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Review

Impact of climate change on wetland ecosystems: A critical review of experimental wetlands

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ABSTRACT

Climate change is identified as a major threat to wetlands. Altered hydrology and rising temperature can change the biogeochemistry and function of a wetland to the degree that some important services might be turned into disservices. This means that they will, for example, no longer provide a water purification service and adversely they may start to decompose and release nutrients to the surface water. Moreover, a higher rate of decomposition than primary production (photosynthesis) may lead to a shift of their function from being a sink of carbon to a source. This review paper assesses the potential response of natural wetlands (peatlands) and constructed wetlands to climate change in terms of gas emission and nutrients release. In addition, the impact of key climatic factors such as temperature and water availability on wetlands has been reviewed. The authors identified the methodological gaps and weaknesses in the literature and then introduced a new framework for conducting a comprehensive mesocosm experiment to address the existing gaps in literature to support future climate change research on wetland ecosystems. In the future, higher temperatures resulting in drought might shift the role of both constructed wetland and peatland from a sink to a source of carbon. However, higher temperatures accompanied by more precipitation can promote photosynthesis to a degree that might exceed the respiration and maintain the carbon sink role of the wetland. There might be a critical water level at which the wetland can preserve most of its services. In order to find that level, a study of the key factors of climate change and their interactions using an appropriate experimental method is necessary. Some contradictory results of past experiments can be associated with different methodologies, designs, time periods, climates, and natural variability. Hence a long-term simulation of climate change for wetlands according to the proposed framework is recommended. This framework provides relatively more accurate and realistic simulations, valid comparative results, comprehensive understanding and supports coordination between researchers. This can help to find a sustainable management strategy for wetlands to be resilient to climate change.

1. Introduction

A wetland is an area with a water table, at, near or above the land surface either seasonally or permanently throughout the year. Wetlands exist globally in every country (except Antarctica) and also in all different types of climates. Depending on different definitions and estimates, they cover only about 5–8% of the world's land surface, but comprise 20–30% of the world's carbon pool (2500 Pg) (Mitsch et al., 2013). Compared to all terrestrial ecosystems, wetlands have the highest carbon density, which makes them play an important role in global biogeochemical and carbon cycles and climate change (Kayranli et al., 2010). Wetlands are ecosystems that are vital both for humankind and nature. They are commonly the most valuable ecosystems in a landscape providing many beneficial ecosystem services (Table 1). Among all wetland services, water purification, flood control and climate change mitigation are the most important services for the human communities (Mitsch and Gosselink, 2007; Scholz, 2015).

Since the 1950s, global climate systems have shown an unprecedented change. The earth's surface has experienced warmer climate for

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Notation

AM	air moisture
BOD	biochemical oxygen demand
CH4	methane
CCV	controlled climate variable
CO2	carbon dioxide
COD	chemical oxygen demand
DO	dissolved oxygen
DOC	dissolved oxygen demand
H	humidity
N2	dinitrogen
P	precipitation
PAR	photosynthetically active radiation
R	radiation
RCM	regional climate model
RCP	representative concentration pathway
SCV	simulated climate variable
SM	soil moisture
ST	soil temperature
T	temperature
TOD	total oxygen demand
WL	water level

each of the past three decades successively. Between 1880 and 2012, the land and ocean surface temperatures have increased by approximately 0.85 °C (range between 0.65 and 1.06 °C) according to Pachauri et al. (2014).

Wetlands play an important role in climate change, because of their capacity to modulate atmospheric concentrations of greenhouse gases such as methane, carbon dioxide and nitrous oxide, which are dominant greenhouse gases contributing to about 60%, 20% and 6% of the global warming potential, respectively (IPCC, 2007).

There are many different factors (biotic and abiotic) that influence the function of wetlands. Climate change has been identified as a major threat to wetlands. It can influence a wetland ecosystem by increasing temperature and also by changing hydrological patterns, which in turn can alter the biogeochemistry of the ecosystem (Erwin, 2009; Stewart et al., 2013). Wetlands have been identified as one of the most productive ecosystem types; i.e. through photosynthesis, they can actively sequester and accumulate carbon as plant biomass or organic matter in soil. The waterlogged condition of wetlands causes inefficient decomposition that exceeds the rate of production. This anoxic state results in a vast amount of carbon accumulation in wetlands, which makes them a sink of carbon (Laiho, 2006).

Since wetlands are often located in a transition zone between an aquatic and a terrestrial ecosystem, their hydrological fluctuation is inevitable. Although they have been known to be resilient to change in general, they may still be highly susceptible to hydrological changes, especially when this change is exacerbated by other sources of disturbance such as climate change, pollution, urbanization and changes in land use (IPCC, 2007).

Climate change can affect wetlands by direct and indirect effects of rising temperature, changes in rainfall intensity and frequency, extreme climatic events such as drought, flooding and the frequency of storms. Altered hydrology and rising temperature can change the biogeochemistry and function of the wetland to the degree that some important services might be turned into disservices. This means that they will no longer provide a water purification service and adversely they may start to decompose and release nutrients to the surface water causing problems such as eutrophication, acidification and brownification in the water bodies (Roulet and Moore, 2006; Stets and Cotner, 2008; Corman et al., 2018).

A higher rate of decomposition than production (photosynthesis) in a wetland as a result of climate change might result in a shift from a sink to a source of carbon; i.e., carbon dioxide and methane emissions to the atmosphere (Laiho, 2006; Flanagan and Syed, 2011). With warmer conditions, more nitrous oxide emissions from wetlands might happen due to higher microbial activity and higher nitrification and denitrification rate as well (Huang et al., 2013; de Klein and van der Werf, 2014). To analyse all of these changes in a wetland, a comprehensive monitoring system is needed to understand how the system responds to the stresses and how they can be adapted to future climate change.

The study of climate change impact on a wetland environment is one of the most critical challenges scientists are facing. According to Stewart et al. (2013), the impact of climate change on a wetland system can be predicted by using various approaches such as modelling, field survey and experiments. A mesocosm experiment is an approach that can be used for climate change studies on ecosystems. This scale of experiment can provide a link between microcosm (which is smaller and of limited realism) and the natural system, which is of high complexity resulting in difficulties to identify processes and interactions. Moreover, mesocoms allow for experiments to be conducted with replication at costs considerably lower than field studies (Kangas and Adey, 1996). Mesocosm experiments under controlled conditions provide scientists with more reliable and consistent findings than field experiments. Isolating the impact of variables from other confounding variables (i.e. those that influence both the dependent variables and independent variables, causing spurious associations) is almost impossible in the field, while mescosm experiment often provide this possibility. Thus in field experiments, it is difficult to attribute an ecosystem response to a particular factor (Stewart et al., 2013).

It is not clear how wetlands, as key contributors to global greenhouse gas budgets, will respond to climate change. There is uncertainty as to whether wetland functions are positive or negative to climate change. It is not also clear which climate factors are more important for changing the role of wetlands from sink to source in terms of greenhouse gases.

Finding a sustainable management strategy that addresses the negative responses of wetlands to climate change is challenging. Understanding the response of wetlands to climate change requires primarily a perception of the complexity of wetlands and the interaction of parameters affecting this ecosystem. In order to develop a comprehensive understanding of the response of wetlands to climate change and also to identify effective management actions to enhance wetland resilience in the catchment landscape, an appropriate methodology needs to be identified. This methodology will help researchers to resolve controversial discussions and reduce uncertainties regarding the effect of climate change on wetlands and the management strategies.

In this review paper the authors assess the potential response of natural wetlands (peatlands) and constructed wetlands to climate change in terms of gas emission and nutrient release. In addition, the impact of key climatic factors such as temperature and water availability on wetlands has been reviewed. The authors identified the methodological gaps and weaknesses in the literature and then introduced a new framework for conducting a comprehensive mesocosm experiment to address the existing gaps in literature to support future climate change research on wetland ecosystems.

1.1. *Aim of the review and method*

This review paper aims to assess the possible responses of a wetland system to climate change. The aim is achieved by the following objectives: (a) investigating the potential response of a natural wetland, peatland and constructed wetland to climate change in terms of gas

Table 1
Overview of wetland ecosystem benefits.

Wetland values in the landscapes			
Provisioning	Regulating	Cultural	Supporting
- Food: fish production, wildlife and fruits (Scholz and Lee, 2005)	- Regulation of climate: greenhouse gas sink, altering local and regional temperature and precipitation retention (Kayranli et al., 2010; Mitch et al., 2013)	- Inspirational and spiritual: source for inspiration and spiritual functions for various cultures (MEA, 2005)	- Soil formation: accumulation of organic matter and retention of sediment (Kadlec and Wallace, 2008; Almuktar et al., 2018)
- Freshwater: domestic water retention and storage, agricultural use and industrial use (Almuktar et al., 2018)	- Regulation of water hydrology: recharge of groundwater (Mitch and Gosselink, 2007)	- Aesthetic: source of beauty and aesthetic values with respect to wetland characteristics (Clarkson et al., 2013)	- Cycling of nutrients: nutrient acquisition, storage, recycling and processing (Scholz and Hedmark, 2010)
- Fuel and fibres: log production, wood for fuel, fodder and peat (Mitch et al., 2009)	- Wastewater treatment and water purification: excess nutrient and pollutant removal as well as process of retention and recovery (Kadlec and Wallace, 2008)	- Educational: source for formal and informal training and education (Mitch et al., 2009)	
- Biochemical: medicine and material production from biota (Scholz and Lee, 2005)	- Regulation of erosion: soil and sediment retention (Mitch et al., 2009)		
- Genetic material: ornamental species and genes for pathogen plant resistance (Clarkson et al., 2013)	- Regulation of natural hazards: controlling of floods and storm protection (Mitch and Gosselink, 2007)		
	- Pollination: habitat for pollinators (Clarkson et al., 2013)		

emission and nutrient release; (b) review and outlining the key experimental wetland studies to identify challenges and gaps in conducting a mesocosm experiment for investigating the impact of the climate drivers and a sustainable management strategy; and (c) assessing the key climate factors, temperature and water availability, affecting the wetland ecosystem.

The knowledge gained by studying the articles about the impact of climate change on wetlands and the lessons learned from the previous experiments are used to propose a clear framework for conducting a mesocosm experiment investigating the impact of climate change scenarios and water level management on wetlands.

Review of peer-reviewed publications was undertaken using ISI-Web of Science, Google Scholar (Google Inc., Mountain View, CA, USA) and Scopus for journal articles published between 1990 and 2020. The most relevant papers in accordance with the objectives of the study were selected, but the grey literature including many reports were not assessed in this review. The focus of the literature review was on constructed wetlands and peatlands. However, we eliminated the permafrost peatlands from the search results.

In order to identify the most important focus of refined papers, we conducted a bibliometric analysis using VOS-viewer software (version 1.6.15). This analysis helped us to illustrate the trend of the research regarding wetland ecosystems and climate change over the selected period. Co-occurrence analysis of the keywords was applied to find the frequencies of the keywords throughout the papers. In total, there were 387 keywords in 161 papers from which the top 33 keywords were analysed and mapped with a minimum occurrence number of three (Fig. 1). The created co-occurrence network map helped us to explore the most important topics regarding wetland ecosystems and climate change and take them into consideration in our review paper.

2. Potential response of peatlands to climate change

2.1. Role of peatlands

A peatland is a type of natural wetland characterized by the accumulation of peat (i.e., incomplete decayed plant material), which contains large amount of organic matter. Peatlands cover approximately 3–4% of the world's land area, and they contain 400-500 Pg of carbon (Gorham et al., 1991), which is equivalent to half of the carbon in the atmosphere, indicating the importance of the dynamics in the carbon cycle (Dise, 2009). For thousands of years, peatlands were persistent carbon sinks, which is a vital service of a peatland to combat climate change. Hence, protection and restoration of peatlands is crucial to preserving their net cooling effect for the atmosphere. Peatlands are situated in temperate-cold climates in the northern hemisphere and are a widespread landscape in the boreal and sub-arctic zones, where they experience a cool and water-saturated state. This state supports an anaerobic condition that leads to a low decomposition rate, resulting in carbon accumulation and production of carbon storage. Climate change is projected to have a serious effect on the peatlands located in boreal and subarctic regions as global warming is anticipated to be rapid in this region (Tarnocai, 2006; Dise, 2009). Exposure to warmer temperatures and drier conditions linked to climate change has been predicted to shift the balance between the ecosystem photosynthesis and respiration (carbon dioxide release from plant and microorganisms), which can reverse the sink function of a peatland to being a source (Flanagan and Syed, 2011; Lund et al., 2012).

2.2. Peatland decomposition and consequences

Elevated temperature coupled with water level drawdown resulting from climate change leads to high rate of peat decomposition. This has some consequences for the aquatic environment, as further export of organic carbon is predicted to occur, which will deteriorate the surface water quality (Pastor et al., 2003; Freeman et al., 2004). However, this consequence is not yet clear, since the export of dissolved organic carbon (DOC) depends on whether the high temperature is accompanied by increased or decreased precipitation (Tranvik and Jansson, 2002).

