Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
e-ISSN: 2395-3454

Vol. 16 No. 3 pp. 813-819 2017

Original Research Paper Open Access

The Use of Constructed Wetlands in Sequestrating Carbon: An Overview

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 24-06-2016
Accepted: 16-07-2016

Key Words:
Carbon sequestration
Climate change
Carbon dioxide
Constructed wetland

ABSTRACT

The increasing carbon dioxide concentration in the atmosphere has triggered the need to look for a mitigating strategy to address climate change. Wetlands have been noted to have the potential in improving water quality, mitigating flood (act as a floodplain) as well as protecting wildlife habitat and coastal area. Wetlands are also capable to sequestrate carbon. Due to rapid developments, natural wetlands are being destroyed day by day. Hence, constructed wetlands have been proposed to emulate the functions of natural wetlands. However, the use of constructed wetlands in sequestrating carbon is yet to be explored. Therefore, the purpose of this paper is to provide an overview and compare the carbon sequestration potential between natural and constructed wetlands. A particular emphasis will be given to the use of constructed wetlands in sequestrating carbon. It is found that constructed wetlands are capable to sequestrate carbon as good as natural wetlands. Sustainable utilization of constructed wetlands as a carbon sink could be one of the effective initiatives to mitigate climate change.

INTRODUCTION

Ever since the industrial revolution, atmospheric concentration of carbon dioxide (CO_2) has drastically increased, from 280 ppmv in 1750 to 367 ppmv in 1999 (Lal 2004) and it is currently increasing at the rate of 3.3 Pg C/year (1.5 ppmv/year) (IPCC 2001). The atmospheric concentration of CO_2 was mainly contributed by fossil fuel combustions that have been actively occurred since the 20th century. Besides that, land use change includes deforestation, biomass burning, as well as conversion of natural forest to agricultural land, which not only contributes to the increasing CO_2 concentration in the atmosphere, but also causes the increasing of other greenhouse gases (GHGs) like methane (CH_4) and nitrous oxide (N_2O) (Lal 2004). The increasing concentration of these GHGs in the atmosphere has led to an increase in the average global surface temperature of 0.6°C since the late 19th century. The mean rate of global temperature increase is observed to be exceeding the critical rate of 0.1°C/decade (Lal 2004).

Many researches have been conducted to remove carbon dioxide from the atmosphere to mitigate the effects due to climate change. One of the initiatives is augmenting the use of wetlands. Wetlands are areas of mainly water saturated soil, including marshes, lakes and floodplains (Kayranli et al. 2010). Wetlands play a major role in the global carbon cycle because they are an important carbon sink for atmospheric carbon dioxide. They also provide many beneficial ecosystem services to humankind, for example, water quality improvement, flood mitigation, wildlife and coastal protection (Mitra et al. 2005, Mitsch & Gosselink 2007). Wetlands have also been estimated to store 20-30 % of the earth's soil pool of 2,500 Pg of carbon (Bridgham et al. 2006) and carbon from the atmosphere due to their anoxic wet conditions (Mitcsh et al. 2013). Furthermore, wetlands have the highest carbon density among all other terrestrial systems.

There have been 3.7 times faster rate of wetlands loss during the 20th and early 21st centuries, with a loss of 64-71% of wetlands among the world since 1900 AD (Davidson 2014). The increasing rate of natural wetlands loss has led to more creation of constructed wetlands which were intended to emulate the functions and values of natural wetlands that have been destroyed. Constructed wetlands aim to provide an ecosystem to counter balance natural wetlands that have been converted for agriculture and urban development, improving water quality, controlling floods and producing food and fibre. Constructed wetland systems have been adopted and applied successfully for the purification treatment of many wastewater since 1980 because most of these systems are easy to practice, have low construction cost and require only a little maintenance (Kadlec et al. 2000, Kayranli et al. 2010, Machate et al. 1997). Scientists have conducted many investigations on the use of wetlands storing carbon, since the concept of wetlands carbon sequestration has been revealed and accepted. However, the use of constructed wetlands in carbon sequestration is still very limited. Hence, in this article, we provide an overview of the use of constructed wetlands in sequestrating carbon and comparing the capability of constructed and natural wetlands in sequestrating carbon.

