for the set-up of algae cultures. For Paper III water was collected from two selected wetlands for the experimental set-up and additional experimental set-up of algae cultures.

Water quality measurements

In my projects, the nutrients I focused on were nitrogen (N) and phosphorus (P), which are essential for organism growth, and also closely linked to eutrophication of aquatic systems. However, these nutrients can be available in different concentrations and can become limiting for an organism's growth. Due to the necessity of these nutrients, changes in concentration can affect the whole aquatic system. Therefore, it is important to limit anthropogenic inputs of nutrients. Nitrogen and phosphorus were measured as total nitrogen (TN) and total phosphorus (TP) which include all the various forms of nitrogen (e.g. nitrite, ammonia, nitrate) and phosphorus (dissolved or particulate).

Furthermore, I focused on total organic carbon (TOC) and water color. TOC includes both particulate and dissolved organic carbon whereas water color is dependent on the amount of dissolved organic carbon as well as metal ions (e.g. iron). Water color was measured as absorbance at 420 nm on a Shimadzu UV-2600 UV-VIS spectrophotometer (Swedish University of Agricultural Science, 2021).

Additionally, algal concentration (total chlorophyll, green algae, cyanobacteria, and diatoms) was measured since algal biomass is closely linked to increased nutrient input. The algal concentration was measured with an AlgaeLabAnalyser (ALA), which measures chlorophyll-a and allocates different algae classes by measuring the fluorescence of algae via stimulation with visible light of different colors, i.e. spectral fluorometry. It is the presence of different pigments in the different classes of algae, and the interaction of these pigments together with chlorophyll-a that leads to different excitation spectra for the different classes. Thus, the ALA uses these different excitation spectra as fingerprints to determine the different algal classes (bbe moldaenke, 2024).

Evaluating the Multifunctionality of wetlands

In order to assess if wetlands have a multifunctional potential, TP, TN, TOC and water color in the monthly samples from the in- and outflows of the nine wetlands in Scania were analyzed (**Paper I**). Furthermore, the nutrient load for the in- and outflows were calculated by multiplying the monthly concentrations of TP (µg/L), TN (mg/L), and TOC (mg/L) with the monthly flow (L/s). The load of TP, TN, and TOC were then converted to kg/day (kg/24h) and normalized for wetland size by dividing the load by wetland area (ha) which yielded a load compensated for wetland size (kg/ha/day). In this study, water color was not flow compensated, instead it was only normalized for wetland size, since it is a value based on the absorbance (420nm) which is dependent on the concentration and chemical composition of dissolved organic matter (DOM) and certain metal ions.

The change in TP, TN, TOC, and water color between the in- and outflow of the wetlands were expressed as removal rate and removal efficiency (Land et al., 2016), to show the reduction per unit time for the different months. Removal rate is the difference in water color and concentrations of TN, TP and TOC (flow compensated or not) between the in- and outflow of the wetlands, whereas removal efficiency is the difference in percent (%). To aid interpretation, the inflow was subtracted from the outflow which yields a negative value if there is less TN, TP, TOC, and water color in the outflow of the wetlands.

Additionally, the spectral slope ratios (S_r) were calculated. The S_r values give an insight into the dominant process (bacterial degradation or photodegradation) in degrading colored dissolved organic matter (CDOM) in the wetlands (Helms et al., 2008).

Algal growth potential and wetlands

To evaluate the potential efficiency of wetlands to reduce algal growth potential (AGP) and temporal variations in the reduction, I performed an algae culture experiment that was run monthly for 14 days over 18 months (**Paper II**). The wetland water as well as the water from Lake Ringsjön were filtered through a 50 µm mesh net prior to experimental set-up to minimize grazing pressure from zooplankton in the cultures. The filtered water from the in- or outflow of the seven wetlands was mixed in a 50:50 ratio with the lake water. The water from Lake Ringsjön served as a standardized inoculum of the phytoplankton present in the lake for each month. The cultures were then allowed to grow in a culture room at a constant temperature of 20 °C and a 12:12 light:dark cycle. Furthermore, all culture flasks were lightly agitated, ventilated, and placed randomly under the light source twice a week. Total chlorophyll, green algae and cyanobacteria were measured using the ALA in all the cultures at day 0 and day 14, with focus on green algae and cyanobacteria since they are typically the primary sources of nuisance biomass and source of toxins (mainly cyanobacteria). Thus, the AGP in each culture flask of the seven wetlands (in- and outflow, respectively) was then calculated for each period (14 days).

Effects of primary producers

After assessing the multifunctionality and AGP for wetlands, I aimed at assessing if, and how much, three common primary producers reduce nutrients and browning, in order to see if we can increase the efficiency of constructed wetlands by planting specific primary producers (**Paper III**). *Elodea*, *Myriophyllum* and a filamentous algae were selected for this study and constitute the treatments, with 7 replicates of each. The experiment was set up in a greenhouse. Plexiglas cylinders containing a mix of 50:50 nutrient rich: high water color wetland water were set up and each cylinder contained either *Elodea*, *Myriophyllum* or filamentous algae. Water samples (TN, TP, TOC, and water color) were collected from the cylinders at the start of the experiment and at the end, after four weeks. The cylinders were checked three times a week to ensure that the primary producers were growing, and the cylinders were then lightly spun around to mix the water. The difference in TP, TN, TOC, and water color between start and end of the experiment, was used as a measure of the reduction by each primary producer. Furthermore, the reduction was normalized by the dry weight of the primary producer, yielding reduction per gram dry weight for the different parameters.