Another consequence of peat decomposition is a higher rate of respiration of decomposed organic matter by microorganisms, which leads to the release of carbon into the atmosphere (Frolking et al., 2011). Peat decomposition is quite a complex process that is dependent on various parameters such as temperature, moisture, aeration, plant composition as well as the microbe community. These factors are in interaction with each other and would change with time and depth. Temperature and water availability play a key role in the decomposition of the peat among all those variables (Bu et al., 2011).

The rate of peat decomposition varies between different types of

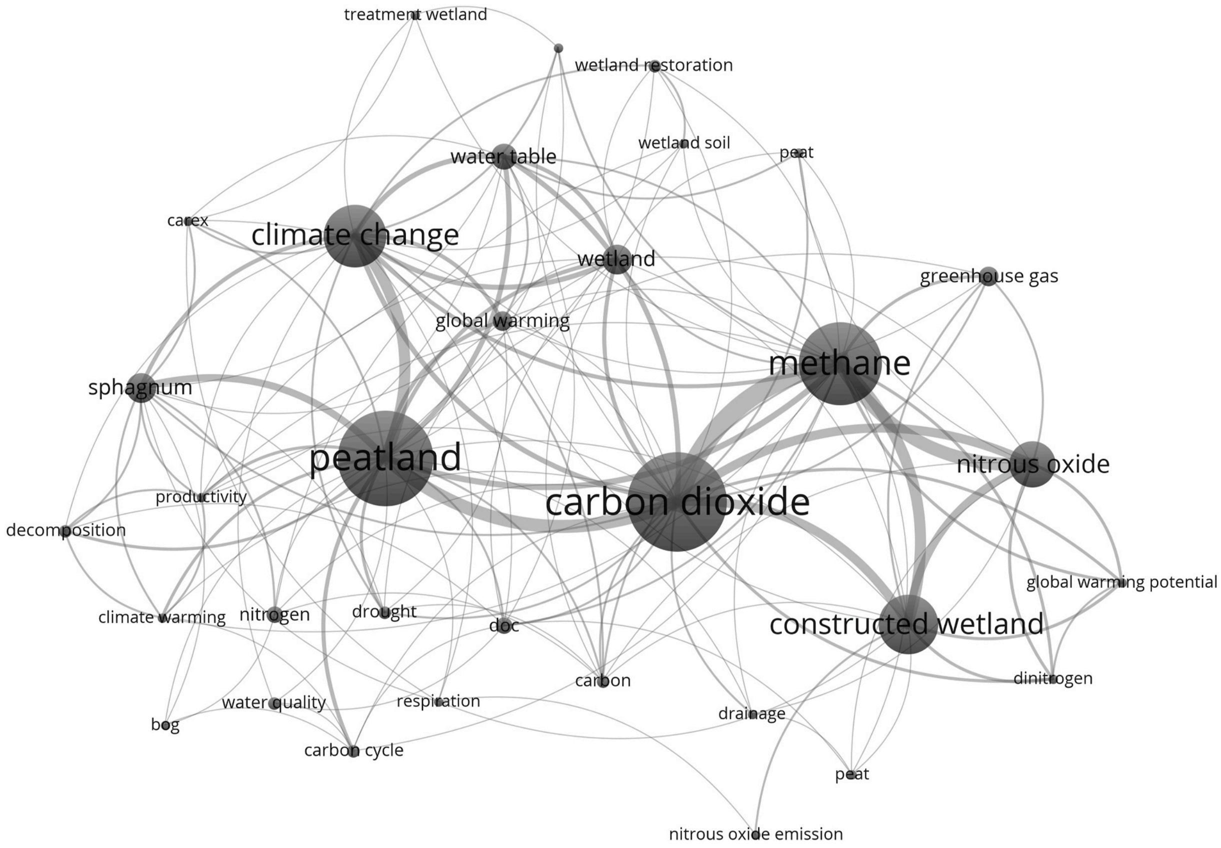

Fig. 1. Co-occurrence network map of the top 33 keywords in the papers used for the review paper. The size of the circles is proportional to the weight of occurrence of the keywords. The strength of the links between the keywords indicates the relationship between the keywords. Similar numbers of co-occurrences of keywords result in close map locations.

peatland. For example, *Sphagnum*-based peat has a lower rate of decay due to the phenolic compounds embedded in the cell walls and also having the hyaline cells. Therefore, *Sphagnum*-dominated bogs are the most productive and efficient peat-forming ecosystems (Turetsky et al., 2008).

In a peatland bog, the upper horizon of peatland that contains the living plants known as acrotelm (depth <0.3 m) contains a high amount of labile organic matter, which is readily decomposable. With higher temperatures, a more frequent oxic state of this layer is expected to occur and this state may reach the catotelm layer (deeper anaerobic layer of peat, depth > 1 m) particularly during the summer, resulting in decomposition of that layer as well (Malmer and Wallén, 2004). Catotelm typically contains recalcitrant organic matter that will be more gradually decomposed over time (Belyea et al., 2004). An extreme detrimental consequence of climate change is likely, if peat decomposition combines with a significant decrease in photosynthesis as a result of drought. This leads to a large amount of carbon dioxide emission into the atmosphere, while the sequestration of carbon will be limited due to the low primary production (carbon dioxide capture by photosynthesis) not being able to offset the carbon dioxide release (Lund et al., 2012; Lafleur et al., 2009). On the other hand, if the rise in temperature coincides with higher precipitation, the primary production may increase and the peatland can maintain its vital role as a natural carbon sink stabilizing climate change (Vitt et al., 2000; Bäckstrand et al., 2010; Bu et al., 2011).

Indirect effects such as succession have been shown to have significant impacts on climate change (Weltzin et al., 2003; Fenner et al., 2005; Dieleman et al., 2015). The peat can be oxidized and degraded with elevated temperatures and evapotranspiration and this contributes to the mineralization of the organic compounds that have been locked up in saturated peat for a long time and release nutrients (Bell et al., 2018). The availability of limited nutrients such as nitrogen and phosphorus facilitates plant growth, particularly the vascular plants, and this will increase the aboveground gross biomass (Berendse et al., 2001). Some studies have indicated that in boreal-forested peatlands, where a longer growing season is expected with climate change, more primary production of vegetation can increase the carbon sink and offset for carbon loss from this ecosystem (Gallego-Sala et al., 2018). However, succession would replace the moss hummock (mound above ground) with tall graminoid vegetation. Bell et al. (2018) revealed that *Sphagnum*-based peat releases significantly less carbon comparing to dwarf shrubs/-graminoids, and graminoids produce more labile litters that can be readily metabolized by microorganisms and produce carbon dioxide and methane to the atmosphere. On the other hand, those vascular plants are more productive than *Sphagnum* moss; i.e. they capture more carbon dioxide from the atmosphere and this could compensate for the negative effect of carbon emissions released from the labile litter of vascular plants (Malmer and Wallén, 2004).

There are, however, uncertainties how climate change will impact on the productivity and decomposition of peatlands. Hence further studies are required to reduce the uncertainty regarding their responses Bell et al. (2018).

2.3. Potential response of constructed wetland to climate change

Constructed wetlands resemble natural wetlands, but they are artificially engineered systems, which mimic natural wetlands, and have been used extensively to treat point and non-point sources of water pollution (Scholz and Lee, 2005; Scholz and Hedmark, 2010). Wastewater from various sources (municipal and industrial wastewater, domestic wastewater, storm water runoff, landfill leachate, runoff from agricultural, etc.) can be efficiently treated using constructed wetlands.

Constructed wetlands are classified typically into free water surface flow (or surface flow) and subsurface flow systems. The free water surface constructed wetlands can be further classified into horizontal subsurface flow and vertical subsurface flow systems. Horizontal subsurface flow and vertical subsurface flow can be combined into one single (hybrid) system to achieve a higher pollutant removal efficiency (Wu et al., 2014).

Gases such as carbon dioxide, methane, and nitrous oxide can be produced during the treatment process in constructed wetland (Fey et al., 1999; Johansson et al., 2003; Teiter and Mander, 2005). The environmental factors may affect the dynamics of greenhouse gas emission from constructed wetlands considerably. These factors can directly or indirectly have an impact on the constructed wetlands, through changes in vegetation, and the aerobic and anaerobic state of the constructed wetlands affecting the heterotrophic microbe activities and consequently greenhouse emissions from this system (Liikanen et al., 2006; Zhu et al., 2007; Wang et al., 2013).

The potential response of a constructed wetland to climate change has been investigated by several studies mainly in terms of water availability (hydro period) and temperature (soil/water), which were reported as the most significant drivers affecting the emission of methane, carbon dioxide and nitrous oxide (Søvik et al., 2006). Teiter and Mander (2005) found that the production of methane in constructed wetlands would increase under a high water table due to the anaerobic condition of the substrate. A low water table in constructed wetlands might result in a significant increase in carbon dioxide as the state of the system changes from anoxic to oxic, which promotes aerobic decomposition and release of carbon dioxide. Vegetation can play a role in the emission of methane at different water level positions. It seems that plants at a low water table play a key role in the transport of methane through aerenchymatous tissue, bypassing the methanotrophic soils at the upper layer. However, this phenomenon may not play a significant role when the water level is high. Moreover, the rate of methanogenesis and methane emission at low water levels might be lower in non-vegetated constructed wetlands than the vegetated ones (Henneberg et al., 2016).

The hydrological regime can have a significant impact on greenhouse gas emission from a constructed wetland. An intermittent loading regime (pulsing regime which mimics the natural wetland) in constructed wetlands with a fluctuating water table could increase abatement of pollutants and result in the elevated emission of greenhouse gases (Mander et al., 2011). However, the results of the studies on this topic are sometimes conflicting. For example, Mander et al. (2011) stated that intermittent loading with more fluctuation in water table in horizontal subsurface flow constructed wetlands results in 7–12 times increase in methane flux compared to a stable water table condition. This is probably due to methane ebullition during the transition from a high to a low water level (Maucieri et al., 2017). This finding contrasts with the results found by Kasak et al. (2016), which indicates that the hydroperiod had no significant impact on methane emission from horizontal subsurface flow constructed wetlands under either stable or fluctuating hydraulic loading rates.

The impact of the intermittent and continuous feeding regime on nitrous oxide emission might vary in different types of constructed wetlands; e. g., the rate of nitrous oxide emission in free water surface constructed wetlands can be similar in continuous or intermittent feeding strategies, while the emission of nitrous oxide from vertical subsurface flow constructed wetlands can be considerably higher during continuous feeding compared to the intermittent feeding mode strategy. This finding in vertical subsurface flow systems can be due to oxidant conditions, which cause incomplete processes of denitrification leading to the release of nitrous oxide rather than dinitrogen (N_2) (Jia et al., 2011). The results of the studies on horizontal subsurface flow and hybrid constructed wetlands demonstrate a higher emission of nitrous oxide due to a fluctuating loading method (Mander et al., 2011; Kasak et al., 2016).

Warmer climate may significantly affect the photosynthesis of plants and the activities of heterotrophic microbes and subsequently the dynamics of the greenhouse gases from constructed wetlands. Carbon dioxide emission was observed to be at a higher rate during summer when the temperature increases (Søvik et al., 2006; Wang et al., 2008). This relates to the higher rate of respiration in constructed wetlands with higher air temperature, which promote microbial activity and plant respiration according to Barbera et al. (2015).

Higher temperature increases the rate of nitrification and denitrification processes and consequently nitrous oxide emission. However, no clear correlation was found between nitrous oxide flux and water/soil temperature in a study by Søvik et al. (2006). Temperature might change the dynamics of methane in the constructed wetland by influencing methane oxidation and microbial community activities (Wang et al., 2013). Mander et al. (2015) reported that there is no considerable seasonal effect on methane emission from horizontal subsurface flow constructed wetlands, while carbon dioxide and nitrous oxide emission were significantly higher in summer than in winter. In contrast, Maucieri et al. (2017) and de la Varga et al. (2015) stated that there was a considerable seasonal variation in methane emission.

Climate change can change the solar radiation in the future. A higher rate of photosynthesis with higher solar radiation is expected, if drought would not stress the plants. However, this can stimulate the release of organic matter in the plant root region, which in turn stimulates methane and carbon dioxide emission (Picek et al., 2007). Barbera et al. (2015) and Maucieri et al. (2017) observed a positive correlation between solar radiation and methane emission in non-vegetated horizontal subsurface flow constructed wetlands, as well as vegetated ones with *Phragmites australis, Arundo donax, Cyperus papyrus, Miscanthus giganteus,* and *Cyperus zizanioides*. However, carbon dioxide emission has been observed to be positively correlated with solar radiation only for the system planted with *C. papyrus* indicating that greenhouse gases emission could be significantly affected by the genotype of plants.

According to a comprehensive literature analysis by Mander et al. (2014b), emission of carbon dioxide from free water surface constructed wetlands could be significantly lower than that from the subsurface flow ones. Moreover, methane emission from vertical subsurface flow constructed wetlands can be lower than the horizontal ones and the highest emission might occur from free water surface systems. However, no significant differences in nitrous oxide emission from various types of subsurface flow constructed wetlands have been reported. These results emphasize the role of soil and sediment oxygen status in the denitrification process and nitrous oxide emission, as well as methanogenesis and methane formation (Maltais et al., 2009).