The role of wetlands in carbon sequestration: Wetlands are sources of GHGs (methane mostly) but at the same time they have a high capacity to sequestrate carbon and store it for a long term (Lal 2004, Mitsch et al. 2010). The process of extracting carbon from the atmosphere is called carbon sequestration (Kayranli et al. 2010). According to Hanson & Hanson (1996), wetland soil normally is fully saturated, located well below the water table and this wetland condition creates anaerobic (anoxic) soil, which can store carbon dioxide and release methane by decreasing the decomposition rate. Bernal & Mitsch (2012) also agreed on this and stated that wetland ecosystems are so productive that they are capable to generate large amounts of organic matter and store it in semi-decomposed state due to the anaerobic condition. Characteristics such as high productivity, high water table, and low decomposition rate related to a wetland lead to carbon storage in the soil, sediment and detritus (Whitting & Chanton 2011). However, in dried wetlands, unsaturated soil serves as atmospheric methane sink whereby methane is absorbed through methanophiles and anaerobic methane-oxidizing bacteria in the soil (Kayranli et al. 2010). The amount of methane released to the atmosphere and absorbed depends on the water table level of wetlands (Moore & Dalva 1993). This is because the water table level determines the presence of aerobic and anaerobic conditions of wetlands, which will control the methane production process (Kelly et al. 1995, Kayranli et al. 2010).

Wetlands have been identified to have the potential in

Table 1: Previous research for the potential of carbon sequestration in wetlands.

Title	Remarks	Author & Year
Greenhouse carbon balance of wetlands: Methane emission versus carbon sequestration	An annual measurement of the relationship between methane emission and net carbon fixation in three wetlands ecosystems and found that all wetlands involved are good in carbon sink.	Whitting & Chanton2001
Global carbon sequestration in tidal, saline wetland soils	Compiled data of carbon equestration for 154 sites in mangroves and salt marshes from the western and eastern Atlantic and Pacific coasts, as well as the Indian Ocean, Mediterraneen Ocean, and Gulf of Mexico. Combining wetlands globally, a total of at least 44.6Tg C yr^{-1} or more of carbon can be stored.	Chmura et al. 2003
Dynamics of carbon sequestration in a coastal wetland using carbon measurements	Estimated the long-term and short-term rates of C accumulation, using C and C isotopic measurements of peat cores collected along a soil chronosequence, in a coastal wetland in north Florida. The long-term C accumulation rates determined by examining the C inventory and the radioactive decay of radiocarbon as a function of depth in the peat cores decrease with time. Due to higher rates of C sequestration and lower methane emission, coastal wetlands could be important C sinks than other ecosystems in a warmer world.	Choi & Wang 2004
Soil carbon cycling and sequestration in a seasonally saturated wetland receiving agricultural runoff	To better understand the role of seasonally-saturated wetlands in sequestrating eroded C, the spatial and temporal dynamics of C and sediment accumulation were measured in a 13-year-old constructed wetland used to treat agricultural runoff. It showed that constructed flow-through wetlands play an important role in carbon storage.	Maynard et al. 2011
Wetlands, carbon, and climate change	Carbon accumulated in soils at seven created and natural wetlands, located at six wetland sites in the temperate zone and tropics in Ohio, Costa Rica and Botswana, and its prove that created wetland sequestrate more carbon than natural.	Mitsch et al. 2012
Comparing carbon sequestration in temperate freshwaterwetland communities	Six temperate wetland communities were examined in Ohio. The wetland types and communities were assessed in detail to determine the role of wetland as carbon sequestering system. It is found that carbon sequestration value is higher in depressional wetland compared to riverine area, and carbon highly sequestered efficiently in water lotus (Nelumbo Lutea) communities area.	Bernal & Mitsch2012