Assessment of algal growth potential in water from different macrophytes

To further investigate the results of **Paper II**, I aimed to estimate how the AGP would differ for the total phytoplankton community (inferred from total chlorophyll measures), green algae, cyanobacteria, and diatoms in water after *Elodea*, *Myriophyllum*, and filamentous algae had grown for four weeks (**Paper III**). Therefore, an algae culture experiment was set up at the start (no primary producers) and end of the experiment (after four weeks with primary producers growing in the water), with a slightly modified method. At each time point, water from the cylinders was mixed with water from Lake Ringsjön in a 50:50 mix, and placed in an algal culture room with a 12h:12h light:dark cycle and a constant temperature of 20°C. Twice a week the culture flasks were agitated and ventilated, as well as systematically re-placed for optimal light availability. The concentration of total chlorophyll, green algae, cyanobacteria, and diatoms was measured using the ALA at day 0 and day 14, allowing the assessment of AGP in the water.

Scenarios and future projections

I aimed to provide future projections until 2040 for the potential of wetlands to mitigate eutrophication and brownification of a recipient lake. Thus, for this study three scenarios were modelled: no additional wetlands, 20% efficient wetlands and 20% inefficient wetlands (**Paper IV**). 20% constitutes the amount of water led through wetlands before entering the lake, a decrease or increase in the percentage will affect the scenarios provided. Therefore, the estimates should be viewed as an intellectual experiment which should be adjusted to any specific catchment.

For this study, Lake Bolmen (56°51'25.1"N 13°40'51.7"E) was used as an example as long-term water quality data is available for the lake, measured yearly since 1966. Lake Bolmen is situated in Småland, southern Sweden and has a surface area of 184 km^2. The maximum depth of the lake is 36 meters, with an average depth of 5.4 meters. The theoretical water residence time is approximately 1.6 years but has been estimated to vary with the inflow to the lake. The catchment area is 1650 km^2 and consists of approximately 64% forest, and 9% wetlands and only 9% agriculture in the catchment.

The removal efficiency from the eleven monthly monitored wetlands were used to calculate the ±95% confidence intervals (CI) of average TP and water color retention rates (% of inflow), which constitutes the efficient and inefficient wetland scenarios. The ±95% CIs for the eleven wetlands were used instead of extreme values of individual wetlands, where the lower 95% CI was used as the efficient retention scenario and the upper 95% CI was used as the inefficient scenario.

Additionally, the euphotic zone for a given water color value in the lake was calculated leading to a shallower euphotic zone with a higher water color (**Paper IV**). Based on this, the euphotic zone changes over time in relation to water color for the three different scenarios in the study, shown as percent water volume in the euphotic zone for Lake Bolmen. It should be noted that water color is not the only factor affecting the penetration of light through the water, but since chlorophyll concentrations in Lake Bolmen are very low, in this case I considered its effect to be negligible. However, chlorophyll concentrations will have to be considered if a similar approach is used in a more eutrophic lake.

Main Findings

Wetlands as a multifunctional mitigation effort

With the ongoing increase in brownification and eutrophication I aimed at finding out if there is a potential to use wetlands as local-scale multifunctional tools to mitigate brownification and eutrophication (**Paper I**). I found that there was a high variability in the efficiency of the wetlands in reducing phosphorus, nitrogen, TOC and water color, both temporally and among the wetlands. My results showed that some wetlands were able to reduce all water quality parameters during some of the months, whereas they only reduced a few during other months. There were also wetlands that rarely had a reduction for TP, TN, TOC, or water color. Furthermore, I found that some wetlands did have a net reduction of phosphorus, nitrogen, water color and TOC simultaneously (Table 1), but there were also wetlands in which this was not the case. These wetlands instead showed a net reduction in either TN, TP, TOC or water color. My data showed that some wetlands had a positive net removal rate, i.e. an increase in nutrients, organic carbon and water color instead. However, there was temporal variation, as these wetlands also showed a reduction during parts of the sampling period. The wetlands that had a reduction in all four parameters were classified as “generalist wetlands”, whereas the ones that only reduced one or two parameters were classified as “specialist wetlands”. Generally, when the specialists were efficient in reducing nutrients, they were not efficient in reducing water color, and *vice versa*. Generalist wetlands, however, did reduce all four parameters but with a lower efficiency than the specialist wetlands.

Table 1. The nine wetlands showed a difference in the removal rate of nitrogen, phosphorus, total organic carbon and water color. There were both specialist and generalist wetlands. A net reduction of the parameter over 18 months is marked with green (-), whereas a net increase is marked in light grey (+).

Wetland	Nitrogen	Phosphorus	Total organic carbon	Water color
Fjelkner	-	-	-	+
Gårdstånga	+	+	+	+
Hinnedal	-	-	-	-
Ljungen	+	+	-	+
Lommarp	-	-	-	-
Perstorp	+	+	+	+
Toarp	+	+	+	-
Venestad	+	+	+	+
Viderup	+	+	+	+

There was high temporal and spatial variations in the efficiency of wetlands to reduce TN, TP, TOC, and water color, with some wetlands showing an efficiency in reducing the parameters during winter as well (Figure 7), although the reduction efficiency was generally higher during summer. There were wetlands that showed a reduction in TP, TN and TOC during winter, with some wetlands also showing a reduction in water color. Furthermore, wetlands that had a continuous flow during all seasons were generally more efficient in reducing nutrients, TOC and/or water color. The wetlands that showed an inefficiency in the reduction of nitrogen, phosphorus, organic carbon and water color, generally had no water flow during longer periods of the year. Therefore a continuous water flow seem to be of importance for the reduction efficiency of the wetlands. Additionally, the wetlands with peat in their catchment area were more unpredictable in their reduction than wetlands with sand, gravel, or silt (**Paper I**). They were also, in general, less efficient in the reduction of phosphorus, nitrogen, total organic carbon and water color and showed a higher variation in the reduction efficiency. Photodegradation was, in general, the dominating process for degradation of colored dissolved organic matter (CDOM). However, in one of the wetlands, microbial degradation was found to be the dominant process.