2.4. Wetland responses to the climate change drivers: experimental studies

Wetland decomposition depends mostly on thermal and hydrologic regimes (Belyea et al., 2004; Lafleur et al., 2005). There are several studies that have employed mesocosms to assess wetland responses to a single (Moore et al., 1998; Tanner et al., 1999; Chimner and Cooper, 2003; Lafleur et al., 2005; Breeuwer et al., 2009; Laine et al., 2014) or simultaneously two climate variables (Weltzin et al., 2000; Updegraff et al., 2001; Blodau et al., 2004; Chivers et al., 2009; Mulot et al., 2015; Bridgham et al., 2019). Rarely, studies have been conducted applying more than two climate variables at the same time (Blodau et al., 2004; Lafleur et al., 2005). Moreover, there were also flask experiments, which were established to determine the effect of the water table position on peat decomposition (Yavitt et al., 1997; Öquist and Sundh, 1998; Kettunen et al., 1999).

All research studies, which investigated the effect of different climate variables on wetlands, considered hydrological parameters and temperature (Bubier et al., 2003; Lafleur et al., 2005; Chivers et al., 2009; Laine et al., 2014; Bridgham et al., 2019) to be the most important factors, which alter the role of ecosystems not only by changing the biogeochemistry of a wetland (Kløve et al., 2010; Laine et al., 2014), but also by changing the plant community structure of this ecosystem (Weltzin et al., 2000; Bragazza et al., 2013; Kuiper et al., 2014; Dieleman et al., 2015).

There are several studies, which have focused on measuring methane and carbon dioxide gas fluxes from wetlands (mostly peatlands) at different temperatures and water levels (Bridgham et al., 1992; Bubier et al., 1998, 2003; Kløve et al., 2010; Maljanen et al., 2001; Updegraff et al., 2001). Water level draw-down either happens due to the active drainage of a wetland or during a drought. This might turn the ecosystem from being a sink of carbon to a source of carbon. Some studies found that the water table is a strong factor determining ecosystem respiration and consequently carbon emission (Bridgham et al., 1992; Silvola et al., 1996; Bubier et al., 2003; Davidson and Janssens 2006). In contrast, other researchers found that temperature is the stronger factor, which influences ecosystem respiration (Bridgham et al., 1992; Glenn et al., 1993; Akinremi et al., 1999; Bubier et al., 1998; Maljanen et al., 2001; Updegraff et al., 2001).

Table 2 shows an overview of key experiments that have used mesocosms to assess the function of wetland ecosystems at different treatments. Water table and temperature are the key variables that have been investigated in those experiments.

3. Main climate change drivers affecting wetland ecosystems

3.1. Water availability

Climate change may cause more evapotranspiration and consequently a water level drawdown and also more flood inundation, which might critically affect the biogeochemistry, water quality (Waddington et al., 2015) and gas emission from wetland ecosystems (Moore and Knowles, 1989).

Chiver et al. (2009) have conducted an experiment in the field and

Table 2

Overview of key experiments, which inspired the proposal for a framework for mesocosm-scale wetland experiments subject to climate change.

Reference	Ecosystem	Duration of the experiment (month)	Control variable	Monitored climate variable	Investigated variable	Mesocosm volume (m^3)	Replicate number	Research aim	Area of origin
Tanner et al. (1999)	Constructed gravel-based wetland mesocosm wetland	–	WL	WL and T	N, TOD (COD, N and BOD), DO, pH, conductivity and redox potential	0.145	3	Evaluate nitrogen removal	North Island and New Zealand
Weltzin et al. (2000)	Bog and fen mesocosm	36	Infrared loading, WL and T	WL	Above-ground net primary production; below-ground net primary production; species composition	1.05–1.47	3	Assess primary productivity of plant species composition	Northern Minnesota, USA
Updegraff et al. (2001)	Bog and fen mesocosm	24 months (just for growing season)	WL and T	WL, T, SM and ST	CO_2 and CH_4 emissions	4.24	3	Assess the response of the respiratory C flux, net primary production to warming and water level	Minnesota, USA
Chimner and Cooper (2003)	Fen	3.5	WL	ST and WL	Respiration (CO_2 flux)	0.23	–	Evaluate relationship between water table position and CO_2 emissions	Colorado, USA
Pastor et al. (2003)	Bog and fen mesocosm	24 months (just for growing season)	WL and T	T and SM	DOC	4.24	3	Investigate the effect of climate warming and water level on DOC export	Minnesota, USA
Blodau et al. (2004)	Oligotrophic peatland	8	H, L, T and WL: CCV	–	Carbon	0.09	–	Assess carbon fluxes and dissolved carbon at two water table positions	Eastern Ontario, Canada
Lafleur et al. (2005)	Ombrotrophic bog	1	WL and peat moisture	T, H, R (PAR), P, SM and WL	Respiration	3.93×10^{-4}	–	Assess relationship between ecosystem respiration, temperature and water table	East of Ottawa, Ontario, Canada
Chivers et al. (2009)	Rich fen	24	WL and T	WL, T and PAR	CO_2 flux	Plot in the field of 120 m^2	1 for WL; 3 for T	Assess CO_2 fluxes	Alaska, USA
Laine et al. (2014)	Oligotrophic peatland (pristine and drained)	5	WL	P	N	0.11	5	Evaluate release of nitrogen	Southern Finland
Mulot et al. (2015)	Peatland (*Sphagnum*)	24	WL and R	T, H, R, P, SM and WL	–	0.02	5	Design and planning support	Switzerland
Leroy et al. (2017)	Peatland (*Sphagnum molinia*)	12	WL, T	WL, T, SM and AM	CO_2 and CH_4 emissions, and DOC concentration	0.085	6	Investigate the impact of plant composition on gas fluxes and DOC concentration	France

Note: AM, air moisture (%); BOD, biochemical oxygen demand (mg/l); CH_4, methane; CCV, controlled climate variable; CO_2, carbon dioxide; COD, chemical oxygen demand (mg/l); DO, dissolved oxygen (mg/l); DOC, dissolved oxygen demand; H, humidity (%); N, nitrogen (mg/l); P, precipitation (mm); PAR, photosynthetically active radiation (μm/s); R, radiation; SCV, simulated climate variable (based on the climate scenario); SM, soil moisture (%); ST, soil temperature (°C); T, temperature (°C); TOD, total oxygen demand (mg/l), WL, water level (mm/cm); -, information unavailable.

compared three different treatments of a rich fen: drought, control (no water level change) and flooding. The corresponding results indicated weak, moderate and great sinks of carbon, respectively. They have also discovered that drought causes a lower gross primary production, whereas the flooded plots had an increased early season gross primary production mostly because of the raised water level and higher light-saturated photosynthesis. This implies that the water saturated condition remains the sink state of the wetland for carbon dioxide. However, methane emission of the system in the flooded condition has to be taken into account, which has not been addressed in this study.

The studies have demonstrated that drought stimulates gas emissions (Maljanen et al., 2001; Clark et al., 2007; Lafleur et al., 2009; Kasak et al., 2016). However, there is still insufficient discussion of the impact of severity and duration of periods of drought on gas emission, which eventually determines the function of wetlands as either carbon a sinks or sources (Lund et al., 2012).

In peatlands, depending on if they are disturbed or pristine, responses are different to the hydrological alternation. Laine et al. (2013) indicated that the drained wetlands would experience more evenly distributed decomposition over time, which reduced nitrogen after drought, while the pristine ones experience a higher rate of mineralised nitrogen over a short period of drought. Moreover, the authors reported insignificant nitrite and nitrate concentrations during the aerobic conditions, raising the question why oxic conditions did not cause oxidation of ammonium compared to other studies (Glatzel et al., 2006; Reiche et al., 2010), where higher concentrations of nitrite and nitrate were observed due to drying and rewetting processes.

Change in aerobic and anaerobic conditions of the wetland as a result of climate change determines the rate of methane and carbon dioxide production. A low water level promotes carbon mineralization and consequently releases carbon dioxide. However, this might affect the rate of carbon immobilization in microbial and plant communities simultaneously (McLatchey and Reddy. 1998).

Blodau et al. (2004) observed in a mesocoms study that all production rates drop with depth, suggesting the importance of fresh litter for release of labile carbon on the top layers of peatlands. In addition, they revealed that by lowering the water table by 30 cm, the anaerobic rates of C production would change significantly in deeper zones of peat by a factor of 2.0–3.5 for dissolved organic carbon, 2.9–3.9 for carbon dioxide and 3–14 for methane.

In constructed wetlands, the emission of methane and carbon dioxide is not necessarily dependent to the hydrological regime. Altor et al. (2008) demonstrated that hydric soils containing substantial microbially available organic carbon release more methane compared to non-hydric soil regardless of type of hydrologic regime (intermittent flooding regime versus continuously inundated conditions). This suggests an important role of substrate in constructed wetlands. Altor et al. (2008) believe that a wetland in the early stage of development contains lower levels of available organic matter and alternate electron acceptors, which limit methanogenesis. Therefore, water level fluctuations might have more impact when the wetlands are more mature and developed.

3.2. Temperature

Temperature is one of the most determinant factors regulating the biogeochemistry of wetlands. Increased temperature enhances the rate of biochemical processes. For instance, the rate of nitrification, denitrification, nitrogen immobilization and organic phosphorus mineralization increases when temperature rises (Reddy and Delaune, 2008).

In future, an increase in temperature will affect the dynamic of greenhouse gases greatly. Both heterotrophic and microbial activity and plant photosynthesis are thermophilic processes that interact with methane and carbon dioxide dynamics (Wang et al., 2013). A direct effect of higher temperature might be an increase in both carbon dioxide and methane production in the wetland, although, an indirect opposite effect of rising temperature might be a reduction of aerobic respiration of organic matter as the temperature reduces the oxygen-holding capacity of the water column in the wetland (Schlesinger and Bernhardt, 2013). A warmer climate will also accelerate the loss of water through evapotranspiration. This leads to a water table drop, resulting in the exposure of top layers of the wetland to the oxygen where the organic matter can be oxidized readily (Lafleur et al., 2005).

It has been predicted that exposure to warmer temperatures and drier conditions associated with climate change will shift the balance between ecosystem photosynthesis and respiration (Flanagan and Syed, 2011). The literature, however, shows contradictory findings. For instance, some studies showed that increasing temperature enhances the respiration of plants to a greater degree than photosynthesis (Christensen et al., 1999; Updegraff et al., 2001; Dorrepaal et al., 2009). In contrast, some others reported a higher rate of primary production than respiration, which helps the wetland to act as a carbon sink functioning as a climate change decelerator (Vitt et al., 2000; Bäckstrand et al., 2010; Bu et al., 2011). Different responses from different types of wetlands to the warmer climate could be due to different species characteristics that suggest that peatlands may mediate their energy, carbon and nutrient budget through potentially differential responses to plant communities (Weltzin et al., 2000).

Lafleur et al. (2005) found a strong relationship between the respiration of a peatland and temperature. On the contrary, there was a weak link between the peatland respiration and the water table depth. This was due to wetter peatlands being more sensitive to water table variability than the drier peatlands. The temperature sensitivity of carbon dioxide emissions can be reduced as the degradation rate of labile compounds has lower temperature sensitivity compared to recalcitrant organic matter (Davidson and Janssens, 2006). At the same time, the temperature sensitivity of methane emissions would be increased implying a possible change in methanogenic communities.

In a study of constructed wetlands by Teiter and Mander (2005), no significant correlation between water, temperature and nitrous oxide flux was found despite of substantially elevated emissions observed for carbon dioxide, nitrous oxide and methane during the warmer periods. However, Bateganya et al. found a significant positive correlation between the water temperature and carbon dioxide, methane and nitrous oxide fluxes in both vegetated and unvegetated constructed wetlands.

4. Methodological gaps and uncertainties in literatures

4.1. Methodological gaps

4.1.1. Lack of a comparative and comprehensive simulation

Researchers undertaking experiments need a proper reference (benchmark) such as the Representative Concentration Pathway (RCP), which is used in predicting future climate change scenarios published by IPCC (2007). Our literature review indicates that the employment of RCP climate scenarios for prediction of future hydrology (Javadinejad et al., 2020; Oo et al., 2020) and greenhouse gas emission provides the modellers with more accurate and reliable comparative results (Gallego-Sala et al., 2018). However, the use of RCP climate scenarios has not yet become common among researchers conducting experiments for study of climate change on ecosystems. The benefit of this reference is that it can be used globally to simulate a realistic degree of change in climate variables for simulation of climate change (see section 7.1.1). Such a reference is absent for many previous mesocosm experiments (Lafleur et al., 2005; Breeuwer et al., 2009; Laine et al., 2014). In addition, there is a lack of comparison between natural and artificial wetlands in terms of their response to future climate change. This comparison would not only offer an understanding of the response of different substrates, but would also determine the direction of future artificial wetland development for policymakers. Establishing more constructed wetlands may improve the quality of water, but they may also contribute to a warmer climate through greenhouse gas emissions.