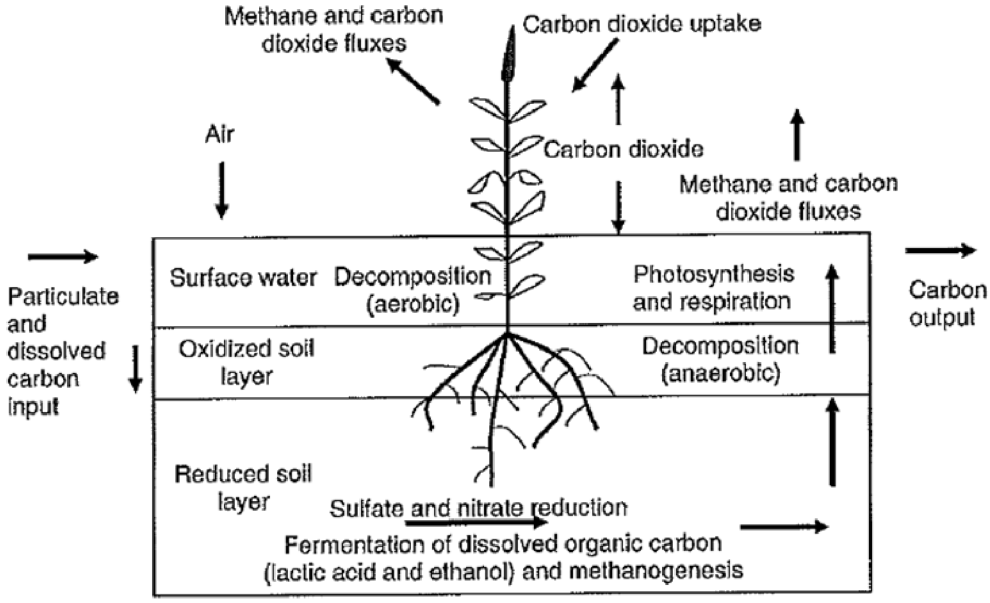

Fig. 1: Process of carbon cycle (Source: Kayranli et al. 2010).

carbon sequestration because there is a need to formulate a proper wetlands management, not only concentrating on the role of wetland as a water treatment agent, but achieving sustainability of wetland ecosystem. As given in Table 1, a number of previous researches that have been conducted to examine the use of wetlands in carbon sequestration and sediment soil, as well as living plant communities within wetland, have been proven as one of the effective carbon sinks (Krogh et al. 2003, Brevik & Homburg 2004, Bedard-Haughn et al. 2006, Kayranli et al. 2010). The findings indicate that wetlands are vital carbon storage and may help us to mitigate the climate changes. In order to achieve the vital aim, we must improve our operations and practices towards these wetlands so that methane fluxes can be minimized and carbon storing could be increased.

Process involved in carbon sequestration: In general, wetland plants grow at a faster rate than they decompose, resulting to a net annual carbon sink (Kayranli et al. 2010). Carbon sequestration involves a set of processes utilizing carbon within wetlands, such as respiration in the aerobic zone, fermentation of dissolved organic carbon, methanogenesis (formation of methane by microbes), reduction of sulphate, iron and nitrate in the anaerobic zone (Kayranli et al. 2010). All these processes are illustrated in Fig. 1. Respiration in the aerobic zone is the biological conversion of carbohydrates to carbon dioxide, while fermentation is the conversion of carbohydrate to chemical compounds such as ethanol and carbon dioxide (Kayranli et al. 2010).

Wetlands contain large amounts of dissolved organic matter where it will induce microbial activity in soil (Bano et al. 1997, Zweifel 1999, Kayranli et al. 2010) to sink carbon and nitrogen, or to be the source of methane. Due to bacterial oxidation, dissolved organic carbon can be converted to inorganic matter (compounds) and stored by mineralization. The organic matter contents within the wetlands also influenced by sort of processes such as biodegradation, sedimentation, and volatilization, whereby it promotes natural organic matter accumulation in soil (Kayranli et al. 2010). Gaseous products are formed under both aerobic and anaerobic conditions. Under anaerobic condition, both carbon dioxide and methane will be formed through the decomposition of organic matter, while only carbon dioxide is formed in aerobic condition (Mitch & Gosselink 2007).

