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Wetlands and carbon revisited

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ABSTRACT

This paper summarizes 19 papers published in a special issue of *Ecological Engineering* under the general banner of wetlands and carbon. Many of the papers were presented at a special session at *EcoSummit 2016* in Montpellier, France in August-September 2016. The papers are in four general categories: estimating greenhouse gas fluxes with eddy covariance; methane and other greenhouse gas emissions from wetlands; carbon sequestration by wetlands; and organic carbon decomposition in wetlands. Overall, we found that further development and wider use of eddy covariance measuring stations could help clarify long-term annual budgets of CO_2 and CH_4 in wetlands and, while CH_4 fluxes in some coastal wetlands such as mangroves can be negligible, some inland wetlands can be significant sources of CH_4 where hydroperiods are the major determinants of the emission rates. The papers here demonstrated a variety of parameters determining dynamics of methane fluxes and carbon sequestration in different wetlands and lead us to suggest that more attention should be paid to detailed analysis of the impact of environmental and management factors on carbon budgets in wetlands. Carbon sequestration is almost always estimated by soil dating methods such as with ^{137}Cs and 210Pb isotopes and results continue to show order of magnitude differences among systems but sometimes among laboratories. This is due to the inexact nature of estimating soil dates over relatively short (~50 year) time horizons. The idea of capping landfills, which are enormous methane sources, with wetlands which could then turn them into carbon sinks is worth investigating further but the design of these systems is still in its infancy. Organic carbon decomposition in wetlands has been investigated extensively for decades and more recently on the biogeochemical processes. 'Enzymic latches" such as phenol oxidase, which can break down phenolics and therefore speed up decomposition, may be key controllers of organic matter decomposition in waterlogged and submerged soils in wetlands. The best approach for balancing greenhouse gases and carbon sequestration remains an enigma, but the papers in this special issue take us one step closer to providing clarity.

1. Introduction

Wetland ecosystems provide an optimum natural environment for the sequestration and long-term storage of carbon dioxide from the atmosphere, yet are natural sources of greenhouse gases emissions, especially methane. Methane is now described on a molecular basis as 34 times more potent as a greenhouse gas than carbon dioxide in a 100-year horizon (IPCC, 2013). Therefore, to many landscape managers and non-specialists, most wetlands are regarded as sources of climate warming or net radiative forcing and nothing else. For example, Mitsch et al. (2013) found that methane emissions in terms of carbon were about 14% of the carbon sequestered in 21 wetlands around the world (Mitsch et al., 2013). This 7.1:1 (sequestration/methane) carbon ratio is equivalent to 19.5:1 as CO_2/CH_4. Comparing this ratio to the global warming potential (GWP_M) ratio of 34 for methane relative to carbon dioxide listed above, it could be concluded that the world's wetlands are net sources of radiative forcing on climate. We argue that many landscape managers would also conclude from that simple comparison that wetlands should not be created or restored.

Publications that emphasize this comparison of the two major carbon fluxes in wetlands are relatively few. Mitsch et al. (2013) and Mitsch and Gosselink (2015) illustrated by dynamic modeling of carbon flux that methane emissions become unimportant within 300 years compared to carbon sequestration in wetlands. Within that time frame, most of the wetlands became both net carbon and radiative sinks. The only wetlands that remained net radiative sources in these comparisons were peatlands that were already sources of CO_2 caused by drainage. Furthermore, Mitsch et al. (2013) and Mitsch (2016) illustrated that the world's wetlands, despite being only about 5–8% of the terrestrial landscape, may currently be net carbon sinks of about 0.83 Pg yr-1 of carbon with an average of 118 g-C m^{-2} yr^{-1} of net carbon retention.

We brought experts who have studied carbon balancing of wetlands

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around the world together to EcoSummit 2016 in Montpellier France to discuss carbon fluxes in wetlands and their controlling factors. The international forum and subsequent papers published in this special issue were also partially organized to continue the discussion that our paper created five years earlier and to revise calculations that may now be needed because of many more wetland data sets since then.

2. EcoSummit 2016

Several of the papers in this special issue are the result of presentations at a special session (symposium) held at the 5th International EcoSummit held in Montpellier, France, on August 29–September 1, 2016. EcoSummit 2016 provided a forum for more than 1300 delegates from 75 countries to focus on finding solutions for today's massive environmental and ecological problems. Sessions were held on ecological engineering, ecological restoration, green infrastructure, adaptation to climate change, earth stewardship, ecohydrology, eco-informatics, ecological modeling, sustainable agriculture, protection of biodiversity, carbon sequestration, human ecology and enhancement of ecosystem services.