Furthermore, the authors have not found any mesocosm experiments in the literature that link wetlands to receiving watercourses. Such a linkage is needed for understanding the interaction between the wetlands and aquatic systems in the catchment scale, facing climate change (see section 7.1.2).

4.1.2. *Lack of accurate and advanced simulators*

In order to perform a dynamic simulation in a mesocosm experiment, an advanced simulator capable of simulating multiple climate variables is needed (Fig. 2). There might be only small variations in climate variables that will cause a gradual long-term change in the wetland ecosystem. An advanced and accurate simulator should be run for a long time to simulate these slight changes (see section 7.1.4). However, the authors could not find such an experimental technology for wetlands in the literature.

4.1.3. *Lack of all-year-around monitoring*

Most of the mesocosm experiments were carried out during the growing season and all the mesocosm experiments in the reviewed literature were ceased during the cold season, primarily due to the malfunction of instruments (Chivers et al., 2009; Mulot et al., 2015). The exclusion of the cold season might underestimate the effect of snow cover, snowmelt and seasonal shifts (as a result of climate change) on wetlands. This may have a significant effect on the wetland biogeochemistry and gas release (see section 7.1.3).

4.1.4. *Lack of simulation of management practices*

In previous mesocosm studies, temperature and water level manipulation was performed to find the most critical drivers affecting the wetland ecosystem function (Blodau et al., 2004; Chivers et al., 2009; Bridgham et al., 2019). However, the examination of the effect of management practices along with the climate change simulation in an experimental wetland has not been performed in the past. Hence, the necessity of management practices for future wetland conservation is uncertain and needs to be properly studied (see section 7.3).

4.2. *Uncertainties in literature*

Wetlands are complex and dynamic ecosystems, which are impacted by climate change that itself is also a complex and dynamic process. By reviewing the literature, the authors have found out that there are still controversial debates as to which factors are most critical in changing the response of a wetland to climate change (see section 4). The question then arises whether, in the face of climate change, wetlands maintain their greenhouse gas sink capacity or become a source of greenhouse gases.

In section 7, the authors will address the literature gaps and limitations by suggesting a new framework (Fig. 2) for future climate change simulation of wetland mesocosm experiments. The new comprehensive framework aims to answer some controversial questions and also to investigate the impact of water level management on wetlands and the associated aquatic systems facing climate change.

5. A new framework for future study of climate change on experimental wetland mesocosms

5.1. *Key considerations for future experimental wetland mesocosms*

The new literature-backed framework addresses the gaps listed in section 6 to support the execution of future mesocosm experiments assessing climate change impacts on wetland ecosystems. The schematic illustration in Fig. 2 promotes the framework suggested for future research on the impact of climate change scenarios on wetland mesocosms and related watercourses receiving wetland outflows (if available). The suggested framework can be used for peatlands and constructed wetland mesocosm experiment. However, in order to develop a comprehensive understanding of the efficiency of different levels of management on wetland water quality, the integration of an aquatic systems as the ultimate recipient of pollution in the landscape will be suggested (Kingsford 2011; Martin-Ortega et al., 2014). Hence, a simulated lake (stagnant water) ecosystem was incorporated into the proposed mesocosm experimental framework as well (Fig. 2). This integration helps researchers to not only measure the direct effect of climate change on the aquatic system (Wise et al., 2009), but also evaluate the effect of wetland management on the aquatic system quality (Whitehead et al., 2009; Alvarez-Mieles et al., 2013).

In the suggested framework (Fig. 2), the authors outlined the steps that should be taken to identify the essential factors that have the greatest effect on wetland climate change mitigation. To understand

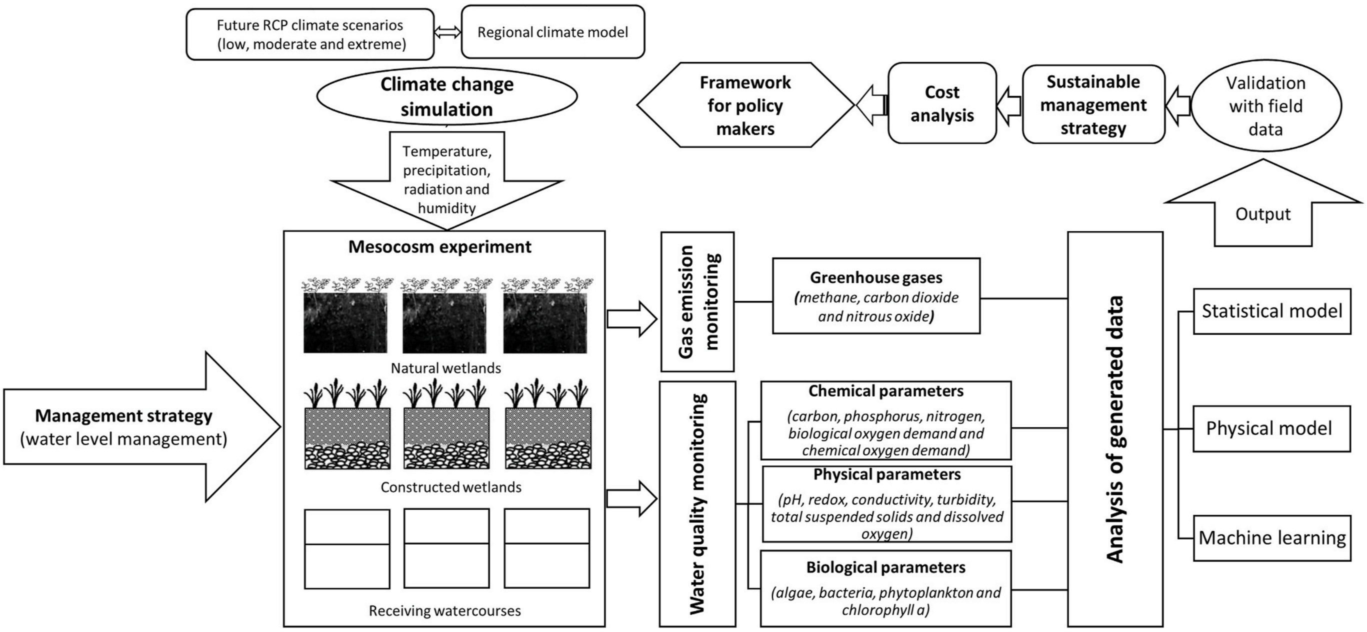

Fig. 2. A new framework for future wetland mesocosm experiments studying the impact of climate change scenarios and water level management. The steps in this framework have been described in section 7 and in the corresponding subsections.

how different factors might change the main function of a wetland such as purifying the water and carbon sequestration, monitoring of water quality and gas emissions is essential. The essential parameters that should be measured for each method of monitoring are shown in Fig. 2. Methods for the analysis of the generated data include statistical analysis, physical modelling and machine learning techniques. Ultimately, the output of the mesocosm experiment should be validated with the field data. Water level management as an example of a suitable management strategy can be used along with the simulation of climate change scenarios (see section 7.1.3). Sustainable wetland management should ensure that wetlands are resilient to climate change. Moreover, the suggested sustainable management needs to be evaluated for the economic constraints and efficiencies to provide policymakers with the best possible management alternatives (Fig. 2).

5.2. Climate change scenario simulation

To promote consistency between different climate change research studies, the application of appropriate references for benchmarking purposes is required. The experimenters can use climate change scenarios adopted by the Intergovernmental Panel on Climate Change (IPCC) for future simulations; for instance, the simulation of future climate scenarios can be based on the climate models using the RCP scenarios released in the IPCC Fifth Assessment Report (AR5, IPCC, 2013) (Fig. 2). In addition, the climate model data have to be downscaled to the scale of the study area to obtain more reliable and realistic results. Furthermore, if mesocosm climate change research is planned to be scaled-up to the regional scale, the Regional Climate Model (RCM) data have to be utilized to create an optimal climate scenario in the experiment. The application of RCP scenarios allows the researchers to generate comparable results. Moreover, RCP scenarios have been and will be used for modelling ecosystems responding to climate change (Spahni et al., 2013; Schneider et al., 2016; Helbig et al., 2020). This allows for a comparison between the model and experimental results as well.

5.2.1. Catchment-scale simulation in mesocosm studies

The dynamic of the wetland connection to the receiving surface water at the catchment scale can be considered in mesocosm experiments in a simplified manner. Understanding the fate of the nutrients exported from the wetland ecosystem at the catchment level is crucial as the leachable nutrients would be ultimately transported to the surface water downstream (Pastor et al., 2003; Freeman et al., 2004; Laine et al., 2013). Moreover, the dynamics of other water system connections to the wetland has to be taken into account as well. The hydrological buffer function of a wetland can be different for various types of wetlands being fed in the catchment from different sources of water (Aurela et al., 2004). For instance, a fen (minerotrophic peatlands) is fed from both rainwater and groundwater, while bogs (ombrotrophic peatlands) are solely dependent on precipitation, which make them more vulnerable to drought (Riutta et al., 2007; Lund et al., 2012). Since nutrient dynamics and gas emissions are highly dependent on hydrology, it is important to simulate all water sources that may affect the wetland system, and vice-versa (Sulman et al., 2010).

In a mesocosm experiment, the simulation of a catchment scale is possible by including lake mesocosms, which receive the outflow of the wetland (Fig. 2). This linkage permits a researcher to estimate the load and exports of nutrients to and from the lake mesocosm. Additionally, potential surface water issues such as eutrophication, acidification and brownification caused by wetland outflow can be investigated (Freeman et al., 2001; Clair et al., 2002; Stets and Cotner, 2008). Understanding of mechanisms and magnitude of changes in nutrient fluxes from wetlands to receiving waterbodies helps researchers to more effectively adapt their catchment management policies to climate change (Price et al., 2003; Kløve et al., 2017).

5.2.2. Simulation of cold season

The cold season should not be ignored in climate change research on wetlands as higher levels of gas emissions could occur in cold conditions than expected (Kløve et al., 2010). Alternation in the cycle of freezing and thawing during winter and spring has an influence on the dynamics of nutrient cycles and also gas emissions from wetlands.

True responses of wetlands to climate change can be evaluated only when the seasonal shift and variations are taken into consideration in the simulation. Seasonal variations have an influence on microbial activity, wetland nutrient composition and gas flux (Fenner et al., 2005). Higher temperature during winter changes the water balance through the change in snow cover, which has some consequences on factors such as plant reproduction and growth (Aerts et al., 2004; Dorrepaal et al., 2004; Bu et al., 2011).

In addition, higher temperatures during the cold season might lead to more winter run-off causing an early winter flood. This leads to changes in water availability during spring and summer (Dawson et al., 2003).

In constructed wetlands, temperature and oxygen transfer play an important role in water treatment. The effect of one factor can be compensated by another during the seasonal cycle. During winter, the function of the plant-mediated oxygen transfer is more pronounced for water treatment as it offsets lower microbial activity caused by cold temperatures (Stein and Hook. 2005). In addition, in both natural and constructed wetlands, cold seasons play an important role in gas exchange and the annual carbon balance. (Zhang et al., 2009; Søvik et al., 2006). The role of cold season events (for instance, freeze-thaw activation in peatlands) should not be underestimated, as it leads to a rapid increase in methane and carbon dioxide emissions, which has to be taken into account in the carbon balance estimation (Panikov and Dedysh 2000; Aurela et al., 2004). It follows that the authors recommend to consider the cold season by simulating frozen soil and snow cover in mesocosm experiments.

5.2.3. Climate control chambers

In order to have an advanced experiment with proper controls of variables, the employment of control technology is recommended. One solution to offset the constrains associated with the simulations of dynamic climate change scenarios is to include more climate variables simultaneously by using advanced climate chambers. These types of chambers are computer-supported programmable facilities, which allow researchers to simulate high resolution data for the climate scenario by accurately regulating key climate variables such as temperature, precipitation, relative humidity and radiation (Verdier et al., 2014). A closed climate chamber system permits the researcher to estimate the water balance of both the climate chamber and the mescosm. In addition, the climate chambers are normally equipped with sensors that would monitor simulation accuracy of the climate variables. Therefore, any possible malfunctioning and simulation errors can be detected, measured and calibrated.

5.3. Monitoring of wetland mesocosms

5.3.1. Multi-variable monitoring

In most wetland mesocosm experiments, researchers have defined different treatments of variables like water table and temperature, and they tried to keep some environmental boundary conditions constant, so that different treatments can be compared with each other (Dalva and Moore, 1993; Blodau et al., 2002; Laine et al., 2014). The challenges with these experiments are that those constant conditions rarely happen in reality, and the fluctuations of the water level, which have an effect on leaching of the substances, might be ignored (Laine et al., 2013). Application of only one or two climate variables would ignore the interaction effect of other variables such as radiation and humidity, while they are of relative importance along with the key variables (Verdier et al., 2014; Barbera et al., 2015).