The potential of constructed wetland to sequestrating carbon: The potential of constructed wetlands to accumulate and store organic matter in the soil received less attention until the recent concerns on carbon sequestration in natural systems have been acknowledged widely (Anderson & Mitsch 2006). Small-scale constructed wetlands used for the treatment of wastewater can be considered as carbon sinks, though it sequestrate very small amounts of carbon, they are considered sizeable carbon sinks due to the difference in energy consumption between the wetland and the equivalent wastewater treatment plant (Ogden 2001). Joroen & Adrie (2014) also concluded that the constructed wetland (place of study: Lankheet) is most likely a sink of carbon dioxide in the present conditions. Annual net amount sequestration of carbon dioxide was 0.27-2.4 kg $m^{-2}y^{-1}$ which represented 12-67% of the carbon dioxide in the biomass. It has also been proven by Maynard

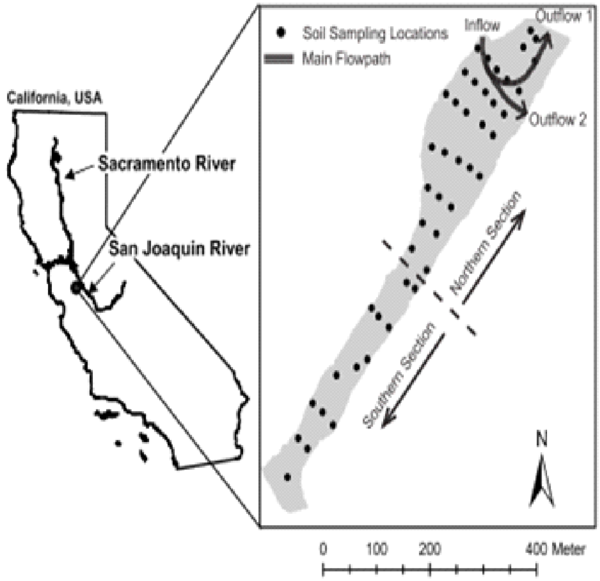

Fig. 2a: Schematic map of study site, sampling locations, inflow and outflow locations.

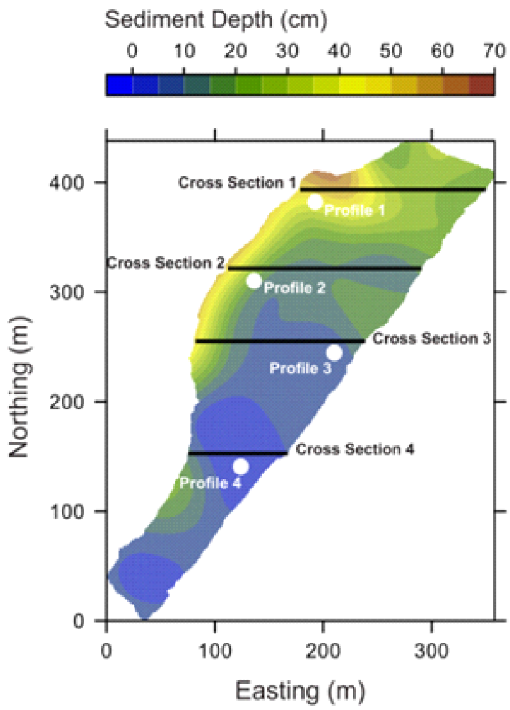

Fig. 2b: Interpolation map showing the depth of sediment accumulation over 13 years in the northern section of the wetland and also sampling locations for sediment cross section 1-4. (Source: Maynard et al. 2011).