EcoSummit 2016 also hosted 11 plenary presentations by some of the world's premier ecologists and environmental scientists including Giovanni Bidoglio, Italy; Sandra Díaz, Argentina; John Philip Grime, UK; Connie Hedegaard, Denmark; Stephen P. Hubbell, USA; Blanca E. Jiménez, Cisneros, France; Sandra Lavorel, France; Bai-Lian (Larry) Li, USA; William J. Mitsch, USA; Mihir Shah, India; and Peter Vitousek, USA. Over 750 presentations were given in 93 scientific sessions. There were also 15 side events in the form of workshops, round tables and world cafés. More than 600 posters were also displayed during EcoSummit 2016.

EcoSummit was founded in the mid-1990s as a forum to meet the demands of scientists working in several new ecological disciplines, and who required a better understanding of the concepts and methods for a holistic use of ecology in environmental management. EcoSummit 2016 was the fifth EcoSummit held around the world since the first one was held twenty years ago in 1996 in Copenhagen, Denmark. Other EcoSummits were then held in Halifax, Nova Scotia, Canada (EcoSummit 2000), Beijing, China (EcoSummit 2007), and Columbus, Ohio, USA (EcoSummit 2012; see http://ecosummit2016.org/ecosummit-2012.asphttp://ecosummit2016.org/ecosummit-2012.asp for a listing of journal special issues from that conference). See the history of previous ecosummits at http://ecosummit2016.org/ecosummit-history.asp

2.1. *EcoSummit 2016 special session on wetland restoration and biogeochemistry—engineering carbon balanced landscapes*

The papers in this special issue are partially based on 14 oral presentations in a special session at EcoSummit 2016 entitled "Wetland Restoration and Biogeochemistry—Engineering Carbon Balanced Landscapes" held on August 30, 2017 (Table 1). A photo of the speakers and participants in that special session is shown in Fig. 1. Other authors of papers not presented in that session or presented as posters in EcoSummit 2016 were also invited to submit to this special issue.

3. This special issue on wetlands and carbon

The 19 papers in this special issue are divided into the following categories: 1. estimating greenhouse gas fluxes with eddy covariance (3 papers); 2. methane and other greenhouse gas emissions from wetlands (8 papers); 3. carbon sequestration by wetlands (5 papers); and 4. organic carbon decomposition in wetlands (3 papers).

3.1. *Estimating greenhouse gas fluxes with eddy covariance*

Three papers of this thematic block are analyzing carbon balance of various wetland ecosystems using the EC technique which has been rapidly developed since 1990s (Baldocchi, 2014), Using combined EC and chamber techniques Rey-Sanchez et al. (2018) detected high rates of methane emission in Old Woman Creek, a coastal marsh of freshwater Lake Erie, Ohio, USA. CH_4 flux was mainly determined by water temperature and wind speed but was also related to respiration and photosynthesis. Different parts of wetlands showed different CH_4 flux rates, whereas mud flats had the highest and open water the lowest rates. Accounting for this heterogeneity improves the accuracy of CH_4 flux estimates.

Duman and Schäfer (2018) compared net ecosystem carbon exchange of native and invasive plant communities in an urban tidal wetland in the New Jersey Meadowlands (USA) in the New York City metropolitan area. Vegetation-based partitioning of fluxes was done using footprint model and light response curves. During restoration, the invasive wetland species *Phragmites australis* was replaced by the native *Spartina alterniflora*. The area with native species had an increased CO_2 uptake during summer days, but also higher CO_2 emissions during nights and winters. Higher emissions can be explained by the input of river water with high organic material content. At the restored site allochthonous carbon input from the river to the wetland was found to be higher. Conclusively, the *S. alterniflora* marsh was serving as a carbon source, releasing CO_2 to the atmosphere.

Morin et al. (2018) measured CO_2 emissions from an oligotrophic temperate lake in Northern Michigan (USA) by the EC method. They found that during two full growing seasons the lake was an overall net carbon source, but emitting significantly less CO_2 than nearby terrestrial ecosystems. The net carbon flux from the lake is primarily correlated with wind speed, indicating the key role of mixing in the upper water layer whereas respiration is more strongly depending on microbial indicators than on gross primary production (GPP). Horizontal advection between the lake and the observation point far from shore was significantly lower than EC-observed vertical turbulent fluxes.