Ultimately, wetland mesocosm experiments aim to understand the underlying mechanisms, which change the role of the wetland in response to climate change. This understanding helps engineers to regulate the factors, which have the most impact on the main beneficial services of the wetlands such as water purification and climate change mitigation.

The authors recommend to monitor numerous variables in wetland mesocosm experiments, as this facilitates engineers to have a better understanding of wetland functions from different point of views. The study of a single parameter might provide a researcher only with a deep understanding of the mechanisms governing a specific variable in response to climate change, but lacks the understanding of interactions and relationships between variables. Fig. 2 shows examples of various biological and physicochemical variables that can be monitored for investigation of water quality and gas emission in an experimental wetland. The advantage of this multi-variable quantification is that it allows the scientists to detect the trend of different types of changes in wetlands responding to climate change over time and ultimately identify the most appropriate management strategy accordingly (Clark et al., 2001; Moomaw et al., 2018). Moreover, various datasets generated in the experiment can be used for the models which simulate the complexity of the ecosystems. These models normally require a high resolution and various parameters to provide a more reliable prediction (Cools et al., 2013).

5.4. *Monitoring of methane and carbon dioxide*

In order to maintain negative climate feedback (i.e. carbon sequestration in form of biomass) of wetlands (particularly peatlands), which is the largest terrestrial carbon store, it is important to understand the processes regulating the emission of both carbon dioxide and methane, as the influence of the climate drivers might act differently for these two gases; for instance, increasing the water table might decrease the carbon dioxide emission, but it might increase the methane emission, which is 23 times more potent as a heat-trapping gas in the atmosphere (Kayranli et al., 2010). Therefore, both carbon dioxide and methane should be taken into account in the proposed framework to determine whether the ecosystem will act as a sink or source of carbon in response to the climate change scenarios (Updegraff et al., 2001). In most cases, the studies demonstrated that wetland water saturation often results in a decrease in the rate of decomposition and lower carbon dioxide emission, though this could increase the emission of methane. In order to find an optimal level of water management to adapt the wetlands to future climate scenarios, quantification of the different biological and physicochemical parameters along with gas emission measurements at different water levels is recommended (Fig. 2).

5.5. *Simulation of water level management*

Monitoring wetland hydrology is essential as it has been demonstrated in literature as the most important factor controlling wetland functions (Bridgham et al., 1992; Silvola et al., 1996; Davidson and Janssens 2006). An investigation of the impact of water level management is proposed for the mesocosm experiment under different climate scenarios. This helps engineers to determine the optimal water level required to maintain the wetland services under different climate scenarios. The most appropriate water level management strategy should eventually benefit the human communities by improving water quality, water regulation and climate change mitigation services at the same time (Kløve et al., 2017).

In some studies, the water level is found to be the best indicator of carbon dioxide and methane emissions (Christensen et al., 1999; Bubier, 1998). There is a critical depth in a certain wetland system at which the maximal emissions occur, for instance Moore and Dalva (1993) and Moore and Roulet (1993) reported in their experiment that at water levels greater than 18 cm, methanogenesis (methane production) decreases and instead methanotrophy (methane consumption) increases. Although the water table has been considered as the best indicator for carbon dioxide and methane emissions in some studies, other research concluded the opposite (Lloyd, 2006). For instance Jacobs et al. (2007) compared Dutch grassland located on peat soil, and found a temperature association for all sites, but high variations in respiration between sites. This variation was due to soil moisture differences. The local water table might have relatively large variations, but the soil moisture variations might remain small. The volumetric water content at the root zone can be high even at a low water table. Therefore, soil water would not be a limiting factor for plant transpiration (Kramer et al., 1997). However, Parmentier et al. (2009) pointed out that shallow water table fluctuation has an effect on ecosystem respiration only if the water level lowering is persistent and thus results in a lowering of the soil moisture content. Otherwise, the respiration of the ecosystem and gross primary production would not vary with the water table. The effect of the water level fluctuation might be different in constructed wetlands. According to Tanner et al. (1999), more frequent water level fluctuation leads to oxygen release in the plant root zone causing higher rate of ammonium oxidation (nitrification) and also microbial oxidation of chemical oxygen demand (COD). Considering the possible differences between the response of peatlands and constructed wetlands, the authors recommend to assess both of them concurrently as the type and degree of the water level management may be entirely different between these two systems.

Overall, optimum wetland services are unlikely to occur during flooding events or during low flow as both circumstances have a negative impact on biomass production. However, this negative impact can be adapted in the long-term mainly due to alternation in plant composition. Additionally, a slightly lower inflow into the wetland causes aerobic conditions, resulting in a low degree of decomposition, which makes nutrients available to plants, promoting their primary productivity (Berendse et al., 2001).

It has been shown in peatlands that the response of carbon dioxide emissions to different water levels may not be proportional along the peat profile since the availability of labile carbon pools in deeper layers would be substantially limited, which results in no further increase in carbon dioxide emission with depth (Chimnar et al., 2003).

Given all these complexities behind the responses of wetlands to different hydrological regimes, finding a sustainable water management strategy is challenging. Hence, it would be logical to identify the hydrological thresholds for the wetland mesocosms in the experiment. This requires an examination of different water management scenarios under different climate scenarios to find the most appropriate and sustainable water management strategy for these valuable ecosystems.

6. Discussion, conclusions and key recommendations

6.1. *Discussion and conclusions*

With a warmer climate in the future, the upper part of the peatland would experience more water loss than the lower part. This former is more vulnerable to moisture as it is more exposed to oxygen, making it more susceptible to decomposition (Updegraff et al., 2001). The rate of heterotrophic respiration in the lower part of the peatland profile depends to some extent on how much oxygen can be diffused and oxidize the organic matter. The amount of oxygen diffusion in the peat profile mainly depends on the peat water content. However, the rate of the autotrophic respiration might be relatively independent of water content. The rate of carbon dioxide emission relies on how primary production and respiration competes in the future. Mitsch et al. (2008) claimed that in future the general positive role of wetlands in terms of carbon sequestration will be more pronounced compared to negative methane emission with climate change. However, climate change in the future might result in droughts that can increase the ecosystem respiration substantially and decrease primary production (Lafleur et al., 2009). Therefore, it will be difficult to predict the role of wetlands in climate change without the consideration of drought.

Our critical review concludes that drought might decrease primary production of the system and elevates aerobic respiration. However, a wetter condition accompanied by a warmer climate might promote photosynthesis to a degree that might exceed the respiration and maintain the role of a peatland as a sink. In another review study, Bu et al. (2011) noted that climate warming would have negative effects on the role of peatlands as carbon sinks due to lower water availability and higher temperatures, which would increase the rate of peat decomposition more than net primary production. Moreover, they reported that climate change would be resulting in succession, shifting from *Sphagnum* to vascular plants, and this would lead to an increase in methane and carbon dixiode emission in the long-term.

A higher production of methane is linked to a high water table and anaerobic conditions. Higher temperatures on the other hand might lower the production of methane through methane oxidation. Concurrently, higher microbial activity in the water and sediment due to higher temperatures can result in higher emissions of methane. A substantial decline in water level, which influences the deeper zone of the peatland, can significantly reduce methane emissions (Blodau et al., 2004).

This literature review indicates that the response of methane to climate change may vary greatly from one type of wetland to another, and the combination of biotic and abiotic factors makes the peatland response to methane emissions rather unpredictable and complex (Updegraff et al., 2001). In line with our review, another critical literature review by Kayranli et al. (2010) shows that the role of many wetland plants and microorganisms in carbon turnover and methane emission is unclear and needs further study. They suggested that more process-level research is needed to predict methane emissions from wetlands. Moreover, they indicated that the differentiation between the production and consumption processes of methane is essential.

The assessment of constructed wetlands showed that the potential contribution of free water surface constructed wetlands to global warming in the future is considered to be small as they have been linked to the lowest carbon dioxide and nitrous oxide emissions compared to other types of constructed wetlands. However, it has been shown that free water surface constructed wetlands can have a high methane emission compared to other types of constructed wetlands due to their predominant anoxic condition. Therefore, the rapid increase in the number of free water surface constructed wetlands should alarm stakeholders and designers to manage these systems properly. Mander et al. (2014b) proposed future studies focusing on hydrological regimes and the development of vegetation and microbial communities to improve the efficiency and management of constructed wetlands in the face of climate change. In addition, Kayranli et al. (2010) found in their literature review that constructed wetlands have a higher carbon sequestration capacity than natural wetlands. They did, however, state that if they were not properly designed and managed, they would function as sources of greenhouse gasses to the atmosphere.

Contradictory results regarding the impact of water levels on methane emissions in constructed wetlands demand further studies. In addition, the impact of vegetation on constructed wetland gas emission has to be studied more as assessments have shown that they can both increase and decrease the carbon sink role of constructed wetlands (Maltais-Landry et al., 2009). It seems that the role of vegetation in constructed wetland gas emission is more important when the water level drops (Henneberg et al., 2016). Therefore, with a higher risk of drought in the future, it would be important to select more suitable plant species with an adequate density to tolerate water shortage and combat climate change through carbon sequestration. After reviewing 224 articles, Maucieri et al. (2017) found that the presence of vegetation increases constructed wetland greenhouse gas emissions relative to non-vegetated ones. However they assumed that vegetated constructed wetland could absorb atmospheric carbon by photosynthesis and act as a carbon dioxide sink and mitigate climate change, but they were uncertain about the impact of plant species on methane emissions.

A comprehensive consideration of the most important wetland services, such as climate change mitigation and water purification, is essential to suggest sustainable and efficient management. However, conducting experiments to find such an approach will often be challenging, mainly because of financial and time constraints (Cools et al., 2013). One way to overcome this challenge is to use process-based models and/or machine learning techniques to analyse experimental data (Olden et al., 2008) (Fig. 2). If the numerous datasets generated in the experiment can be sufficiently representative of the pattern of change in the systems, then a sophisticated algorithm should be capable to recognize and predict the response of the system properly and save money, time and resources (Maleki et al., 2019). Machine learning approaches are flexible in capturing the complexity of the interactions and relationships between variables, making it an ideal approach for modelling a wetland ecosystem (Berry et al., 2003). In a literature review, Blodau et al. (2002) also suggested the development of models capable of capturing interaction dynamics and processes for predicting greenhouse gas emissions from wetland. However, the improvement of model parameterization is supported by the result of a robust and sophisticated experiment.

Consistent with the suggested framework (see section 7), Bu et al. (2011) indicated that mesocosm experiments involving multiple factors and allowing environmental conditions is important for understanding of mechanistic relationship between variables in the wetland. Therefore, it can be concluded than conducting our suggested mesocosm experiment allows for the simulation of more realistic (based on RCP) and high-resolution (based on RCM) climate variables. Employment of an advanced simulator will simulate dynamics of climate change; i.e. the simulation of various climate variables as well as the cold season. This coordinated mesocosm experiment facilitates consistency and provides a more valid comparison between different mesocosm experiments. Any uncertainty about the impact of change in temperature and water level as well as their interactions might be resolved over time using the proposed framework. In addition, multi-variable monitoring provides a comprehensive insight into both positive and negative feedback from wetlands on climate change. This helps to find appropriate management actions that can be used by the environmental managers to maintain the wetland services and mitigate climate change. However, it is important to note the limitations of our proposed framework associated with the mesocosm experiment, as it is performed on a limited spatial and temporal scale. Simplification is unavoidable in most forms of mesocosm experiments. Therefore, they cannot represent all the complexities of natural ecosystems. Hence, researchers should use the results of mesocosm experiment cautiously for generalization purposes.

6.2. Key recommendations

- One method to study the effect of climate change on wetland function is to monitor wetlands along a latitudinal gradient, evaluating and comparing their response to different climates. However, this type of study demands a lot of time, effort and coordination between scientists, conducting the experiments in different locations across the latitudinal gradient. Therefore, a long-term simulation of climate change in a rigorous mesocosm experiment, which addresses the gaps and challenges mentioned earlier in section 6, would be recommnnded instead.
- The hybrid-constructed wetlands have been identified as a valuable approach for controlling water quality improvement as well as mitigating greenhouse gas emissions. Pulsing water regime, enhancing the growth of aquatic macrophytes and controlled harvesting of them are the most recommendable methods for mitigation of methane (Mander et al., 2014b). However, the response of nitrous oxide emission due to these methods is not yet clear as studies report conflicting results. Furthermore, carbon dioxide emission can be stimulated by a pulsing approach. Hence, monitoring of both nitrous oxide and carbon dioxide emissions during this process would be highly recommended.