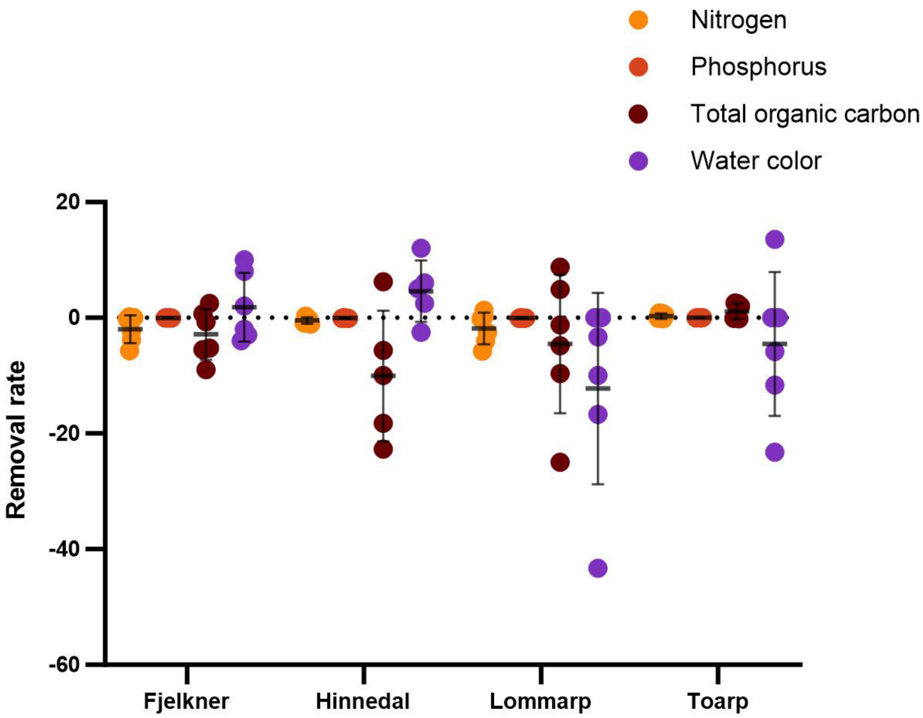

Figure 7. Some wetlands showed a net retention in removal rate during the winter season (October – March) for nitrogen (kg/day/ha), phosphorus (kg/day/ha), total organic carbon (kg/day/ha) as well as for water color (mgPt/L/ha). Negative values denote a reduction whereas positive values denote an increase. The net retention is visualized by mean values ±SD, with individual values as dots. Four of the wetlands with a water flow during the majority of the months are used as examples.

Wetlands as managements tools to reduce algal growth potential

Eutrophication leads to an increased risk of algal blooms in aquatic systems, affecting several ecosystem services provided. Therefore, I aimed to answer the question if wetlands could be used as a local scale management tool to counter act algal blooms by decreasing the algal growth potential in adjacent waters. I found that there was a high potential for wetlands to reduce the AGP, even though there were temporal variations both within and between wetlands (**Paper II**). For example, I could show that there was a reduction in AGP for green algae (Figure 8). Additionally, the wetlands that contained a lot of pasturelands and/or agriculture in the catchment often had higher variation in AGP over the year, as seen in e.g. Fjelkner, Gårdstånga and Viderup (**Paper II**).