Development and wider use of EC technique in measurement carbon balances in freshwater lakes (see Vesala et al., 2012) will possibly clarify freshwater ecosystem's role in global carbon cycle because most of publications present freshwater lakes like significant net sources of carbon (Bastviken et al., 2011; Kortelainen et al., 2011). The carbon balance in freshwater inland wetlands is even less known. Contributions in our special issue demonstrate elevated CO_2 and CH_4 emissions in freshwater wetlands (Duman and Schäfer, 2018; Rey-Sanchez et al., 2018). Similarly, a meta-analysis provided by Lu et al. (2017) on CO_2 balance of inland and coastal wetlands measured using EC method showed that inland wetlands were small CO_2 sinks or nearly CO_2 neutral, while coastal wetlands provided large CO_2 sinks.

3.2. *Methane and other greenhouse gas emissions from wetlands*

Eight papers in this special issue provide information on soil/sediment respiration and CH_4 emissions in peatlands of the Americas (Veber et al., 2018), cypress swamps (Pereyra and Mitsch, 2018) and coastal mangroves (Cabezas et al., 2018) in subtropical Florida, fens (Duval and Radu, 2018; Radu and Duval, 2018), treatment wetlands (Hernandez et al., 2018), wetland mesocosms (Schultz and Pett, 2018), and tidal freshwater marshes (RoyChowdhury et al., 2018).

Veber et al. (2018) analyzed relations among CO_2, CH_4 and nitrous oxide (N_2O) emissions and the physical and chemical conditions of the peat in following peatland ecosystems in a natural and managed transitional bog in Quebec, Canada, a natural páramo and grazed peatland in the Colombian Andes, and a bog and a fen in Tierra del Fuego, Argentina. The dark static chamber-based analyses of GHG emissions showed that (1) intensive peatland management increases emissions of all GHGs with the highest impact on N_2O-N emissions and ecosystem respiration; (2) nitrous oxide emissions were mostly controlled by Total Inorganic Nitrogen (TIN), C/N ratio, and soil temperature. Proposed mitigation measures include the regulation of grazing intensity and replacement of arable fields with grasslands.

Table 1
Presentations at EcoSummit 2016 in Special Session "Wetland Restoration and Biogeochemistry—Engineering Carbon Balanced Landscapes" in Montpellier, France, August 30, 2016. Speaker is indicated by [a] for multiple-author presentations.