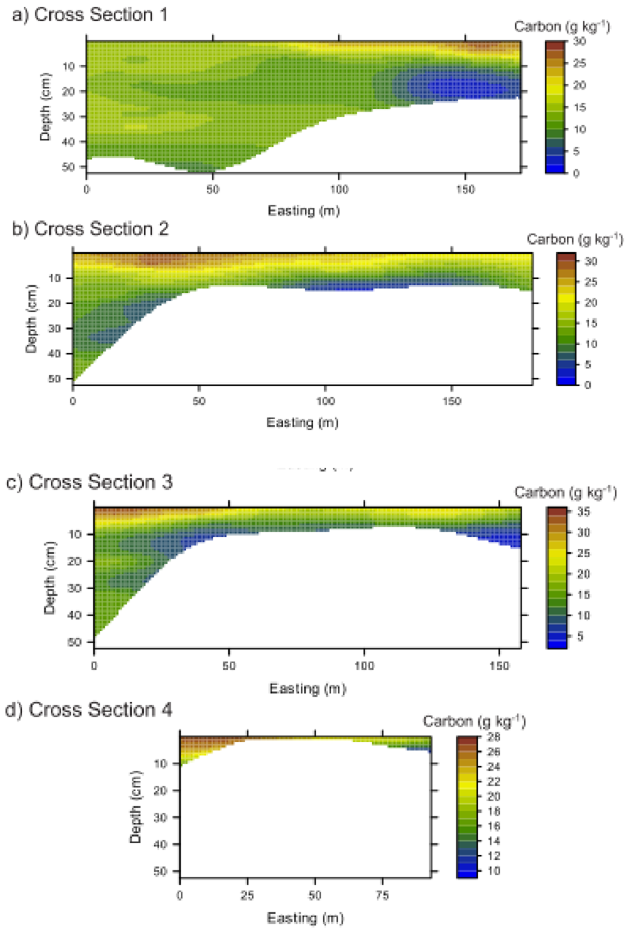

Fig. 3: Maps showing vertical cross-section of sediment carbon concentration along four transects running west to east (Source: Maynard et al. 2011).

et al. (2011) that constructed wetland can store carbon for a long term, whereby the study was conducted at a 13 years old constructed wetland located at the west of the San Joaquin River in California's Central Valley (Fig. 2a).

The research site used to be the floodplains, but it was converted to an agriculture land in the 1930s and restored into a wetland in the early 1990s. In brief, the findings show that agricultural activity significantly increases the rate of carbon storage within wetlands and causes the accumulation of nutrients to the ecosystem, which also being claimed by McCarty & Ritchie (2002). The study area experienced hot dry summers (mean summer temperature = 24°C) and cool moist winters (mean winter temperature = 8 °C) with a mean annual precipitation of 28 cm. There is a concrete relationship between climate and soil, which means the organic carbon content decrease with increasing temperature and organic matter decomposition (Maynard et al. 2011). Hence, if temperature continually increases, the decomposition of organic matter would also increase, and consequently wetlands could become a major carbon source. However, in this study it is not clearly stated the correlation between carbon sequestration values and temperature. The wetland

Table 2: Findings on every different location of soil sedimentation depth (Source Maynard et al. 2011).

Cross section	Findings
Cross section 1 Located in the area where sedimentation was highest from the input towards the output	In the area proximal to the input along cross section 1 (0 and 50 m easting of the wetlands), C concentration was uniform with depth ranging from 10 to 15 g kg^{-1} up to 50 cm of sediment depth. With the increasing distance from the input (125 to 175 m), sediment thickness decreased, approximately 20 cm and SOC decreased with depth from 25 to 30 g kg^{-1} in the surface layer to 3 to 5 g kg^{-1} in deeper layers.
Cross Section 2 and 3 Moderate soil deposition area	There was a trend of high C concentration in the surface layer range between 25 to 35 g kg^{-1}, which decreased with depth (5 to 15 g kg^{-1}) of soils.
Cross Section 4 Located in the zone of low sedimentation Sediment thickness above the antecedent layer range from 2-10 cm	Carbon concentration was high in this region and decreased with increasing distance to the east, ranging between 18 to 28 g kg^{-1} in the west (0-25 m to the west) to 10 to 18 g kg^{-1} along the 70-90 cm of eastern end of the transections.