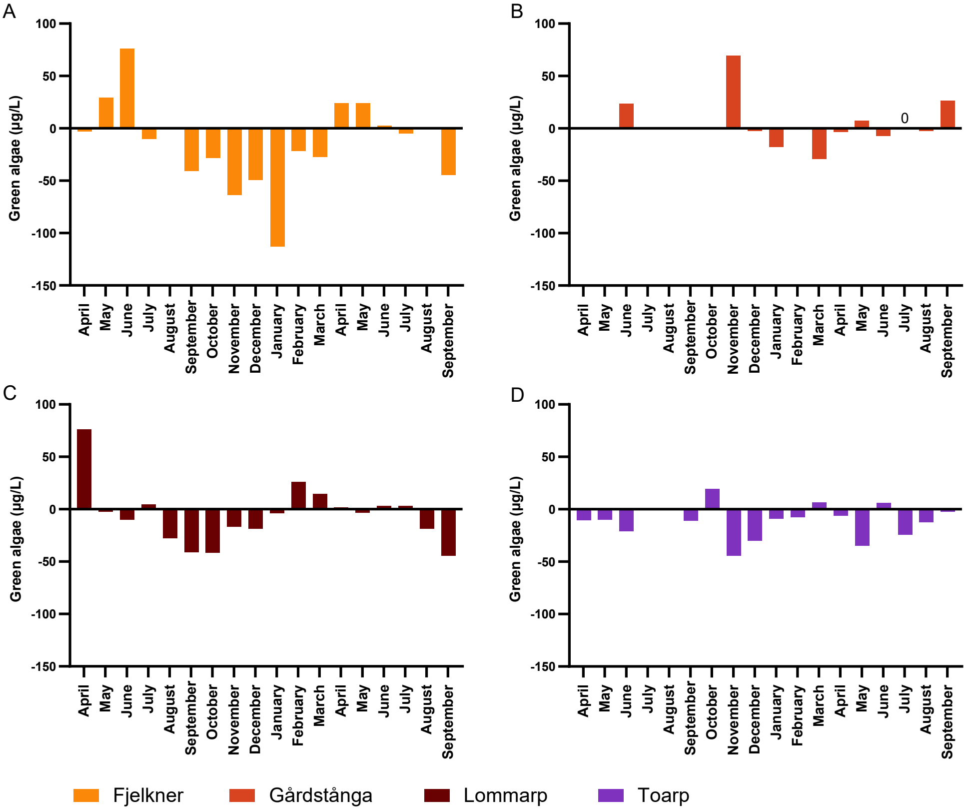

Figure 8. Algal growth potential for green algae (µg/L) in the four wetlands Fjelkner (A), Gårdstånga (B), Lommarp (C), and Toarp (D). Negative values denotes that the algae grew better in the water from the inflow of the wetlands, whereas positive values denotes that they grew better in the water from the outflow. Wetlands chosen as examples are wetlands that had a water flow during the majority of the months sampled, from April 2020 until September 2021. When marked with a 0, it denotes that there were no difference in the algal growth potential between the in- and outflow. Furthermore, when values are missing it means that the wetlands were either frozen to the bottom or dried up.

Furthermore, AGP for cyanobacteria was generally reduced as the water flowed through a wetland (Figure 9). My data showed that there was a temporal variation in the AGP within wetlands for different phytoplankton taxa, i.e. there could be a reduction in the AGP for cyanobacteria but not for green algae (e.g. Fjelkner in September 2021, Gårdstånga in June and September 2021, Lommarp in April 2020, Toarp in October 2020, and July 2021) or *vice versa*. Furthermore, the efficiency in AGP reduction for green algae and cyanobacteria varied among wetlands, with some wetlands showing a higher efficiency in reducing the growth of green algae whereas others reduced cyanobacteria (**Paper II**). However, there were less cyanobacteria biomass than green algae in the wetlands and there were months where no cyanobacteria could be detected in the wetlands.

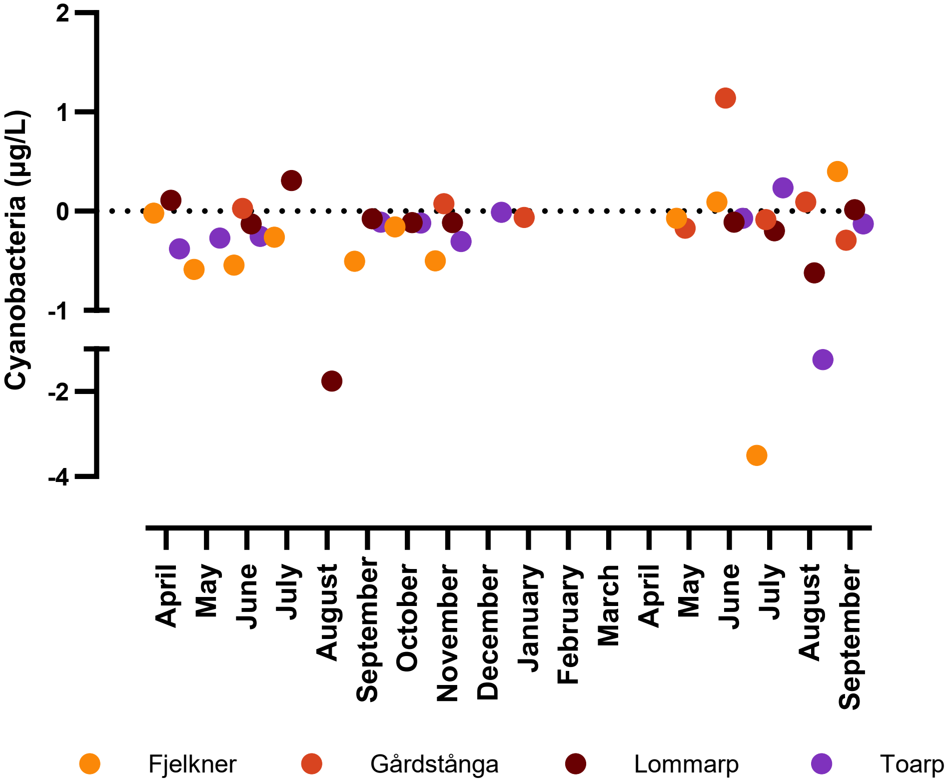

Figure 9. Algal growth potential for cyanobacteria (µg/L) in the four wetlands Fjelkner, Gårdstånga, Lommarp, and Toarp. Negative values denotes that the cyanobacteria grew better in the water from the inflow of the wetlands, whereas positive values denotes that they grew better in the water from the outflow. Wetlands chosen as examples are wetlands that had a water flow during the majority of the months sampled, from April 2020 until September 2021. In case of missing values, it denotes that there either was no detected cyanobacteria for that month, or the wetlands were either frozen to the bottom or dried up.

Effects of primary producers

There is often a large biodiversity of primary producers growing in constructed wetlands, including different taxa of filamentous algae and submerged macrophytes.