14:00 – 18:00	Session 32 – Wetland Restoration and Biogeochemistry-Engineering Carbon Balanced Landscapes *Room: Pasteur, Level 0* Session Organizer: William J. Mitsch, *Everglades Wetland Research Park, Florida Gul f Coast University, USA*
14:00–14:15	Wetlands, carbon, and climate change revisited W.J. Mitsch[a], L. Zhang, and J. *Villa, Florida Gulf Coast University, USA and Corporacion Universitaria Lasallista, Colombia*
14:15–14:30	Engineering natural wetlands for enhanced carbon sequestration C. Freeman, *Bangor University, Wales, UK*
14:30–14:45	The effects of anthropogenic disturbance on carbon storage and accretion in wetland soils at the national regional scales S. Fennessy[a], A. Nahlik, D. Wardrop, J. Moon, *Kenyon College, USA, Penn State University, USA*
14:45–15:00	Methane emission from natural and constructed wetlands: Implications for mitigation U. Mander[a], J. Tournebize, J. Parn, *University of Tartu, Estonia, IRSTEA, France*
15:00–15:15	Role of the soil microbiome in wetland coupled carbon biogeochemistry: A multi-omics approach T. RoyChowdhury[a], Y.M. Kim, C. Nicora, H. Diefenderfer, J. Cliff, T. Metz, L.A. McCue, J. Stegen, J. Jansson, V. Bailey et al *Pacific Northwest National Laboratory, USA*
15:15–15:30	Combining eddy-covariance and chamber measurements to determine the methane budget from a small, heterogeneous urban wetland park T.H. Morin, G. Bohrer[a], K.C. Stefanick, A.C. Rey-Sanchez, W.J. Mitsch The *Ohio State University, USA, Florida Gulf Coast University, USA*
15:30–15:45	Methane dynamics in a restored and natural wetland–implications for restoration K.V.R.Schafer[a], T. Duman *Rutgers University, Newark, USA, National Science Foundation, USA*
15:45–16:00	From lowlands to mountain tops: Carbon flow and stock measurements in tropical wetlands of different hydrogeomorphic classes for resource management and planning J.A. Villa[a] F.H.Moreno, J.C. Quevedo, A.M. Osorno, J.M. Marulanda, *Corporacion Universitaria Lasallista, Colombia, Universidad Nacional de Colombia-Sede Medellin, Colombia*
16:00–16:30	Refreshment break
16:30–16:45	Plant community effects on biomass production and methane emissions from experimental wetlands: Applications for restoration R.E.Schultz[a], L. Pett, *SUNY Plattsburgh, USA*
16:45–17:00	Using stable isotopes to determine source and fate of carbon in a coastal wetland B. Bernal[a], J.P. Megonigal *Smithsonian Environmental Research Center, USA*
17:00–17:15	Modeling greenhouse gas chemistry and transport in heterogeneous wetlands T.H. Morin[a], G. Bohrer, A.C. Rey-Sanchez, K.C. Stefanik, K.V.R. Schafer, W.J. Mitsch *The Ohio State University, USA, Rutgers University, USA, Florida Gulf Coast University, USA*
17:15–17:30	Greenhouse gas balance quantification using an automatic chamber system shows large contrasts in CH4 emission of peatland restoration projects J. van Huissteden[a] C. Straathof, B. vande Riet, VU *University, The Netherlands, Landschap Noord-Holland, The Netherlands, B-Ware, The Netherlands*
17:30–17:45	Temperature dependence of greenhouse gas release from rich and poor fen soils of Ontario, Canada T.P. Duval[a], D.D.Radu, *University of Toronto Mississauga, Canada*
17:45–18:00	Peat capping: Natural capping of wet landfills by peat formation S.F. Harpenslager, C.C. Overbeek, J.P.Van Zuidam,.J.G.M.Roelofs, S. Kosten, L.P.M. Lamers[a], *Queen Mary University of London, UK, University of Amsterdam, The Netherlands, FLORON, The Netherlands, Radboud, University Nijmegen, The Netherlands*

[a] presented the paper.

Pereyra and Mitsch (2018) determined and compared CH_4 fluxes from 6 subtropical *Taxodium* swamps in southwest (SW) Florida with different hydroperiods and land-use conditions. Chamber method was used for flux analyses. CH_4 fluxes from the protected reference sites of Corkscrew Swamp Sanctuary were significantly higher than fluxes from the disturbed (partially drained) sites in more managed landscapes. More continuous surface flooding at the reference sites compared to seasonal flooding at the disturbed wetlands is possibly the main cause for the differences in CH_4 emissions, while deeper water and higher soil temperatures at measurement times did not have a significant impact.

Cabezas et al. (2018) compared CH_4 fluxes in two mangrove tidal creeks in SW Florida. In most cases of chamber measurements, no CH_4 emission was observed with the lowest emissions at the end of a typical wet season and the highest emissions in the middle of the dry season. This study concluded that mangroves in SW Florida are clearly net sinks of both carbon and radiative forcing when the low emission rates were compared to previous studies of carbon sequestration in the same tidal creeks (Marchio et al., 2016) and therefore were beneficial for mitigating climate warming. These results are in good accordance with the findings from Lu et al. (2017) and others and demonstrate why the term "blue carbon" for coastal wetland carbon retention has received so much attention.

Duval and Radu (2018) determined the effect of increasing temperature and soil organic matter (SOM) quality on rates of GHG production in lab incubations from peat soils formed under different plant functional types of temperate rich and poor fens of southern Ontario, Canada. The study showed that SOM quality differed by plant functional type and the quality of SOM, together with soil temperature explained variability in GHG production. Lignin and cellulose content controlled CO_2:CH_4 ratio, thus, maintenance of moss and shrubs could help minimizing carbon losses. To determine impact of rainfall regime on CH_4 fluxes from a cool temperate fen the same authors (Radu and Duval, 2018) conducted a field manipulation experiment where irrigation treatments were used to simulate different seasonal rainfall regimes over three vegetation types found in a poor fen in southern Ontario, Canada: *Sphagnum capillifolium* (moss); *Carex oligoperma* (sedge); and *Chamaedaphne calyculata* (shrub). The rainfall frequency and intensity were manipulated within a growing season without changing seasonal totals. Decreased frequency of rain led to greater CH_4 fluxes from moss and sedge areas but not in shrub areas. Water table increase in sedge areas exponentially increased the CH_4 emission. There were significantly greater CH_4 fluxes from all communities with increasing days since the previous rainfall event. Longer duration between rain events in future could lead to increased peatland CH_4 flux if shrub expansion is contained.