- The impact of constructed wetland age on greenhouse gas emissions needs to be studied further as some research indicates that the developed wetlands can function as carbon sink with climate change (Whitting and Chanton 2001), whereas some other studies report a higher rate of carbon dioxide and methane with age as a result of more accumulation of organic matter and unchanged nitrous oxide emission (Altor et al., 2008; de la Varga et al., 2015).
- Drought is the most deleterious climate phenomenon, which might considerably damage the wetland ecosystem especially for peatlands. This may trigger a shift from the dominant plants, *Sphagnum* mosses, to the more drought-tolerant vascular plants. Therefore, studying the succession of vegetation in peatlands before any management action would be recommended. The management strategy should protect *Sphagnum* mosses, which have a low decay rate, maintain the optimal water level to avoid peat decomposition and promote the rate of photosynthesis.
- In our proposed framework, water level management has been suggested to be examined along with climate scenarios simulation (Fig. 2); it would be highly recommended to examine different levels of management to monitor the response of the wetland intensively. This close evaluation of the system benefits researchers in finding a critical water level at which the wetland maintains its vital services and negative climate feedback role; i.e. a higher rate of primary production than respiration in the ecosystem. The definition of the critical water level, accompanied with reasonable knowledge about the succession in vegetation and biogeochemical characteristics of wetlands, helps researchers to suggest a practical plan for optimal management, adapting wetlands to future climate change scenarios.

Author statement

Shokoufeh Salimi: Data curation, Investigation, Methodology, Visualization, Writing – original draft. Suhad Almuktar: Writing – original draft. Miklas Scholz: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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References

Aerts, R., Cornelissen, J.H.C., Dorrepaal, E., Van Logtestijn, R.S.P., Callaghan, T.V., 2004. Effects of experimentally imposed climate scenarios on flowering phenology and flower production of subarctic bog species. Global Change Biol. 10, 1599–1609. https://doi.org/10.1111/j.1365-2486.2004.00815.x.

Akinremi, O.O., McGinn, S.M., McLean, H.D.J., 1999. Effects of soil temperature and moisture on soil respiration in barley and fallow plots. Can. J. Soil Sci. 79, 5–13. https://doi.org/10.4141/S98-023.

Almuktar, S.A., Abed, S.N., Scholz, M., 2018. Wetlands for wastewater treatment and subsequent recycling of treated effluent: a review. Environ. Sci. Pollut. Control Ser. 25, 23595–23623. https://doi.org/10.1007/s11356-018-2629-3.

Altor, A.E., Mitsch, W.J., 2008. Methane and carbon dioxide dynamics in wetland mesocosms: effects of hydrology and soils. Ecol. Appl. 18, 1307–1320. https://doi.org/10.1890/07-0009.1.

Alvarez-Mieles, G., Irvine, K., Griensven, A.V., Arias-Hidalgo, M., Torres, A., Mynett, A.E., 2013. Relationships between aquatic biotic communities and water quality in a tropical river–wetland system (Ecuador). Environ. Sci. Pol. 34, 115–127. https://doi.org/10.1016/j.envsci.2013.01.011.

Aurela, M., Laurila, T., Tuovinen, J.P., 2004. The timing of snow melt controls the annual CO_2 balance in a subarctic fen. Geophys. Res. Lett. 31 https://doi.org/10.1029/2004GL020315.

Bäckstrand, K., Crill, P.M., Jackowicz-Korczyñski, M., Mastepanov, M., Christensen, T.R., Bastviken, D., 2010. Annual carbon gas budget for a subarctic peatland, Northern Sweden. Biogeosciences 7, 95–108. https://doi.org/10.5194/bg-7-95-2010.

Barbera, A.C., Borin, M., Cirelli, G.L., Toscano, A., Maucieri, C., 2015. Comparison of carbon balance in Mediterranean pilot constructed wetlands vegetated with different C4 plant species. Environ. Sci. Pollut. Control Ser. 22, 2372–2383. https://doi.org/10.1007/s11356-014-2870-3.

Bell, M.C., Ritson, J.P., Verhoef, A., Brazier, R.E., Templeton, M.R., Graham, N.J.D., Freeman, C., Clark, J.M., 2018. Sensitivity of peatland litter decomposition to changes in temperature and rainfall. Geoderma 331, 29–37. https://doi.org/10.1016/j.geoderma.2018.06.002.

Belyea, L.R., Malmer, N., 2004. Carbon sequestration in peatland: patterns and mechanisms of response to climate change. Global Change Biol. 10, 1043–1052. https://doi.org/10.1111/j.1529-8817.2003.00783.x.

Berendse, F., Van Breemen, N., Rydin, H., Buttler, A., Heijmans, M., Hoosbeek, M.R., Lee, J.A., Mitchell, E., Saarinen, T., Vasander, H., Wallén, B., 2001. Raised atmospheric CO2 levels and increased N deposition cause shifts in plant species composition and production in Sphagnum bogs. Global Change Biol. 7, 591–598. https://doi.org/10.1046/j.1365-2486.2001.00433.x.

Berry, P.M., Dawson, T.P., Harrison, P.A., Pearson, R., Butt, N., 2003. The sensitivity and vulnerability of terrestrial habitats and species in Britain and Ireland to climate change. J. Nat. Conserv. 11, 15–23. https://doi.org/10.1078/1617-1381-00030.

Blodau, C., 2002. Carbon cycling in peatlands A review of processes and controls. Environ. Rev. 10, 111–134. https://doi.org/10.1139/a02-004.

Blodau, C., Basiliko, N., Moore, T.R., 2004. Carbon turnover in peatland mesocosms exposed to different water table levels. Biogeochemistry 67, 331–351. https://doi.org/10.1023/B:BIOG.0000015788.30164.e2.

Bragazza, L., Parisod, J., Buttler, A., Bardgett, R.D., 2013. Biogeochemical plant-soil microbe feedback in response to climate warming in peatlands. Nat. Clim. Change. https://doi.org/10.1038/nclimate1781.

Breeuwer, A., Robroek, B.J.M., Limpens, J., Heijmans, M.M.P.D., Schouten, M.G.C., Berendse, F., 2009. Decreased summer water table depth affects peatland vegetation. Basic Appl. Ecol. 10, 330–339. https://doi.org/10.1016/j.baae.2008.05.005.

Bridgham, S.D., Richardson, C.J., 1992. Mechanisms controlling soil respiration (CO2 and CH4) in southern peatlands. Soil Biol. Biochem. 24, 1089–1099. https://doi.org/10.1016/0038-0717(92)90058-6.

Bridgham, S.D., Johnston, C.A., Pastor, J., Updegraff, K., Bridgham, S.D., Johnston, C.A., Pastor, J., Updegraff, K., 2019. Potential feedbacks of northern wetlands on climate change – an outline of an approach to predict climate-change impact. Bioscience 45, 262–274. https://www.jstor.org/stable/1312419.

Bu, Z., Hans, J., Li, H., Zhao, G., Zheng, X., Ma, J., Zeng, J., 2011. The response of peatlands to climate warming: a review. Acta Ecol. Sin. 31, 157–162. https://doi.org/10.1016/j.chnaes.2011.03.006.

Bubier, J.L., Crill, P.M., Moore, T.R., Savage, K., Varner, R.K., 1998. Seasonal patterns and controls on net ecosystem CO2 exchange in a boreal peatland complex. Global Biogeochem. Cycles 12, 703–714. https://doi.org/10.1029/98GB02426.

Bubier, J., Crill, P., Mosedale, A., Frolking, S., Linder, E., 2003. Peatland responses to varying interannual moisture conditions as measured by automatic CO2 chambers. Global Biogeochem. Cycles 17. https://doi.org/10.1029/2002GB001946.

Chimner, R.A., Cooper, D.J., 2003. Influence of water table levels on CO_2 emissions in a Colorado subalpine fen: an in situ microcosm study. Soil Biol. Biochem. 35, 345–351. https://doi.org/10.1016/S0038-0717(02)00284-5.

Chivers, M.R., Turetsky, M.R., Waddington, J.M., Harden, J.W., McGuire, A.D., 2009. Effects of experimental water table and temperature manipulations on ecosystem CO2 fluxes in an Alaskan rich fen. Ecosystems 12, 1329–1342. https://doi.org/10.1007/s10021-009-9292-y.

Christensen, T.R., Jonasson, S., Callaghan, T.V., Havström, M., 1999. On the potential CO2 release from tundra soils in a changing climate. Appl. Soil Ecol. 11, 127–134. https://doi.org/10.1016/S0929-1393(98)00146-2.

Clair, T.A., Arp, P., Moore, T.R., Dalva, M., Meng, F.R., 2002. Gaseous carbon dioxide and methane, as well as dissolved organic carbon losses from a small temperate wetland under a changing climate. Environ. Pollut. 116, S143–S148.

Clark, J.S., Carpenter, S.R., Barber, M., Collins, S., Dobson, A., Foley, J.A., et al., 2001. Ecological forecasts: an emerging imperative. Science 293, 657–660. https://doi.org/10.1126/science.293.5530.657.

Clark, J.M., Lane, S.N., Chapman, P.J., Adamson, J.K., 2007. Export of dissolved organic carbon from an upland peatland during storm events: implications for flux estimates. J. Hydrol. 347, 438–447. https://doi.org/10.1016/j.jhydrol.2007.09.030.

Clarkson, B.R., Ausseil, A.-G.E., Gerbeaux, P., 2013. Wetland ecosystem services. Ecosystem Services in New Zealand: Conditions and Trends. Manaaki Whenua Press, Lincoln, pp. 192–202. https://www.landcareresearch.co.nz/_data/assets/pdf_file/0020/77042/1_14_Clarkson.pdf.

Cools, J., Johnston, R., Hattermann, F.F., Douven, W., Zsuffa, I., 2013. Tools for wetland management: lessons learnt from a comparative assessment. Environ. Sci. Pol. 34, 138–145. https://doi.org/10.1016/j.envsci.2013.01.013.

Corman, J.R., Bertolet, B.L., Casson, N.J., Sebestyen, S.D., Kolka, R.K., Stanley, E.H., 2018. Nitrogen and phosphorus loads to temperate seepage lakes associated with allochthonous dissolved organic carbon loads. Geophys. Res. Lett. 45, 5481–5490. https://doi.org/10.1029/2018GL077219.

Dalva, M., Moore, T., 1993. The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. J. Soil Sci. 44, 651–664. https://doi.org/10.1111/j.1365-2389.1993.tb02330.x.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165–173. https://doi.org/10.1038/nature04514.

Dawson, T.P., Berry, P.M., Kampa, E., 2003. Climate change impacts on freshwater wetland habitats. J. Nat. Conserv. 11, 25–30. https://doi.org/10.1078/1617-1381-00031.

De la Varga, D., Ruiz, I., Álvarez, J.A., Soto, M., 2015. Methane and carbon dioxide emissions from constructed wetlands receiving anaerobically pretreated sewage. Sci. Total Environ. 538, 824–833. https://doi.org/10.1016/j.scitotenv.2015.08.090.

Dieleman, C.M., Branfireun, B.A., McLaughlin, J.W., Lindo, Z., 2015. Climate change drives a shift in peatland ecosystem plant community: implications for ecosystem function and stability. Global Change Biol. 21, 388–395. https://doi.org/10.1111/gcb.12643.

Dise, N.B., 2009. Peatland response to global change. Science 326, 810–811. https://doi.org/10.1126/science.1174268.

Dorrepaal, E., Aerts, R., Cornelissen, J.H., Callaghan, T.V., Van Logtestijn, R.S., 2004. Summer warming and increased winter snow cover affect *Sphagnum fuscum* growth, structure and production in a sub-arctic bog. Global Change Biol. 10, 93–104. https://doi.org/10.1111/j.1365-2486.2003.00718.x.

Erwin, K.L., 2009. Wetlands and global climate change: the role of wetland restoration in a changing world. Wetl. Ecol. Manag. 17, 71. https://doi.org/10.1007/s11273-008-9119-1.

Fenner, N., Freeman, C., Reynolds, B., 2005. Observations of a seasonally shifting thermal optimum in peatland carbon-cycling processes; implications for the global carbon cycle and soil enzyme methodologies. Soil Biol. Biochem. 37, 1814–1821. https://doi.org/10.1016/j.soilbio.2005.02.032.

Fey, A., Benckiser, G., Ottow, J.C.G., 1999. Emissions of nitrous oxide from a constructed wetland using a ground filter and macrophytes in waste-water purification of a dairy farm. Biol. Fertil. Soils 29, 354–359. https://doi.org/10.1007/s003740050565.

Flanagan, L.B., Syed, K.H., 2011. Stimulation of both photosynthesis and respiration in response to warmer and drier conditions in a boreal peatland ecosystem. Global Change Biol. 17, 2271–2287. https://doi.org/10.1111/j.1365-2486.2010.02378.x.

Freeman, C., Evans, C.D., Monteith, D.T., Reynolds, B., Fenner, N., 2001. Export of organic carbon from peat soils. Nature 412, 785. https://doi.org/10.1029/2018GL077219, 785.

Freeman, C., Fenner, N., Ostle, N.J., Kang, H., Dowrick, D.J., Reynolds, B., Lock, M.A., Sleep, D., Hughes, S., Hudson, J., 2004. Export of dissolved organic carbon from peatlands under elevated carbon dioxide levels. Nature 430, 195. https://doi.org/10.1038/nature02707.

Frolking, S., Talbot, J., Jones, M.C., Treat, C.C., Kauffman, J.B., Tuittila, E.S., Roulet, N., 2011. Peatlands in the Earth's 21st century climate system. Environ. Rev. 19, 371–396. https://doi.org/10.1139/a11-014.