Different taxa often display different functional traits in ecosystems (discussed e.g. in Zhang et al., 2018), and there is a potential that different species of primary producers also vary in their efficiency to reduce phosphorous, nitrogen, TOC and water color. Thus, the macrophyte communities might have an influence on wetland efficiency in reduction of TN, TP, TOC and water color as well as algal growth potential (AGP) in downstream aquatic systems, i.e. potentially reducing phytoplankton blooms. Hence, planting, or in other ways favoring, specific primary producers, might be a measure to increase the efficiency of constructed wetlands to reduce nutrients, TOC, and water color. To examine this, I set up a microcosm experiment to estimate the efficiency of three common wetland primary producers (*Elodea*, *Myriophyllum* and filamentous algae) in reducing phosphorus, nitrogen, TOC and water color.

My results showed that the three primary producers varied in their efficiency in reducing nitrogen, phosphorus, TOC and water color. *Elodea* was efficient in reducing all four parameters, whereas *Myriophyllum* and filamentous algae were efficient in reducing nitrogen, phosphorus and water color (**Paper III**). However, there was an increase in TOC in replicates in which filamentous algae and *Myriophyllum* had grown. The variation in primary producer efficiency suggests that a high diversity of primary producers in a constructed wetland is likely beneficial in order to raise the efficiency in reducing phosphorus, nitrogen, TOC and water color.

To further evaluate the potential effects of macrophytes on phytoplankton AGP, I designed an experiment to compare the growth of green algae, cyanobacteria and diatoms that were either exposed to water where neither filamentous algae, *Elodea* or *Myriophyllum* had grown vs. water where the different primary producers had grown for four weeks (**Paper III**). My results showed that cyanobacterial and diatom AGP was reduced when cultured in water in which *Elodea* or *Myriophyllum* had been growing previously. Green algae AGP generally decreased when grown in water where *Elodea* had been present but increased when cultured in water in which *Myriophyllum* had been growing previously (Figure 10). All three phytoplankton groups increased their AGP when cultured in water in which filamentous algae had been growing previously, compared to when cultured in water where no macroflora had previously grown. To summarize, AGP for all three phytoplankton groups decreased when *Elodea* had been present in the water but increased if cultured in water where filamentous algae had been growing. The effect of *Myriophyllum* on phytoplankton AGP varied between the taxa, with green algae showing a positive AGP, while cyanobacteria and diatoms had a negative AGP.

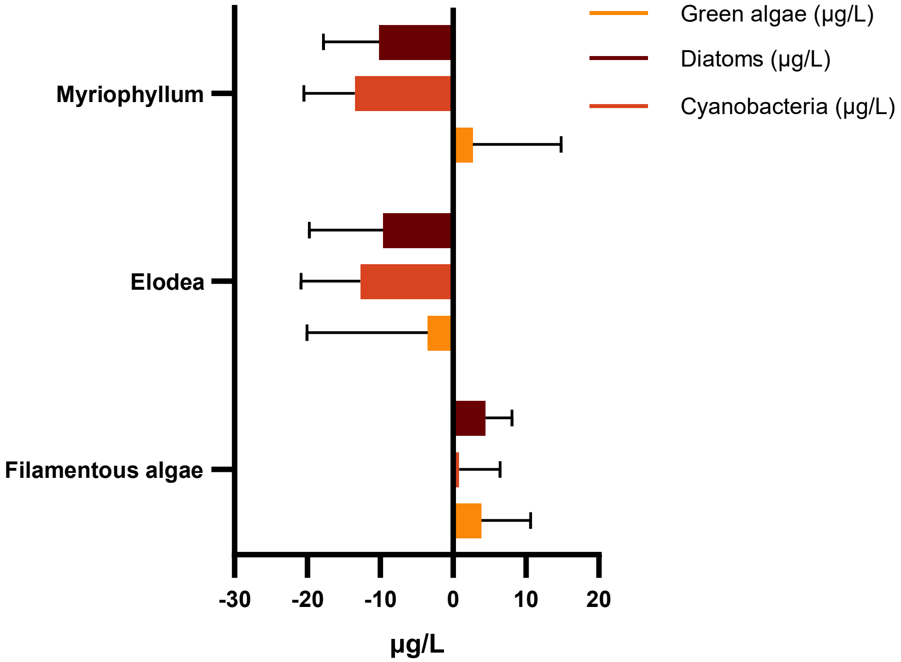

Figure 10. Difference in algal growth potential (AGP) for green algae, cyanobacteria and diatoms in cultures grown in water where no filamentous algae, *Elodea*, or *Myriophyllum* had grown subtracted from AGP in cultures grown in water where the previosly mentioned primary producers had been growing for four weeks (mean values ±SD).

Scenarios for the future

Wetlands have the potential to mitigate as well as expedite eutrophication and brownification depending on their efficiency (**Paper I**). Thus, in a future perspective, it is of importance to construct wetlands that are efficient for the ecosystem service intended. If an inefficient wetland is constructed in the catchment area of a lake, there might be an increase in nutrient concentrations as well as water color of the water flowing out from the wetland to downstream systems. The increased water color will in turn decrease the euphotic zone of downstream lakes – potentially leading to a change in the trophic web of the lake (**Paper IV**). If the wetlands instead are efficient in reducing nutrients and water color, the euphotic zone will increase (Figure 11) and with the reduction in nutrients the risk of algal blooms will decrease.