Hernandez et al. (2018) investigate CH_4 and N_2O emissions and pollutant removal in constructed wetland (CW) mesocosms planted with the subtropical ornamental plant *Zantedeschia aethiopica* to treat polluted river water. Likewise, CH_4 and N_2O emissions in zones planted with macrophytes (*Typ*ha sp and *Cyperus papyrus*) versus zones planted with *Zantedeschia aethiopica* in a pilot scaled CW treating municipal wastewater were compared. The average CH_4 emissions were significantly higher in surface flow (SF) type mesocosms than in the subsurface flow (SSF) type mesoscosms, whereas plant density did not affect emissions. SSF CWs showed higher ammonia and nitrate removal efficiencies than SFCW and also showed higher N_2O emissions.

Fig. 1. Presenters and Participants in Session 32 on "Wetland Restoration and Biogeochemistry: Engineering Carbon Balanced Landscapes" at EcoSummit 2016, Montpellier, France, August 30, 2016.

Differences in CH_4 emissions in the zones planted with native wetland plants in comparison with zones planted with *Zantedeschia aethiopica* might indicate that CH_4 production and consumption in CW are influenced differently by the ornamental plants than by native wetland plants.

Schultz and Pett (2018) analyzed plant community effects on CH_4 fluxes, root surface area, and carbon storage in experimental wetland mesocosms. Three plant groups that represented different growth forms (i.e., "functional groups": ferns, reeds and tussocks) were planted in mesocosms to represent four levels of functional diversity and every combination of functional groups at each diversity level. CH_4 fluxes did not vary by functional group richness level or composition. Presence of the reed and tussock functional groups decreased fluxes while functional group richness did not have a significant effect on plant carbon storage. The results indicate that planting reed and tussock functional groups in dense clumps during restoration could maintain a high level of carbon storage and relatively low CH_4 emissions.

RoyChowdhury et al. (2018) studied temporal dynamics of CO_2 and CH_4 loss potentials in response to rapid hydrological shifts in tidal freshwater wetland soils and found that soil redox rather than antecedent moisture regime drives microbe-mediated biogeochemical transformation of dominant electron acceptors. Also, the results demonstrate that extended and short-term saturation create conditions conducive to increasing metabolite availability for anaerobic decomposition processes, with a significant lag in methanogenesis. Under wet conditions, acetate-dependent sulfate and iron reduction may govern anaerobic carbon metabolism and constrain methanogenesis.

3.3. Carbon sequestration by wetlands

Carbon sequestration is one of the most important ecosystem services provided by wetlands and it occurs in wetlands at a greater rate than in any other ecosystem on the planet (Mitsch et al., 2013; Mitsch and Gosselink, 2015). Yet we continue to be surprised that many scientists emphasize only greenhouse gas emissions from wetlands rather than carbon sequestration in climate change policy documents, e.g., IPCC (2013). This section of our special issue contains 5 papers on carbon sequestration in wetlands. Some of the papers briefly discuss methane and other greenhouse gas emissions but they mostly emphasize carbon sequestration and illustrate methods for estimating it.

Villa and Bernal (2018) provided a meta-analysis of 110 peer-reviewed studies of wetland carbon sequestration from around the world and gave "an overview of the current policies and guidelines in which C sequestration in wetlands is framed as an ecosystem management practice." They found that the most frequently used approach in 1037 independent measurements in the 110 publications was soil dating (68%) through methods such as ^{137}Cs and 210Pb isotopes followed by direct measurement (31%). Using carbon budgets to estimate NEE (net ecosystem exchange) by eddy covariance techniques) was only used in one of these 1037 estimates to estimate carbon sequestration. Of the wetland types evaluated for carbon sequestration, coastal salt marshes (43.7%) and freshwater marshes (19.1%) were most frequently studied, followed by non-forested peatlands (14.3%), forested swamps (11.3%), and finally mangrove swamps (7.7%). Of the 333 carbon sequestration rates investigated, 40.5% were in boreal climates, 35.4% in temperate climates, 22.2% in the tropics, and 1.8% in arid climates. Using the extent of wetlands in the world reported by Mitsch and Gosselink (2015), temperate wetlands are over-represented while tropical wetlands are under-represented. Using average carbon sequestration rates presented by Mitsch et al. (2013) for climatic regions, boreal climates are over-represented as average carbon sequestration rates in northern peatlands are a fraction of the rates normally measured in temperate and tropical climes. The paper concludes with a review of a variety of methods that have been used to translate carbon sequestration and methane emissions into wetland management, particularly wetland restoration and creation. There is still no fully accepted method despite models being proposed by Mitsch et al. (2013), Neubauer and Megonigal (2015) and others. The issue remains an enigma that has discouraged wetland creation for carbon sequestration and other ecosystem services with little regard for the fact that wetlands disappeared at an alarming rate in the 19th and 20th centuries and continue to do so in some regions of the world (Mitsch and Gosselink, 2015).