has a surface area of 7.3 ha with a long (850 m) and narrow (85 m) design and an average water depth of ~0.6 m. The spatial patterns of carbon (C) within the different soil depositional environments are presented via four, 2-D cross-sections (Fig. 2b and Fig. 3). Each cross section runs from west to east, showing the distribution of C with the depth. The findings of the C storage in wetland soil sediments are presented in Table 2. Through the findings, it proves that constructed wetlands are capable to sequestrate and also store carbon for a long term, but the contribution of carbon sequestration vary from different depth of sediment accumulation among the wetland areas. However, there are several researches indicating that constructed wetlands could be either a sink or a source of CO_2 depending on the time scale of research and the environmental management involved (Brix et al. 2001, Thiere et al. 2011). Also in comparison to that of Maynard et al. (2011), Landry et al. (2009) claimed that constructed wetlands emit 2 to 10 times more GHGs than natural wetland, but they observed unplanted wetland systems in their investigation, while the wetland observed by Maynard et al. (2011) was a well planted 13 year old constructed wetland converted to agriculture in 1930s. The presence of plants is important because it may improve the diffusion of gases through water and affect the methane production (Zhu & Sikora 1995).

Comparison of carbon sequestration in constructed and natural wetlands: Stern (2007) claimed that, to estimate with precision a wetland's carbon sequestration capacity, it is more accurate to differentiate between wetland types. A research had been done by Mitsch et al. (2012) **t**o compare the ability of both natural and constructed wetlands in sequestrating carbon. The types of wetlands involved, varied in the vegetation and functions. The wetlands involved are, two 1-ha created flow through temperate marshes wetlands at the Wilma H. Schiermeier Olentangy River Wetland Research Park (ORWRP) in the campus of the Ohio State University. The western basin, named Wetland 1, was planted with 13 native species of macrophytes in May 1994, while the eastern basin, named Wetland 2, was allowed to colonize naturally. The next wetland involved was a 56-ha natural flow-through marsh discharging into Lake Erie (Old Woman Creek Wetland). It was located in northern Ohio adjacent to Lake Erie (Mitsch & Reeder 1991, Bernal & Mitsch 2012). This wetland received water from the 69-km^2 agricultural watershed and, allowing lake water to flow into the wetland when the sand barrier of the lake was broken. Dominant plant communities in the wetland were *Nelumbo lutea, Typha* spp.*, Scirpus fluviatilis* and *Phragmites australis*. Followed with, a 112 ha tropical wetland that located in the campus of Earth University in the Caribbean lowlands of eastern Costa Rica. The climate was humid as a 10-year precipitation average of 3,463 mm/year. This wetland was dominated by water-tolerant species, for example, *Spathiphyllum friedricsthalii, Dracontium* sp.*, Raphia taedigera* and *Calathea crotalifera,* with surrounding hardwood trees and palms, like *Pentaclethra macroloba* and *Terminalia oblonga* (Mitsch et al. 2008).

The other three wetlands involved were a 3 ha tropical rainforest isolated wetland (La Selva wetland), located in a tropical rain forest within the La Selva Biological Research Station area at the confluence of the Puerto Viejo and the Sarapiqui Rivers, a 1200 ha seasonally wet tropical floodplain known as Palo Verde. Wetland and tropical seasonally flooded inland delta, named Okavango Delta in Botswana was a 12,000 km^2 (total flooded area during average years) to 15,000 km^2 (total area inundated during extremely wet years) tropical freshwater wetland in the semi-arid Kalahari Basin of northern Botswana, Africa. La Selva wetland was a rainforest wetland dominated by canopy, subcanopy, and understory tree species, such as *Anaxagorea*

Table 3: Comparison of carbon sequestration between 7 wetlands in Ohio, Costa Rica, and Botswana with different types of wetlands and climate (Source: Mitsch et al. 2012).