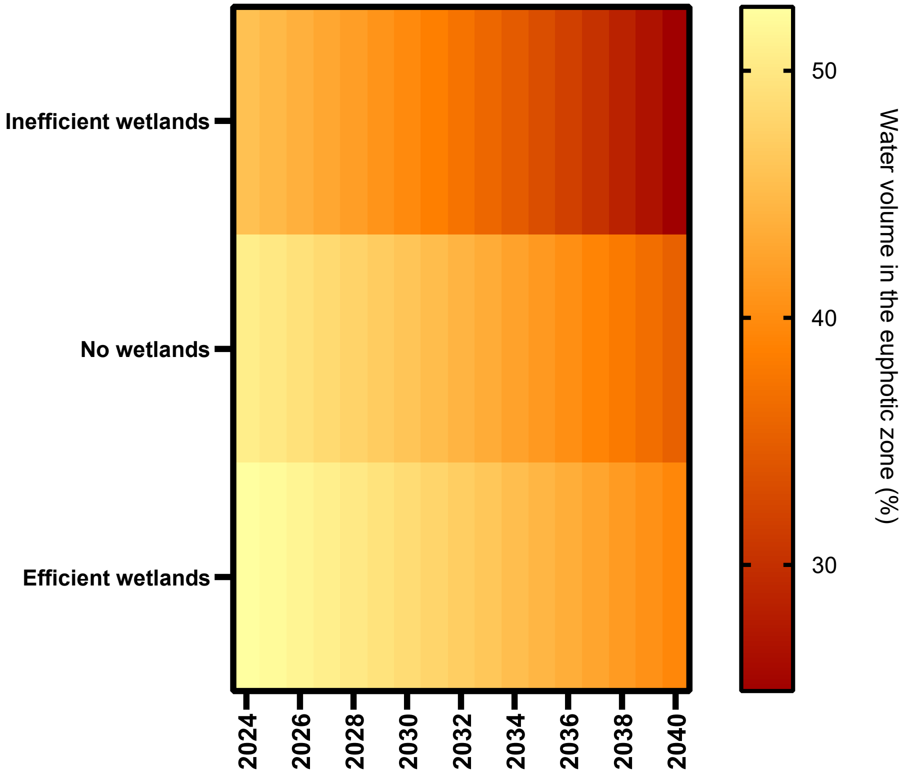

Figure 11. Change over time in the water volume (%) of the lake in the euphotic zone, i.e. the zone where photosynthesis can occur, from 2024 until 2040 for the three scenarios where water either pass through no wetlands, efficient wetlands or inefficient wetlands in the catchment area before reaching the downstream lake, in this case our study object, Lake Bolmen, southern Sweden.

The construction of wetlands in the catchment area of the lake may not counteract the increasing trends of phosphorus and water color. However, with the construction of efficient wetlands there will be a considerable mitigation that will consist of time (Figure 12) before we would reach the same level as without efficient wetlands in the catchment area of the lake (**Paper IV**). The increase in nutrients and water color, could be slowed, and the time could be used to implement additional restoration measures or other solutions to counteract and potentially even reverse the current increasing trend. Thus, it would be a potential delay of eutrophication and brownification of aquatic systems.

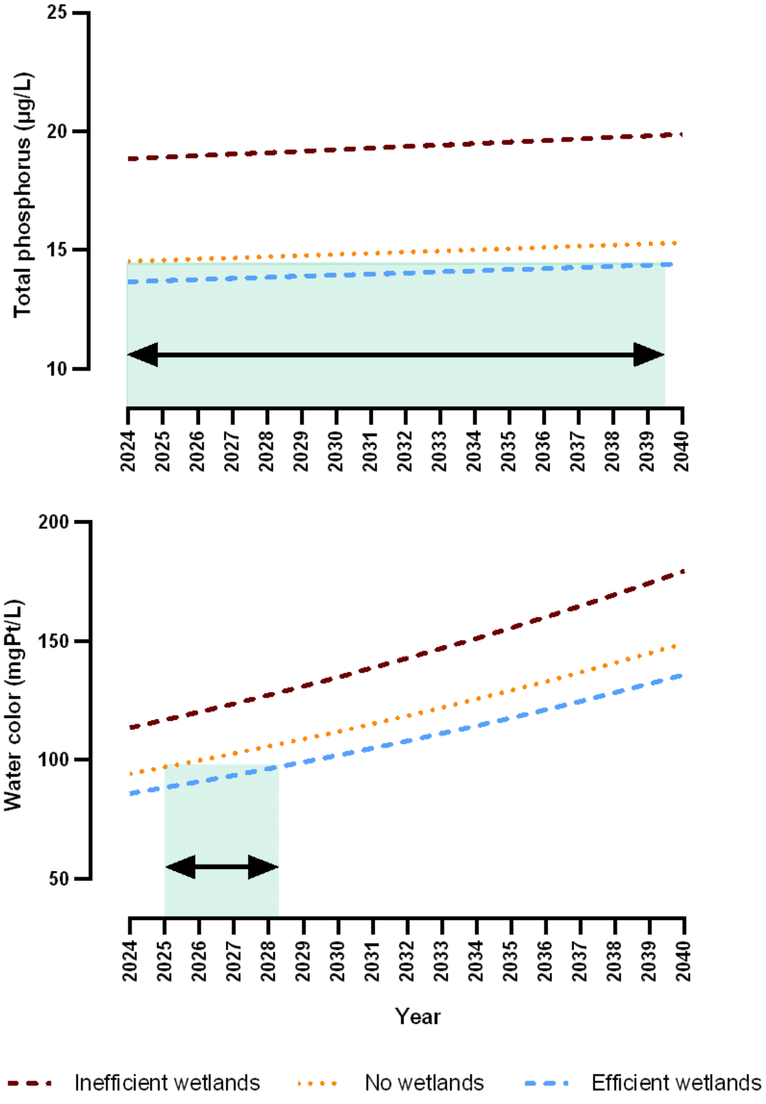

Figure 12. Changes over time based on the three future scenarios for total phosphorus (A) and water color (B) in a lake for the years 2024 until 2040. The three scenarios are water running through no wetlands (yellow dotted line), efficient wetlands (lower 95% CI, blue dashed line) or inefficient wetlands (upper 95 CI, red dashed line) before entering a lake. Additionally, with efficient wetlands in the catchment area of a lake there will be a gain in time (green boxes with black arrows) before phosphorus and water color will be on the same level as without any wetlands in the catchment area.