Fennessy et al. (2018) used ^{137}Cs isotope analysis to compare carbon sequestration at 29 sites in Pennsylvania and Ohio in east/midwest USA while describing the sites with hydrology and floristic quality indicators. Carbon accretion rates ranged from 7.7 to 149 g-C m^{-2} yr^{-1} with highest carbon sequestration in the wetlands with the low floristic quality as defined by a Floristic Quality Assessment Index (FQAI) that ranges from 0 (for invasive species) to 10 (wetland vegetation species limited to specific wetland conditions) as used in Ohio and some other USA states. They found, not surprisingly, that carbon sequestration is highest in conditions where plant FQAI indices were low (2.3 ± 0.5) and lowest where plant FQAI indices were high (4.6 ± 0.6). They also concluded that carbon sequestration was correlated to sediment accretion rates as would be expected since the ^{137}Cs method estimates carbon sequestration based on two variables—sedimentation and carbon density in the soil.

Craft et al. (2018) compared carbon sequestration and nutrient (N and P) burial in five wetlands in Midwestern USA and four wetland sites in the Czech Republic. Carbon sequestration rates (47–50 g-C m^{-2} yr^{-1}) in the nine floodplain and depressional wetlands were low compared to rates estimated for temperate climate wetlands reported by Mitsch et al. (2013) and Mitsch and Gosselink (2015). Craft et al. (2018) concluded that sedimentation rates in disturbed agricultural landscapes were more important than the landscape position of the wetlands in carbon and nutrient retention.

Harpenslager et al. (2018) introduce the idea of "peat capping" of landfills by investigating a recent (2011) construction of a 100-ha wetland in the Netherland on top of a landfill that was active during 1927–1981. Overbeek et al. (2018) conducted litterbag experiments at these same wetlands to estimate decomposition of the new wetland vegetation in 2013-14, three growing seasons after the wetlands were created. The wetland became naturally colonized with emergent (e.g., *Typha* spp., *Phragmites australis*, *Glyceria maxima*) and submerged vegetation (e.g. *Potamogeton* spp., *Myriophyllum spicatum*) but retained some introduced submerged/floating *Stratiotes aloides*. Harpenslager et al. (2018) compared freshwater wetland basins that were isolated with clay levees on top of this landfill, some with sandy soils, some with additional clay added to the sand, and others that had primarily organic top soil. Diffusive fluxes of CO_2 and CH_4 were measured in fixed and floating chambers for more than one year. Carbon sequestration was estimated from net ecosystem exchange (NEE) determined from the net CO_2 and CH_4 exchanges. *Typha* wetlands on organic soils were often carbon sources (ave = +300 g-C m^{-2} yr^{-1}) while clay and sandy soil wetlands were usually net carbon sinks (-10 to −600 g-C m^{-2} yr^{-1}). The authors conclude that "when quick results are important, for instance when capping a highly contaminated landfill, …the application of 'preferably recycled' clay or organic soil is necessary to obtain a biomass production high enough for the build-up of an organic layer within a short period." Overbeek et al. (2018) suggest that in the early years after wetland construction "it may be beneficial to optimize production instead of minimalizing decomposition rates" to optimize carbon sequestration in these wetlands. The idea of capping landfills, which are enormous methane sources, with autotrophic wetlands that could then serve as counterbalancing carbon sinks is appealing. The design must be done carefully so that it does provide a system that is systematically a carbon sink and not another carbon source.