Gallego-Sala, A.V., Charman, D.J., Brewer, S., et al., 2018. Latitudinal limits to the predicted increase of the peatland carbon sink with warming. Nat. Clim. Change 8, 907–913. https://doi.org/10.1038/s41558-018-0271-1.

Glatzel, S., Lemke, S., Gerold, G., 2006. Short-term effects of an exceptionally hot and dry summer on decomposition of surface peat in a restored temperate bog. Eur. J. Soil Biol. 42, 219–229. https://doi.org/10.1016/j.ejsobi.2006.03.003.

Glenn, S., Heyes, A., Moore, T., 1993. Carbon dioxide and methane fluxes from drained peat soils, southern Quebec. Global Biogeochem. Cycles 7, 247–257. https://doi.org/10.1029/93GB00469.

Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. Ecol. Appl. 1, 182–195. https://doi.org/10.2307/1941811.

Helbig, M., Waddington, J.M., Alekseychik, P., Amiro, B.D., Aurela, M., Barr, A.G., Black, T.A., Blanken, P.D., Carey, S.K., Chen, J., Chi, J., Desai, A.R., Dunn, A., Euskirchen, E.S., Flanagan, L.B., Forbrich, I., Friborg, T., Grelle, A., Harder, S., Heliasz, M., Humphreys, E.R., Ikawa, H., Isabelle, P.-E., Iwata, H., Jassal, R., Korkiakoski, M., Kurbatova, J., Kutzbach, L., Lindroth, A., Ottosson Löfvenius, M., Lohila, A., Mammarella, I., Marsh, P., Maximov, T., Melton, J.R., Moore, P.A., Nadeau, D.F., Nicholls, E.M., Nilsson, M.B., Ohta, T., Peichl, M., Petrone, R.M., Petrov, R., Prokushkin, A., Quinton, W.L., Reed, D.E., Roulet, N.T., Runkle, B.R.K., Sonnentag, O., Strachan, I.B., Taillardat, P., Tuittila, E.-S., Tuovinen, J.-P., Turner, J., Ueyama, M., Varlagin, A., Wilmking, M., Wofsy, S.C., Zyrianov, V., 2020. Increasing contribution of peatlands to boreal evapotranspiration in a warming climate. Nat. Clim. Change 1–6. https://doi.org/10.1038/s41558-020-0763-7.

Henneberg, A., Brix, H., Sorrell, B.K., 2016. The interactive effect of *Juncus effusus* and water table position on mesocosm methanogenesis and methane emissions. Plant Soil 400, 45–54. https://doi.org/10.1007/s11104-015-2707-y.

Huang, L., Gao, X., Guo, J., Ma, X., Liu, M., 2013. A review on the mechanism and affecting factors of nitrous oxide emission in constructed wetlands. Environmental earth sciences 68, 2171–2180. https://doi.org/10.1007/s12665-012-1900-z.

IPCC, 2007. Climate Change 2007 Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC. https://doi.org/10.1017/CBO9781107415324.004.

Jacobs, C.M.J., Jacobs, A.F.G., Bosveld, F.C., Hendriks, D.M.D., Hensen, A., Kroon, P.S., Moors, E.J., Nol, L., Schrier-Uijl, A., Veenendaal, E.M., 2007. Variability of Annual CO 2 Exchange from Dutch Grasslands. https://hal.archives-ouvertes.fr/hal-00297893.

Javadinejad, S., Dara, R., Jafary, F., 2020. Climate change scenarios and effects on snow-melt runoff. Civil Engineering Journal 6, 1715–1725. https://doi.org/10.28991/cej-2020-03091577.

Jia, W., Zhang, J., Li, P., Xie, H., Wu, J., Wang, J., 2011. Nitrous oxide emissions from surface flow and subsurface flow constructed wetland microcosms: effect of feeding strategies. Ecol. Eng. 37 (11), 1815–1821. https://doi.org/10.1016/j.ecoleng.2011.06.019.

Johansson, A.E., Klemedtsson, Å.K., Klemedtsson, L., Svensson, B.H., 2003. Nitrous oxide exchanges with the atmosphere of a constructed wetland treating wastewater: parameters and implications for emission factors. Tellus B 55, 737–750. https://www.tandfonline.com/doi/abs/10.3402/tellusb.v55i3.16363.

Kasak, K., Mõtlep, R., Truu, M., Truu, J., Kõiv-Vainik, M., Espenberg, M., Paiste, P., Kirimäe, K., Mander, Ü., 2016. Hydrated oil shale ash mitigates greenhouse gas emissions from horizontal subsurface flow filters for wastewater treatment. Water Air Soil Pollut. 227, 320. https://doi.org/10.1007/s11270-016-3007-8.

Kayranli, B., Scholz, M., Mustafa, A., Hedmark, Å., 2010. Carbon storage and fluxes within freshwater wetlands: a critical review. Wetlands 30, 111–124. https://doi.org/10.1007/s13157-009-0003-4.

Kettunen, A., Kaitala, V., Lehtinen, A., Lohila, A., Alm, J., Silvola, J., Martikainen, P.J., 1999. Methane production and oxidation potentials in relation to water table fluctuations in two boreal mires. Soil Biol. Biochem. 31, 1741–1749. https://doi.org/10.1016/S0038-0717(99)00093-0.

Kingsford, R.T., 2011. Conservation management of rivers and wetlands under climate change–a synthesis. Mar. Freshw. Res. 62, 217–222. https://doi.org/10.1071/MF11029.

Kløve, B., Sveistrup, T.E., Hauge, A., 2010. Leaching of nutrients and emission of greenhouse gases from peatland cultivation at Bodin, Northern Norway. Geoderma 154, 219–232. https://doi.org/10.1016/j.geoderma.2009.08.022.

Kløve, B., Berglund, K., Berglund, Ö., Weldon, S., Maljanen, M., 2017. Future options for cultivated Nordic peat soils: can land management and rewetting control greenhouse gas emissions? Environ. Sci. Pol. 69, 85–93. https://doi.org/10.1016/j.envsci.2016.12.017.

Kramer, P.J., Boyer, J.S., Carlson, W.C., 1997. Water relations of plants and soils. For. Sci. 43, 151–152.

Kuiper, J.J., Mooij, W.M., Bragazza, L., Robroek, B.J., 2014. Plant functional types define magnitude of drought response in peatland CO2 exchange. Ecology 95, 123–131. https://doi.org/10.1890/13-0270.1.

Lafleur, P.M., 2009. Connecting atmosphere and wetland: trace gas exchange. Geography Compass 3, 560–585. https://doi.org/10.1111/j.1749-8198.2008.00212.x.

Lafleur, P.M., Moore, T.R., Roulet, N.T., Frolking, S., 2005. Ecosystem respiration in a cool temperate bog depends on peat temperature but not water table. Ecosystems 8, 619–629. https://doi.org/10.1007/s10021-003-0131-2.

Laiho, R., 2006. Decomposition in peatlands: reconciling seemingly contrasting results on the impacts of lowered water levels. Soil Biol. Biochem. 38, 2011–2024. https://doi.org/10.1016/j.soilbio.2006.02.017.

Laine, M.P., Strömmer, R., Arvola, L., 2013. Nitrogen release in pristine and drained peat profiles in response to water table fluctuations: a mesocosm experiment. Applied and Environmental Soil Science. https://doi.org/10.1155/2013/694368, 2013.

Laine, M.P.P., Strömmer, R., Arvola, L., 2014. DOC and CO2-C releases from pristine and drained peat soils in response to water table fluctuations: a mesocosm experiment, 2014, article ID 912816 Appl. Environ. Soil Sci.. https://doi.org/10.1155/2014/912816.

Liikanen, A., Huttunen, J.T., Karjalainen, S.M., Heikkinen, K., Väisänen, T.S., Nykänen, H., Martikainen, P.J., 2006. Temporal and seasonal changes in greenhouse gas emissions from a constructed wetland purifying peat mining runoff waters. Ecol. Eng. 26, 241–251. https://doi.org/10.1016/j.ecoleng.2005.10.005.

Lloyd, C.R., 2006. Annual carbon balance of a managed wetland meadow in the Somerset Levels, UK. Agric. For. Meteorol. 138, 168–179. https://doi.org/10.1016/j.agrformet.2006.04.005.

Lund, M., Christensen, T.R., Lindroth, A., Schubert, P., 2012. Effects of drought conditions on the carbon dioxide dynamics in a temperate peatland. Environ. Res. Lett. 7, 045704 https://doi.org/10.1088/1748-9326/7/4/045704.

Maleki, S., Soffianian, A.R., Koupaei, S.S., Baghdadi, N., Mohamad, E.H., Sheikholeslam, F., Pourmanafi, S., 2019. Wetland restoration prioritization using artificial neural networks. Wetlands 1–14. https://doi.org/10.1007/s13157-019-01165-8.

Maljanen, M., Hytönen, J., Martikainen, P.J., 2001. Fluxes of N2O, CH4 and CO2 on afforested boreal agricultural soils. Plant Soil 231, 113–121. https://doi.org/10.1023/A:1010372914805.

Malmer, N., Wallén, B., 2004. Input rates, decay losses and accumulation rates of carbon in bogs during the last millennium: internal processes and environmental changes. Holocene 14, 111–117. https://doi.org/10.1191/0959683604hl693rp.

Maltais-Landry, G., Maranger, R., Brisson, J., Chazarenc, F., 2009. Greenhouse gas production and efficiency of planted and artificially aerated constructed wetlands. Environ. Pollut. 157, 748–754. https://doi.org/10.1016/j.envpol.2008.11.019.

Mander, Ü., Maddison, M., Soosaar, K., Karabelnik, K., 2011. The impact of pulsing hydrology and fluctuating water table on greenhouse gas emissions from constructed wetlands. Wetlands 31, 1023–1032.

Mander, Ü., Dotro, G., Ebie, Y., Towprayoon, S., Chiemchaisri, C., Nogueira, S.F., Jamsranjav, B., Kasak, K., Truu, J., Tournebize, J., Mitsch, W.J., 2014b. Greenhouse gas emission in constructed wetlands for wastewater treatment: a review. Ecol. Eng. 66, 19–35. https://doi.org/10.1016/j.ecoleng.2013.12.006.

Mander, Ü., Maddison, M., Soosaar, K., Koger, H., Teemusk, A., Truu, J., Well, R., Sebilo, M., 2015. The impact of a pulsing water table on wastewater purification and greenhouse gas emission in a horizontal subsurface flow constructed wetland. Ecol. Eng. 80, 69–78. https://doi.org/10.1016/j.ecoleng.2014.09.075.

Martin-Ortega, J., Allott, T.E., Glenk, K., Schaafsma, M., 2014. Valuing water quality improvements from peatland restoration: evidence and challenges. Ecosystem Services 9, 34–43. https://doi.org/10.1016/j.ecoser.2014.06.007.

Maucieri, C., Barbera, A.C., Vymazal, J., Borin, M., 2017. A review on the main affecting factors of greenhouse gases emission in constructed wetlands. Agric. For. Meteorol. 236, 175–193. https://doi.org/10.1016/j.agrformet.2017.01.006.

McLatchey, G.P., Reddy, K.R., 1998. Regulation of organic matter decomposition and nutrient release in a wetland soil. J. Environ. Qual. 27, 1268–1274. https://doi.org/10.2134/jeq1998.00472425002700050036x.

Mitsch, W.J., Tejada, J., Nahlik, A., Kohlmann, B., Bernal, B., Hernández, C.E., 2008. Tropical wetlands for climate change research, water quality management and conservation education on a university campus in Costa Rica. Ecol. Eng. 34, 276–288. https://doi.org/10.1016/j.ecoleng.2008.07.012.

Mitsch, W.J., Gosselink, J.G., Zhang, L., Anderson, C.J., 2009. Wetland Ecosystems. John Wiley and Sons, Hoboken, NJ.

Mitsch, W.J., Bernal, B., Nahlik, A.M., Mander, Ü., Zhang, L., Anderson, C.J., Jørgensen, S.E., Brix, H., 2013. Wetlands, carbon, and climate change. Landsc. Ecol. 28, 583–597. https://doi.org/10.1007/s10980-012-9758-8.

Moomaw, W.R., Chmura, G.L., Davies, G.T., Finlayson, C.M., Middleton, B.A., Natali, S. M., Perry, J.E., Roulet, N., Sutton-Grier, A.E., 2018. Wetlands in a changing climate: science, policy and management. Wetlands 38, 183–205. https://doi.org/10.1007/s13157-018-1023-8.

Moore, T.R., Dalva, M., 1993. The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. J. Soil Sci. 44, 651–664. https://doi.org/10.1111/j.1365-2389.1993.tb02330.x.

Moore, T.R., Roulet, N.T., Waddington, J.M., 1998. Uncertainty in predicting the effect of climatic change on the carbon cycling of Canadian peatlands. Climatic Change 40, 229–245. https://doi.org/10.1023/A:1005408719297.