Conclusions and future perspectives

Wetlands have been shown to provide several ecosystem services (see e.g. Ferreira et al., 2023, García-García et al., 2016, Haddis et al., 2020, Land et al., 2016, Lee et al., 2009, Lu et al., 2009, Mitsch et al., 2015), but the multifunctionality of wetlands is currently being debated, and several studies have highlighted the issues with trade-offs in ecosystem services provided by wetlands (e.g. Ballantine et al., 2015, Bledsoe et al., 2020, Hambäck et al., 2023). Furthermore, wetlands are often considered to increase water color and TOC, especially when situated on peatland (Canham et al., 2004, Gergel et al., 1999, Lundin et al., 2017, Mattsson et al., 2009, Nieminen et al., 2021). In this thesis I show that wetlands have the potential to mitigate both brownification and eutrophication, as well as a risk of expediting them (**Paper I** and **IV**). Additionally, there is a potential for multifunctionality in some, but not all, wetlands with regards to reduction of nitrogen, phosphorus, total organic carbon and water color. Thus, it is possible that wetlands can have the capacity for multifunctionality, but there are no guarantees. The studies in this thesis have shown that there is high variation in wetland efficiency with regards to nutrient, TOC and water color reduction, and this variation cannot be fully explained by seasonal variations, wetland design or the catchment area.

In the studies performed within my thesis work, I show that wetlands that were less efficient in the reduction of phosphorus, nitrogen, TOC and water color were those that dried up during summer drought and were without water for a longer period. Previous studies have shown that nutrients can leach from the sediments during rewetting after a drought (e.g. Macek et al., 2020, McComb and Qiu, 1998, Song et al., 2007, Venterink et al., 2002), highlighting the importance of designing wetlands so that they have a constant water flow during most parts of the year, and thus counteract drought. This might be of considerable importance in a climate change perspective, when dry seasons might become drier and wet seasons wetter (Mallakpour et al., 2018). Wetlands with a continuous flow would have a higher possibility to retain the ecosystem services in a future climate warming context. By designing constructed wetlands in the landscape so that they have a continuous water flow, the water is slowed down, which would enable in-water processes to have sufficient time to be performed. This seems to be of importance during all seasons, since some wetlands were efficient in reducing phosphorus, nitrogen, TOC and water color also during the winter season, although the efficiency generally was higher during summer (**Paper I**). In a broader context, the efficiency of the wetlands in the landscape can be expected to increase in a climate change perspective, since temperatures are predicted to increase (Thuiller, 2007), which might suggest that the importance of wetlands in the landscape will grow in the future.

The wetlands in my study showed a considerable potential in reducing algal growth potential (AGP) with regards to both green algae and cyanobacteria (**Paper II**). This suggests that wetlands can be used as local-scale tools to reduce algal blooms in adjacent waters. When water from a catchment flows through a wetland located upstream of a lake, the potential for algal growth in the lake is often significantly reduced. This is of considerable importance for the water quality and ecosystem services provided by downstream lakes, rivers, and coastal areas. It also provides incentives for restoring and constructing wetlands in the landscape. Additionally, in a climate change context with warmer temperatures causing prolonged phytoplankton growth periods, as well as higher frequency and intensity of phytoplankton blooms (Dore, 2005, Thuiller, 2007, Trenberth, 2011), the potential of wetlands to reduce algal growth potential may become even more important. Furthermore, the importance of wetlands to continue to act as nutrient sinks in the landscape in the face of climate change has previously been highlighted (e.g. Griffiths and Mitsch, 2020).

In aquatic ecosystems, macrophytes and filamentous algae are important players, as they provide substrate for microorganisms, hiding places for young fish and macroinvertebrates, as well as taking up nutrients from the water column and sediment (Dvořák, 1996, Gagnon et al., 2007, Gonzalez Sagrario and Balseiro, 2010, Rejmankova, 2011). In the study I performed, the macrophytes varied in their efficiency in reduction of nutrients, TOC and water color (**Paper III**). Thus, the macroflora in wetlands might influence both wetland efficiency and the likelihood of multifunctionality. By performing microcosm experiments using three primary producers (in monoculture) growing in wetland water, I could show that efficiency of nutrient, TOC and water color reduction varied among *Elodea*, *Myriophyllum* and filamentous algae. This suggests that a high diversity of macrophytes and filamentous algae will increase the efficiency of the wetlands more than a monoculture. With a higher diversity in taxa, the primary producers can potentially complement one another and thus have positive influences on wetland efficiency, as shown by e.g. Engelhardt and Ritchie (2001). However, wetlands with low-diversity vegetation, e.g. dominated by tall emergent vegetation, have previously been shown to also increase the efficiency in nitrogen retention (Weisner and Thiere, 2010). Moreover, macrophytes may also inhibit cyanobacterial growth e.g. through allelopathy or high nutrient utilization (Mohamed, 2017, Nakai et al., 2012) although there is an inconsistency in the effects of macrophytes (Maredová et al., 2021), indicating that not all macrophytes may have the potential to decrease cyanobacterial growth. However, with macrophytes and filamentous algae growing in the wetlands, the AGP for cyanobacteria will likely decrease (**Paper III**). Thus, a wetland maintaining a widespread macroflora could potentially be a mitigation effort to counteract cyanobacterial blooms.