3.4. Organic carbon decomposition in wetlands

Because northern peatlands store 455 Pg of organic carbon, one-third of the world's soil carbon, understanding the processes that affect this carbon's decomposition in these water-logged, mostly boreal, wetlands is urgent, given that changes in climate are occurring that could reduce this water logging. Carbon accumulates in anaerobic soils because "phenolic inhibitors slow the rate of decomposition to below that of photosynthetic production" (Dunn and Freeman, 2018). Water logging of peat soils suppresses the activity of phenol oxidase, one of only a few enzymes capable of breaking these inhibitors down. This concept has been referred to as the "enzymic latch" (Freeman et al., 2001). Three papers in this special issue (Dunn and Freeman, 2018; Dunn et al., 2018; Friesen et al., 2018) are from Chris Freeman's lab in Bangor, Wales, and feature experiments or reviews related to peat decomposition and this enzymic latch. Dunn and Freeman (2018) describe the importance of the molecular weight of phenols in inhibiting effect of peat decomposition. Peat samples were taken from a blanket bog in Wales and emissions of CH_4 and CO_2 were measured in addition to the molecular weight of the phenolic compounds. They found that the higher the molecular weight, the slower the decomposition of soluble organic matter in wetlands. Dunn et al. (2018) describe an experiment designed to investigate the importance of light intensity on the enzymic latch. They hypothesized that phenol oxidase activity in the rhizosphere of peatland plants could be manipulated by varying the intensity of light to which peatland plants are exposed. Their 6-week experiment, conducted in 45 *Sphagnum-Eriophorum-Calluna* peat moss mesocosms set up with plants from a North Wales blanket bog in controlled laboratory light conditions, showed no significant differences in phenol oxidase activity in 3 distinct light conditions. Results were not different among the three species of peat mosses either. They did suggest that if light was somehow manipulated in some sort of ecoengineering or geoengineering approach (not described in any detail) that "the order of peatland plants to achieve maximized suppression of organic matter decomposition is therefore: *Calluna* > *Sphagnum* > *Eriophorum*."

Friesen et al. (2018) provided a review paper on organic carbon decomposition in subtropical/tropical mangrove swamps and the so-called "blue carbon" sequestration as described in another paper in this special issue (Cabezas et al., 2018). They summarize the roles of benthic macrofauna, hydrology, and microbial activity in the decomposition of organic matter in mangrove swamps. Macrofauna such as crabs are described as having the role of improving litter quality for microbial decomposition but microbial decomposition in mangroves is slow because of phenolic concentrations in the litter. They conclude that there is still an incomplete picture of decomposition in mangroves, including how phenolics influence the rate of decomposition in mangrove litter. Yet mangroves are generally described as one of the more important coastal wetlands providing blue carbon sequestration, partially because of their normally low level of emissions of methane as described by Cabezas et al. (2018).

4. Conclusions

Further development and wider use of eddy covariance measuring stations could help clarify long-term annual budgets of CO_2 and CH_4 in wetlands. Results of papers from this special issue showed that CH_4 fluxes in some coastal wetlands such as mangroves can be negligible while various inland wetlands can be significant sources of CH_4. However, the results also demonstrated a variety of parameters determining dynamics of methane fluxes in different wetlands. Therefore, more attention should be paid to detailed analysis of the impact of environmental and management factors on CH_4 budgets. Estimating carbon sequestration is almost always done by soil dating methods such as with ^{137}Cs and 210Pb isotopes and rarely if at all by estimating NEE (net ecosystem exchange) by eddy covariance techniques. The precision is simply not there with both GPP and R being such high fluxes. Carbon sequestration rates in wetlands continue to show order of magnitude differences among systems but sometimes among laboratories. This could be due the inexact nature of estimating soil dates over relatively short (~50 year) time horizons. The idea of capping landfills, which are enormous methane sources, with wetlands, which could then turn them into carbon sinks, is interesting and worth investigating further but the design of these systems is still in its infancy. Organic carbon decomposition in wetlands has been investigated extensively for decades and more recently on the processes and main contributors to both decomposition and preventing it from happening. Phenol oxidases, among the few enzymes capable of breaking down phenolics, which in turn inhibit decomposition, are referred to as "enzymic latches" and may be one of the key controllers of organic matter decomposition in waterlogged and submerged soils in wetlands. The balance between greenhouse gases and carbon sequestration remains an enigma with many unknowns. But we believe that the papers in this special issue take us one step closer to providing clarity on how to estimate and compare the carbon fluxes that are involved.

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