Mulot, M., Villard, A., Varidel, D., Mitchell, E.A.D., 2015. A mesocosm approach to study the response of Sphagnum peatlands to hydrological changes: setup, optimisation and performance. Mires Peat 16, 1–12.

Olden, J.D., Lawler, J.J., Poff, N.L., 2008. Machine learning methods without tears: a primer for ecologists. Q. Rev. Biol. 83, 171–193. https://doi.org/10.1086/587826.

Oo, H.T., Zin, W.W., Kyi, C.C.T., 2020. Analysis of streamflow response to changing climate conditions using SWAT model. Civil Engineering Journal 6, 194–209. https://doi.org/10.28991/cej-2020-03091464.

Öquist, M., Sundh, I., 1998. Effects of a transient oxic period on mineralization of organic matter to CH4 and CO2 in anoxic peat incubations. Geomicrobiol. J. 15, 325–333. https://doi.org/10.1080/01490459809378086.

Pachauri, R.K., Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N.K., Edenhofer, O., Elgizouli, I., Field, C. B., Forster, P., Friedlingstein, P., Fuglestvedt, J., Gomez-Echeverri, L., Hallegatte, S., Hegerl, G., Howden, M., Jiang, K., Jimenez Cisneroz, B., Kattsov, V., Lee, H., Mach, K.J., Marotzke, J., Mastrandrea, M.D., Meyer, L., Minx, J., Mulugetta, Y., O'Brien, K., Oppenheimer, M., Pereira, J.J., Pichs-Madruga, R., Plattner, G.K., Pörtner, H.O., Power, S.B., Preston, B., Ravindranath, N.H., Reisinger, A., Riahi, K., Rusticucci, M., Scholes, R., Seyboth, K., Sokona, Y., Stavins, R., Stocker, T.F., Tschakert, P., van Vuuren, D., van Ypserle, J.P., 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Ipcc, p. 151. https://epic.awi.de/id/eprint/37530.

Panikov, N.S., Dedysh, S.N., 2000. Cold season CH4 and CO2 emission from boreal peat bogs (West Siberia): winter fluxes and thaw activation dynamics. Global Biogeochem. Cycles 14, 1071–1080. https://doi.org/10.1029/1999GB900097.

Parmentier, F.J.W., Van der Molen, M.K., De Jeu, R.A.M., Hendriks, D.M.D., Dolman, A. J., 2009. CO2 fluxes and evaporation on a peatland in The Netherlands appear not affected by water table fluctuations. Agric. For. Meteorol. 149 (6–7), 1201–1208. https://doi.org/10.1016/j.agrformet.2008.11.007.

Pastor, J., Solin, J.B.S.U.K., Harth, C., Weishampel, P., Dewey, B., Solin, J., Bridgham, S. D., Updegraff, K., Harth, C., Weishampel, P., Dewey, B., 2003. Global warming and the export of dissolved organic carbon from boreal peatlands. Oikos 100, 380–386. https://doi.org/10.1034/j.1600-0706.2003.11774.x.

Picek, T., Čížková, H., Dušek, J., 2007. Greenhouse gas emission from a constructed wetland—plants as important source of carbon. Ecol. Eng. 31, 98–106. https://doi.org/10.1016/j.ecoleng.2007.06.008.

Price, J.S., Heathwaite, A.L., Baird, A.J., 2003. Hydrological processes in abandoned and restored peatlands: an overview of management approaches. Wetl. Ecol. Manag. 11, 65–83. https://doi.org/10.1023/A:1022046409485.

Reddy, K.R., DeLaune, R.D., 2008. Biogeochemistry of Wetlands: Science and Applications. CRC press.

Reiche, N., Lorenz, W., Borsdorf, H., 2010. Development and application of dynamic air chambers for measurement of volatilization fluxes of benzene and MTBE from constructed wetlands planted with common reed. Chemosphere 79, 162–168. https://doi.org/10.1016/j.chemosphere.2010.01.017.

Riutta, T., Laine, J., Tuittila, E.S., 2007. Sensitivity of CO2 exchange of fen ecosystem components to water level variation. Ecosystems 10, 718–733. https://doi.org/10.1007/s10021-007-9046-7.

Roulet, N., Moore, T.R., 2006. Browning the waters. Nature 444, 283–284. https://doi.org/10.1038/444283a.

Schlesinger, W.H., Bernhardt, E.S., 2013. Biogeochemistry: an Analysis of Global Change. Academic press.

Schneider, R.R., Devito, K., Kettridge, N., Bayne, E., 2016. Moving beyond bioclimatic envelope models: integrating upland forest and peatland processes to predict ecosystem transitions under climate change in the western Canadian boreal plain. Ecohydrology 9, 899–908. https://doi.org/10.1002/eco.1707.

Scholz, M., 2015. Wetland Systems to Control Urban Runoff, second ed. Elsevier, Amsterdam.

Scholz, M., Hedmark, Å., 2010. Constructed wetlands treating runoff contaminated with nutrients. Water, Air, Soil Pollut. 205, 323. https://doi.org/10.1007/s11270-009-0076-y.

Scholz, M., Lee, B.H., 2005. Constructed wetlands: a review. Int. Journal Environm. Stud. 62, 421–447. https://doi.org/10.1080/00207230500119783.

Silvola, J., Alm, J., Ahlholm, U., Nykanen, H., Martikainen, P.J., 1996. CO2 fluxes from peat in boreal mires under varying temperature and moisture conditions. J. Ecol. 219–228. https://doi.org/10.2307/2261357.

Søvik, A.K., Augustin, J., Heikkinen, K., Huttunen, J.T., Necki, J.M., Karjalainen, S.M., Kløve, B., Likanen, A., Mander, Ü., Puustinen, M., Teiter, S., Wachniew, P., 2006. Emission of the greenhouse gases nitrous oxide and methane from constructed wetlands in Europe. J. Environ. Qual. 35, 2360–2373. https://doi.org/10.2134/jeq2006.0038.

Spahni, R., Joos, F., Stocker, B.D., Steinacher, M., Yu, Z.C., 2013. Transient simulations of the carbon and nitrogen dynamics in northern peatlands: from the Last Glacial Maximum to the 21st century. Clim. Past 9, 1287–1308. https://doi.org/10.5194/cp-9-1287-2013.

Stein, O.R., Hook, P.B., 2005. Temperature, plants, and oxygen: how does season affect constructed wetland performance? Journal of Environmental Science and Health 40, 331–1342. https://doi.org/10.1081/ESE-200055840.

Stets, E.G., Cotner, J.B., 2008. The influence of dissolved organic carbon on bacterial phosphorus uptake and bacteria-phytoplankton dynamics in two Minnesota lakes. Limnol. Oceanogr. 53, 137–147. https://doi.org/10.4319/lo.2008.53.1.0137.

Stewart, R.I.A., Dossena, M., Bohan, D.A., Jeppesen, E., Kordas, R.L., Ledger, M.E., Meerhoff, M., Moss, B., Mulder, C., Shurian, J.B., Suttle, B., Thompson, R., Trimmer, M., Woodward, G., 2013. Mesocosm experiments as a tool for ecological climate-change research. In: Advances in Ecological Research, vol. 48. Academic Press, pp. 71–181. https://doi.org/10.1016/B978-0-12-417199-2.00002-1.

Sulman, B.N., Desai, A.R., Saliendra, N.Z., Lafleur, P.M., Flanagan, L.B., Sonnentag, O., Mackay, D.S., Barr, A.G., van der Kamp, G., 2010. CO2 fluxes at northern fens and bogs have opposite responses to inter-annual fluctuations in water table. Geophys. Res. Lett. 37 https://doi.org/10.1029/2010GL044018.

Tanner, C.C., D'Eugenio, J., McBride, G.B., Sukias, J.P.S., Thompson, K., 1999. Effect of water level fluctuation on nitrogen removal from constructed wetland mesocosms. Ecol. Eng. 12, 67–92. https://doi.org/10.1016/S0925-8574(98)00055-X.

Tarnocai, C., 2006. The effect of climate change on carbon in Canadian peatlands. Global Planet. Change 53, 222–232. https://doi.org/10.1016/j.gloplacha.2006.03.012.

Teiter, S., Mander, Ü., 2005. Emission of N2O, N2, CH4, and CO2 from constructed wetlands for wastewater treatment and from riparian buffer zones. Ecol. Eng. 25, 528–541. https://doi.org/10.1016/j.ecoleng.2005.07.011.

Tranvik, L.J., Jansson, M., 2002. Climate change (Communication arising): terrestrial export of organic carbon. Nature 415, 861. https://doi.org/10.1038/415861b.

Turetsky, M.R., Crow, S.E., Evans, R.J., Vitt, D.H., Wieder, R.K., 2008. Trade-offs in resource allocation among moss species control decomposition in boreal peatlands. J. Ecol. 96, 1297–1305. https://doi.org/10.1111/j.1365-2745.2008.01438.x.

Updegraff, K., Bridgham, S.D., Pastor, J., Weishampel, P., Harth, C., 2001. Response of CO2 and CH4 emissions from peatlands to warming and water table manipulation. Ecol. Appl. 11, 311–326. https://doi.org/10.1890/1051-0761(2001)011[0311:ROCACE]2.0.CO;2.

Verdier, B., Jouanneau, I., Simonnet, B., Rabin, C., Van Dooren, T.J., Delpierre, N., Lobert, J., Abbadie, L., Ferrère, R., Le Galliard, J.F., 2014. Climate and atmosphere simulator for experiments on ecological systems in changing environments. Environ. Sci. Technol. 48, 8744–8753. https://doi.org/10.1021/es405467s.

Vitt, D.H., Halsey, L.A., Bauer, I.E., Campbell, C., 2000. Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Can. J. Earth Sci. 37, 683–693. https://doi.org/10.1139/e99-097.

Waddington, J.M., Morris, P.J., Kettridge, N., Granath, G., Thompson, D.K., Moore, P.A., 2015. Hydrological feedbacks in northern peatlands. Ecohydrology 8 (1), 113–127. https://doi.org/10.1002/eco.1493.

Wang, Y., Inamori, R., Kong, H., Xu, K., Inamori, Y., Kondo, T., Zhang, J., 2008. Influence of plant species and wastewater strength on constructed wetland methane emissions and associated microbial populations. Ecol. Eng. 32, 22–29. https://doi.org/10.1016/j.ecoleng.2007.08.003.

Wang, Y., Yang, H., Ye, C., Chen, X., Xie, B., Huang, C., Zhang, J., Xu, M., 2013. Effects of plant species on soil microbial processes and CH4 emission from constructed wetlands. Environ. Pollut. 174, 273–278. https://doi.org/10.1016/j.envpol.2012.11.032.

Weltzin, J.F., Pastor, J., Harth, C., Bridgham, S.D., Updegraff, K., Chapin, C.T., 2000. Response of bog and fen plant communities to warming and water-table manipulations: appendix B. Methods for estimation of ANPP in mesocosm plots. Ecology 81, 3464–3478. https://doi.org/10.1890/0012-9658(2000)081[3464:ROBAFP]2.0.CO;2.

Weltzin, J.F., Bridgham, S.D., Pastor, J., Chen, J., Harth, C., 2003. Potential effects of warming and drying on peatland plant community composition. Global Change Biol. 9, 141–151. https://doi.org/10.1046/j.1365-2486.2003.00571.x.

Whitehead, P.G., Wilby, R.L., Battarbee, R.W., Kernan, M., Wade, A.J., 2009. A review of the potential impacts of climate change on surface water quality. Hydrol. Sci. J. 54, 101–123. https://doi.org/10.1623/hysj.54.1.101.

Whiting, G.J., Chanton, J.P., 2001. Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration. Tellus B 53, 521–528. https://doi.org/10.3402/tellusb.v53i5.16628.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A., Edmonds, J., 2009. Implications of limiting CO2 concentrations for land use and energy. Science 324, 1183–1186. https://doi.org/10.1126/science.1168475.

Wu, S., Kuschk, P., Brix, H., Vymazal, J., Dong, R., 2014. Development of constructed wetlands in performance intensifications for wastewater treatment: a nitrogen and organic matter targeted review. Water Res. 57, 40–55. https://doi.org/10.1016/j.watres.2014.03.020.

Yavitt, J.B., Williams, C.J., Wieder, R.K., 1997. Production of methane and carbon dioxide in peatland ecosystems across North America: effects of temperature, aeration, and organic chemistry of peat. Geomicrobiol. J. 14, 299–316. https://doi.org/10.1080/01490459709378054.

Zhang, L., Scholz, M., Mustafa, A., Harrington, R., 2009. Application of the self-organizing map as a prediction tool for an integrated constructed wetland agroecosystem treating agricultural runoff. Bioresour. Technol. 100 (2), 559–565. https://doi.org/10.1016/j.biortech.2008.06.042.

Zhu, N., An, P., Krishnakumar, B., Zhao, L., Sun, L., Mizuochi, M., Inamori, Y., 2007. Effect of plant harvest on methane emission from two constructed wetlands designed for the treatment of wastewater. J. Environ. Manag. 85, 936–943. https://doi.org/10.1016/j.jenvman.2006.11.004.