The results of my studies show that the construction of wetlands might be beneficial to ecosystems as well as society, with their ability to reduce phosphorus, nitrogen, TOC and water color, as well as the AGP of different algae taxa. The construction of efficient wetlands in the catchment area of a lake can thus mitigate the present trends of increased nutrient concentration and water color in aquatic systems. However, with restoration measures at a local scale the manifestation of the mitigation would be in time gained, i.e. the increasing trend would slow down, and it will take a longer time for the phosphorus concentration and water color to reach the same level as without wetlands in the catchment. Thus, there would be a possible delay in the eutrophication and brownification. Additionally, increased eutrophication and brownification might have negative impacts on the depth of the euphotic zone in lakes, i.e. the clarity of the water. A decrease in the euphotic zone will influence the primary production in the lake since less light will reach down in the water column, which will affect macrophytes, periphyton as well as phytoplankton (Berthold and Paar, 2021, Vasconcelos et al., 2016). Thus, while it is important to have the benefits of constructing or restoring wetlands in mind, the potential risks should also be considered (**Paper IV**). Surface waters, e.g. lakes and rivers, are the main drinking water sources worldwide, and the surrounding catchment will often affect the quality of drinking water sources or reservoirs, for example by the amount of inorganic or organic matter contained in the water (Kritzberg et al., 2020, Matilainen et al., 2011). The higher water color and TP concentration in a lake used as a drinking water reservoir, the more treatment the water has to go through in order to produce healthy drinking water. With more treatment there will be higher costs and potential health hazards in the form of chemicals used for water treatment. This highlights the importance of monitoring the wetlands after construction to see if the wetlands are performing the intended ecosystem function.

The decisions to restore or construct wetlands as mitigation efforts to increase biodiversity or nutrient reduction are often made at the local scale, for individual wetland projects (Thorslund et al., 2017). The complexity of the large-scale system is often simplified and the connectivity, between for example surface water and ground water, overlooked (Borer et al., 2014). Additionally, when ecological restoration measures in the landscape have been performed there is often a lack of monitoring afterwards to see whether the restoration has had the desired effect or not, and if the wetland is performing the intended function (Benayas et al., 2009, Browne et al., 2018, Wortley et al., 2013). Ecological restoration measures are not necessarily without risks, which is why proper monitoring of the function after restoration should be advised. The restoration and construction of wetlands hold a potential in mitigating eutrophication and brownification (**Paper I**), but there are still knowledge gaps in the ideal placement and design to make sure the function of the wetland perform the ecosystem service intended for the area where it is restored or constructed. Research is needed to assess the design and placement of generalist wetlands in order to reduce risk of constructing inefficient wetlands. Furthermore, there may also be advantages to construct several specialist wetlands in connectivity to one another, which could complement one another and increase the efficiency, as well as slowing down the water in the landscape and allowing for more in-system processes to take place. The potential to use several specialist wetlands in the same catchment should therefore be investigated, since there might be a potential of the wetlands to be used as complements to each other, thus increasing the efficiency of the overall system (as suggested by e.g. Hambäck et al., 2023). Additionally, there should be a focus on minimizing the risks by identifying which design, placement, and size constructed wetlands should have in order to perform the function intended and for the highest efficiency as well as monitoring wetlands after construction.

To summarize, there is a multifunctional capacity amongst some wetlands, but not all. Generalist wetlands have the potential to mitigate eutrophication and brownification in aquatic systems and thus function as an in-system multifunctional tool in the landscape (**Paper I**). There is also a potential to use the wetlands as a local-scale tool to mitigate algal blooms, since they reduce the AGP for both green algae and cyanobacteria (**Paper II**). There may also be a potential in increasing the efficiency in constructed wetlands with the establishment of macrophytes, where a variation in macrophyte and filamentous algae taxa may be preferred (**Paper III**). Additionally, the presence of macrophytes and filamentous algae may reduce the growth potential of cyanobacteria (**Paper III**). The potential of wetlands to reduce nutrients, TOC, water color and AGP is at present crucial given the increasing amounts of organic and inorganic substances reaching aquatic ecosystems. Furthermore, efficient wetlands will provide us with time for counteracting eutrophication and brownification either through further research on mitigation efforts or by in-system restoration measure, as well as slow down the decrease of the euphotic zone in receiving lake waters (**Paper IV**). Besides the main conclusions in this thesis, the research led to several unresolved questions. For example, the land-use and soil composition in the catchment area as well as the design and placement varied between the generalist wetlands. Additionally, the dominant process for degradation of CDOM varied between the generalist wetlands with photodegradation being the dominant process in one, whilst bacterial degradation was the dominant process in the other (determined through a calculation of the spectral slope ratio (Helms et al., 2008)). Furthermore, even though peat often is linked to an increase in DOC and water color in aquatic systems (see e.g. Mattsson et al., 2009, Nieminen et al., 2021), one of the generalist wetlands contained the highest percentage of peat in its catchment area (9%). Interestingly, the wetland with the highest efficiency in reduction of water color also had a high amount of peat in its catchment area (**Paper I**).

Therefore, I believe it is of importance to understand the possible sources and sinks of nutrients and organic matter into the wetlands as well as the design and placement best suited for mitigation. This knowledge is important to predict the potential usage of constructed wetlands in the landscape to mitigate undesirable effects on aquatic systems. In order to use wetlands as mitigation efforts for eutrophication and brownification, it is of importance that acquired knowledge reaches the stakeholders and wetland managers as well.

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