Climate	Humid temperate			Humid tropical		Dry tropical	
Wetland type	Created-flow through wetlands		Natural flow-through wetland	Natural flow-through wetland	Natural isolated wetland	Natural floodplain	Natural inland delta
Wetland name	Olentangy River Wetland Research Park (ORWRP) Wetland 1	Wetland 2	Old Women Creek, Ohio Costa Rica	Earth University	La Selva Costa Rica	Palo Verde Costa Rica Botswana	Okawango delta,
Carbon sequestrationg C m^{-2} y^{-1}	-219	-267	-143	-306	-84	-84	-82

(-) sign indicates the decreasing amount in atmosphere

crassipetala, Pentaclethra macroloba, and Rinorea deflexiflora (King 1996). Palo Verde wetland was a seasonally flooded floodplain freshwater marsh in western Costa Rica that experienced distinct wet and dry seasons due to both rainfall and occasional river flooding from the Tempisque River. The plants dominated also affected the distinct seasons, whereby floating aquatic and emergent plants such as *Eichhornia crassipes*, *Thalia geniculata* and *Typhado mingensis* dominated the permanent and saturated ponds during the wet season, whereas, grasses and sedges, such as *Eleocharis* sp., *Cyperus* sp., *Paspalidium* sp., *Paspalum repens* and *Oxycaryum cubense* dominated during the dry season (Crow 2002).

The carbon sequestration value that have been determined among the wetlands were four tropical wetlands sequestrated between 42-306 g C m^{-2} $year^{-1}$, with an average sequestration rate of 129 g C m^{-2} $year^{-1}$ while the one natural temperate zone wetland in Ohio sequestrated 143 g C m^{-2} $year^{-1}$. This proved that wetlands in the temperate zone sequestrated carbon much higher than tropical, which is also in agreement with Bernal et al. (2012). Carbon accumulation in the two created flows-through wetlands in Ohio were higher at 219 and 267 g C m^{-2} $year^{-1}$ for the planted and unplanted macrophytes wetlands respectively, which means 53-87% higher than carbon sequestration in the natural flow-through Ohio wetlands (Table 3). Generally, four out of five most effective wetlands in net retention of carbon were in the temperate zone. In their study of seven wetlands, the two constructed freshwater marshes in Ohio and the flow-through tropical slough in Costa Rica were the most effective for net carbon retention. The constructed wetlands sequestered more carbon and emitted less methane than the natural flow-through wetland in Ohio at Old Woman Creek. The flow- through tropical slough in humid tropical Costa Rica was similar in geomorphology and hydrology to these wetlands and has also high net carbon retention due to the flow-through conditions to optimize carbon sequestration, while keeping methane emissions low in all of these wetlands. The carbon sequestration findings are given in Table 3.

CONCLUSIONS

Different types of wetland systems, namely natural and constructed wetlands, have the potential to sequestrate carbon. Each wetland provides a potential sink area for atmospheric carbon. The wetlands across the world are significant sinks for carbon on the order of 830 Tg/year. However, if the wetlands, particularly constructed wetlands are not being managed and designed properly, they could become the sources of greenhouse gases since methane production is also a natural behaviour of wetlands. Due to the proven say that constructed wetlands can sequestrate carbon more than natural wetland, hence, there is a need for researchers to study the potential factors that might affect the constructed wetland in carbon sequestration, especially factors that can minimize the methane production in wetlands. In addition, a proper management plan for different types and function of constructed wetlands should be developed so that constructed wetlands could be utilized with benefits to society, environment and economy by considering the benefits and cost savings that wetlands could provide us.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support provided by the Universiti Kebangsaan Malaysia in the form of Dana Impak Perdana (DIP-2015-008) and ArusPerdana (AP-2014-009).

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